ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCE

MSc THESIS

Burak KURDAK

A SINGLE PHASE PLL BASED ACTIVE POWER FILTER SOLUTION FOR POWER QUALITY PROBLEMS IN RAILWAY ELECTRIFICATION SYSTEMS USING SCOTT TRANSFORMER

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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ABSTRACT

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Transportation is one of the biggest energy consumer especially automobiles. In a world where energy conservation and environmental protection are growing concerns, the development of electric vehicle technology has taken on an accelerated pace. Electrified railway system has big advantages to save energy, environmental factor and mass capacity compare with their rivals for example automobiles and aircrafts. Therefore the electrified railway has increased its share and importance on transportation system at last twenty years. Due to growing capacity and complexity of the railway systems, it introduced us with power quality problems. Power quality is become more a critical issue and it requires more careful control.

The aim of this paper is to introduce electrified railway system and mitigate the power quality problems in the 25 kV AC railway system and decrease the harmful effects to utility electric network using proposed topology. The method has two different parts. First one is an EPLL based single phase active power filter that can compensate the load reactive and harmonic current. The second one is Scott transformer can decrease unbalanced voltage on the network.

The performance and efficiency of the proposed method are investigated with simulation studies by PSCAD / EMTDC.

Key Words: Single phase active filter, Scott transformer, enhanced phase locked loop, power quality

ÖZ

YÜKSEK LİSANS

ELEKTRİKLİ RAYLI SİSTEMLERDE GÜÇ KALİTESİ PROBLEMLERİ İÇİN SCOTT TRAFO KULLANILARAK PLL TABANLI TEK FAZ AKTİF FİLTRE ÇÖZÜMÜ

Burak KURDAK

ELEKTRİK ELEKTRONİK MÜHENDİSLİGİ ANABİLİM DALI
FEN BİLİMLERİ ENSTİTÜSÜ
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Ulaşım sektörü en büyük enerji tüketicilerin biridir, özellikle arabalar. Cevreyi koruma ve enerji tasarrufu konularının giderek önem kazandığı dünyada, elektrikli araçların gelişimide hız kazanmıştır. Elektrikli demiryolu sistemleri enerji tasarrufu, çevresel faktörler ve yük kapasitesi açısından kıyaslanınca rakipleri örneğin uçak ve arabalara göre büyük avantajlara sahiptir. Bu nedenle son yirmi yılda elektrikli demiryollarının ulaşım sektöründeki payı ve önemi artmıştır. Geçen zamanda raylı sistemlerin artan kapasitesi ve karmaşıklığına bağlı olarak güç kalitesi problemleri ile karşılaşılmıştır. Bu problemler dikkatli kontrol edilmesi gereken, daha kritik bir hal almıştır.

Bu tezin amacı elektrikli raylı sistemleri tanıtmak ve önerilen metodu kullanarak 25 kV AC elektrikli demiryollarındaki güç kalitesi problemlerini ve elektrik şebekesine verilecek zararları azaltmaktır. Önerilen metod iki ayrı parçadan oluşmaktadır. Birincisi yükün reaktif ve harmonik akımlarını düzeltebilen EPLL'li tek faz aktif güç filtresidir. İkinci parça ise şebeke üzerindeki voltaj dengesizliğini azaltan Scott trafodur.

Önerilen metodun performansı ve verimliliği PSCAD/EMTDC programında farklı simülasyon çalışmalarıyla incelenmektedir.

Anahtar Sözcükler: Tek faz aktif filtre, Scott transformatör, geliştirilmiş faz döngü kilit, güç kalitesi

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LIST OF SYMBOLS

g	Gravity
m	Mass of vehicle
F	Force
R	Resistance of vehicle
km	Kilometer
k	Machine constant
p	The number of poles
Z	The number of conductors in the armature
ϕ	Magnetic flux per pole
T	The motor torque
Rf	Field resistance
Rar	Armature resistance
Lf	Field inductance
If	Field current
Iar	Armature current
Vb	The brush voltage
Ns	The synchronous speed of the motor in rpm
f	The supply frequency in hertz
P	Number of pole pairs
Ns	The synchronous speed in rpm
Nb	Base speed in rpm
Vmain	Voltage on main side catenary
Vteaser	Voltage on teaser side catenary
Ist	Teaser current
Ism	Main current
Is	Source Current
Iapf	Active power filter current
Vcap	DC link capacitor voltage

G	Gate firing signal
Iload	Load current
Err	Error signal to produced filter current

LIST OF ABBREVIATIONS

AC	Alternative Current
APF	Active power filter
ASME	American Society of Mechanical Engineers
AT	Auto Transformer
BT	Boosting Transformer
CPW	Catenary Protection Wire
CSI	Current Source Inverter
DC	Direct Current
DFT	Discrete Fourier Transform
EMF	Electro Motive Force
EPLL	Enhanced Phase-Locked Loop
GTO	Gate Turn-Off Thyristor
HV	High Voltage
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated Gate Bipolar Thyristor
IM	Induction Motor
Km	Kilometer
LPF	Low Pass Filter
PCC	Point of Common Coupling
PD	Phase Detector
PI	Proportional-Integral
PLL	Phase-Locked Loop
PQ	Power Quality
PU	Per-Unit
PWM	Pulse Width Modulation
RPM	Revolution Per Minute
RMS	Root Mean Square
SVC	Static Var Compensators
THD	Total Harmonic Distortion

VCO	Voltage Controlled Oscillator
VSI	Voltage Source Inverter
VSC	Voltage Source Converter

1.INTRODUCTION

Rail transport is the conveyance of passengers and goods by means of wheeled vehicles running along railways (or railroads). Rail transport is part of the logistics chain, which facilitates international trade and economic growth. Rail transport is capable of high capacity and is energy efficient, but lacks flexibility and is capital intensive. Despite the competition of airplanes, buses, trucks and cars, trains still play a major transportation role in society, filling specific markets such as high-speed and nonhigh-speed intercity passenger service, heavy haul of minerals and freight, urban light rail systems and commuter rail.

Transportation has a big share in energy consumption especially in case of automobiles. Railway is suitable for regular mass transportation and it is remarkably energy saving in comparison with its rivals, i.e. automobiles and aircraft. It holds an advantageous position in the field of commuter transportation, medium distance passenger transportation within three hours and heavy haul as large as ten thousand tons. Shifting transportation media from trucks and automobiles to railways is very important to settle future energy and environmental issue. (Watabane, 1999)

All around the world, the consequences of ever increasing automobile traffic had resulted in traffic congestion and severe environmental damage. Some countries have no exception. With the development of economy and the increasing population in worldwide cities, the transportation situation is getting worse. The ever-growing attractively of the private car has even worsened this situation. Therefore, a long-term traffic planning for big cities is needed to reduce the traffic congestion and the environmental pollution of inner urban transportation, as well as the general traffic situation of intercity transportation.

European studies estimate that by 2015 passenger traffic will increase 40 percent and cargo by 70 percent. This amount cannot be covered by the road alone. In the modal split the contribution of rail transport will increase to 10 percent for passenger transport and 15 percent for cargo. This means that the absolute rail transport of passengers will increase by a factor of 2 and goods by a factor of 3. The

modal split is mainly influenced by the cost of transport and by punctuality. The high energy efficiency of rail transport is one of its great advantages, especially in view of the requirements of the Kyoto Protocol concerning the emission of carbon dioxide. Nevertheless, railways have a great potential for increasing that energy efficiency even further, and one which directly correlates to reduced emissions. (Gunselmann, 2005)

On the other hand the cost of diesel fuel is increasing day by day .When the cost of the diesel was very cheap most of the countries were not interested in alternative methods for power supply systems. But after the diesel fuel was increased to high values the electrification of railway interest rose to peak level.

Related to all these reasons and with putting the boundaries away between the countries to improve trade, electrification of railway was spread very quickly after nineties. During the time when the traffic of the electrified railway system was grown rapidly and it introduced us new problems of power quality and integration of systems.

Basically the overall of railway system, railway electrification will be introduced in following chapters. However the main subject of this study is based on 25 kV AC electrified railway system power problems and solving the power quality problems with proposed method.

Major elements of electrified railway system, design criteria and the factors that determine appropriate system design will be discussed in chapter two.

The physical forces that effects train performance will be investigated in chapter three.

Even though the railway electrification is an extremely wide engineering area to study and understand, the systems will be introduced as detailed as possible in chapter four. The configurations, application methods, the component that build up the electrification system will be studied both for AC and DC supplied systems. And also the status of electrified railway in Turkey will be investigated in chapter four.

The different types of traction motors, their characteristics and several types of drivers will be introduced to understand basically the loads and their effects to the power system in chapter five.

In chapter six the power quality issues, the major problems and different solutions that have been already used in market will be investigated.

As a results of all information that had been collected from references during studies, have led us a new proposal method to solve problems. The component of the proposed method will be introduced in chapter seven.

The railway electrification load is one of the worst kinds of load for an electrical utility to supply. The only load which gives more challenge to the utility is arc furnace load. The railway electrification load is highly intermittent, irregular, low load factor and poor power factor. The railway electrification load creates system voltage and current unbalance, generates harmonics and results in voltage flicker. Because of the above characteristics the railway electrification load generally requires oversized substation facilities. It stresses the electrical utility equipment more and also causes interference with other customer loads and often complaints from the other utility customers, etc. (Bhargava, 1996)

An electrified railway line resembles a typical power transmission and distribution system. The major difference is that the loads (trains) move and change operation modes frequently. Power demand varies over a wide range and a load may even become a source when regenerative braking is allowed. Other uncertainties are resulted from a number of factors, such as service scheduling, train speed, traffic demands, track layout, traction equipment control and drivers behavior to name a few. (Ho, Chi, Wang, Leungt, 2004)

The electric trains that are fed by single phase 25kV AC catenary line are shown in Figure 1.1. A single-phase load is an unbalanced load to the three-phase power system. In an electric train, the single-phase AC power is rectified into the DC power. This leads to the generation of harmonic currents. As a result, an electric railway load is a large unbalanced and harmonic-generating load. Dividing the catenary line to the in-coming and out-going sides makes it possible to present each side as a separate single-phase load. (Hooman, Wilsun, 2008)

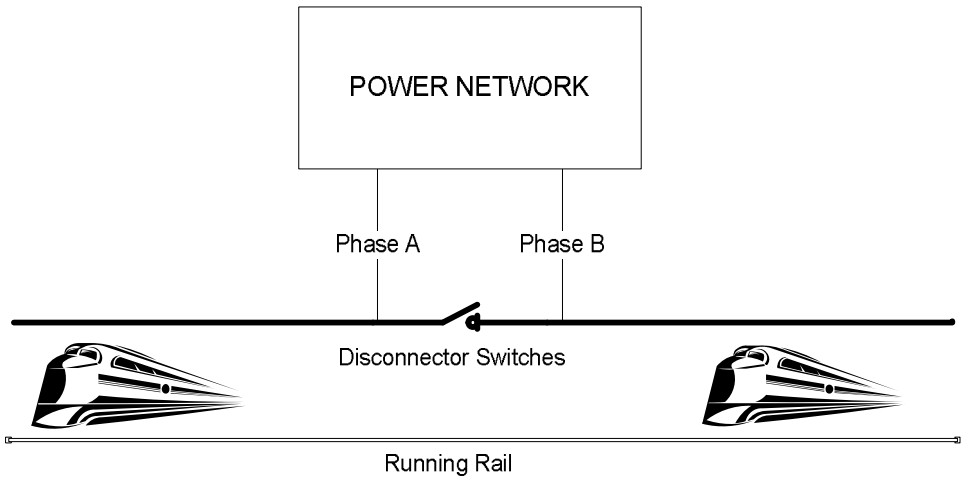

Figure 1.1. Single-phase AC catenary line supplies the electric train

As a result of these the major power quality problems in 25 kV AC railway systems could be listed as in below.

1- Unbalanced load due to single phase catenary connection.
2- Unbalanced load due to moving and changing loads (train).
3- Harmonic current generated by train rectifiers.
4- Reactive power due to big power demands of trains.
5- Voltage flicker due to moving load from one section to another

In order to solve all these problems proposed topology will be presented and simulated in this paper. The simulation of model will be done with PSCAD/ EMTDC The proposed model can be divided into four main elements (Fig 1.2.).

1- Single Phase Active Power Filter
2- Scott Transformer
3- Loads (Train)
4- A New Reference Current Generator Enhanced Phase Locked Loop

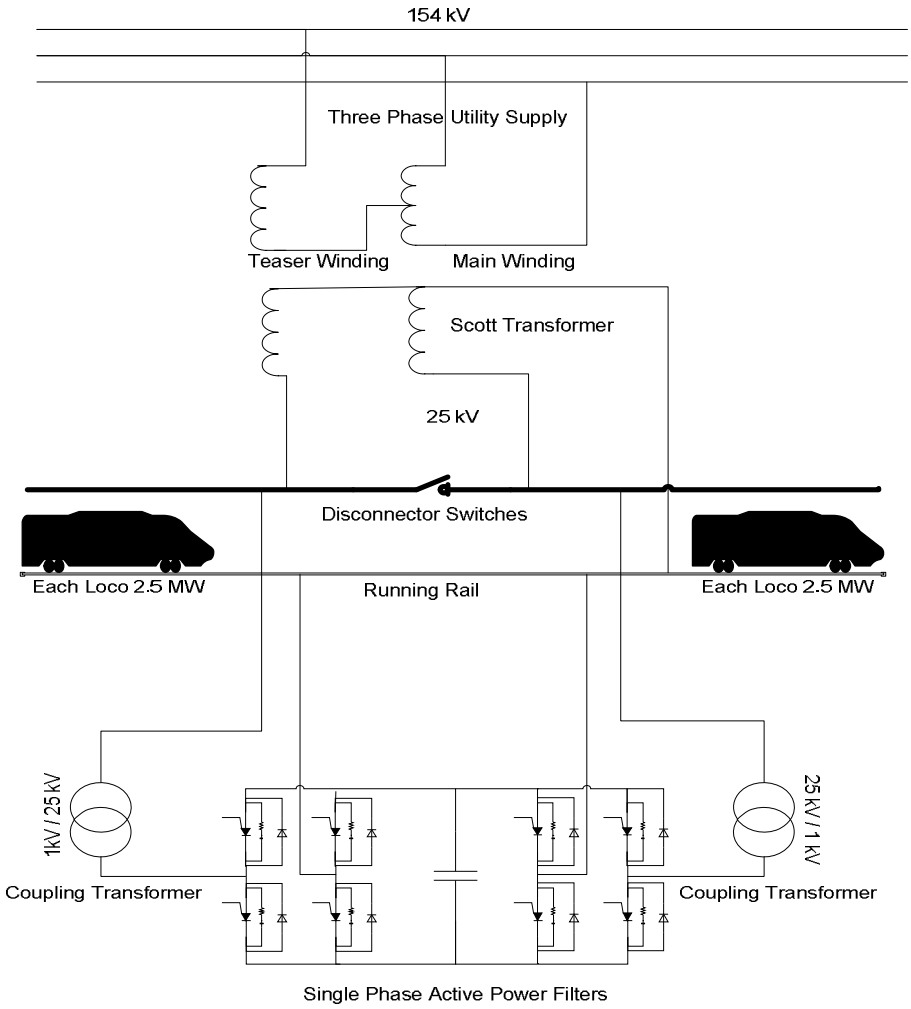

Figure 1.2. Proposed Model

An active power filter is proposed for the electrified railway power supply system, which can compensate the load's reactive and harmonic current, and is suitable for the system adopting asymmetrical transformer. The filter consists of two single-phase 4-quadrant converters connected back to back through the dc-link capacitor. Decoupled by the capacitor, the converters can be controlled separately, which simplified the control process and improve the switching efficiency. The coupling transformers are placed in front of the active filter that will adjust voltage level of converter to catenary.

Scott transformer is a widely used transformer that converts the three-phase supply into two single-phase power supplies. It has been used in many electric railway systems to reduce the unbalance problem, for instance in Tokaido-

Shinkansen electric railway. If two loads are equal, Scott transformer presents them as one balanced three phase load to the three-phase supply system. This solves the imbalance problem. Nevertheless, these two single-phase loads are rarely equal in reality. The transformer still draws unbalanced power from the system. However, the degree of unbalance is reduced in comparison with the case in which loads are directly connected the system. (Hooman, Wilsun, 2008)

Active compensation of harmonics, reactive power and unbalance is required for improving power quality, control and protection an integral part of an active compensation device is the detection unit which generates the reference signals. Various methods, e.g. Discrete Fourier Transform (DFT), Phase-Locked Loop (PLL), notch filtering and theory of instantaneous reactive power have been presented in the literature for this purpose

EPLL technique will be used in this model to control and generate the required reference signals of active power filter. A single-phase signal processing system for extraction of harmonic and reactive current components Active Power Filters (APF), the system is based on an enhanced phase-locked loop (EPLL) system and its features with respect to other methods are as follows.

• It simultaneously extracts harmonic and reactive current components independently.

• Its structure is adaptive with respect to frequency.

• Its structure is robust with respect to the setting of the internal parameters.

• Its performance is immune to noise and external distortions.

• Accuracy and speed of its response are controllable.

• Its structural simplicity provides major advantage for its implementation within embedded controllers. (Karimi. Mokhtari, Iravani, 2004)

2.DESIGN PRINCIPLE OF ELECTRICAL RAILWAY

Railway engineering is one of oldest of the formal engineering disciplines, tracing its roots to the early 19th century and birth of steam-power in Britain.

This branch of engineering developed through the efforts of engineers and railroad companies to make railway systems safer, more reliable, more powerful, and more cost efficient. Railway engineering has evolved into a diverse profession, requiring talents in a number of .

Historically, railway engineering was strictly a mechanical engineering discipline, encompassing pressure vessel design, purely mechanical vehicle components, and hand-powered switches. However, railway engineering has become more reliant on electronic systems, specifically control and communications. As an example of this interdependence, the Rail Transportation Division of the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronic Engineers (IEEE) hold a joint conference each year to discuss advances in railroad-related research, development, and testing.

2.1.Railway Engineering Disciplines

Railway engineering contains many sub-disciplines, including:

- Vehicles – This division includes the design, construction, and testing of railroad vehicles, including locomotives and rolling stock. Activities may include aerodynamic design and testing for high-speed locomotives, vehicle suspension design to improve rider comfort in passenger vehicles etc…
- Traction Systems – This includes the design, development, and testing of electric, diesel, or hybrid locomotive traction systems.
- Track – Track engineering can include developing rail maintenance procedures, designing track bed foundations, and specifying rail components such as switches.

- Wheel/Rail Interaction – Wheel/rail interaction is concerned with the forces between the stationary rail and passing wheels. This can include wheel/rail profile optimization, analysis of hunting behavior, and development of wheel and rail force monitoring systems.
- Infrastructure – Infrastructure includes the design, fabrication, and maintenance of bridges, tunnels, grade crossings, and rights-of-way.
- Signaling and Communication – This division of railway engineering is concerned with the electrical and voice signals needed to control a railway system. This can include dispatch protocols, signaling logic, and communication infrastructure, both on board vehicles and in wayside systems.(Susan Kristoff)

The vehicles and traction systems are the main player that will be introduced more detailed in this thesis.

2.1.1.Vehicles

2.1.1.1.Light Rails

A light rail train basically stops frequently almost every mile or two. Usually have two or three cars, requiring quick acceleration and stopping. The power requirements for these trains are low and are usually less than a MW. The light rails can be fed easily from a low voltage DC system. The substations are two to three miles apart and are generally authorized located near the train station. (Bhargava, 1999)

2.1.1.2.Commuter and Intercity Trains

The Commuter trains are usually long trains serving suburban areas, traveling at top speed of up to 125 miles. They have higher power demand and are fed from high voltage 15 to 25 kV catenary systems. The commuter trains stops are 5-10 miles apart, giving them time to run at higher speeds of up to 125 miles, unless restricted by other limitations like the signaling system, track condition etc. They can be fed

from one of the several alternate systems and require more considerations of power quality etc. The power needs are 3 to 4 MW.

The High Speed Inter-city Trains run at higher speeds and may have more carriages. The power demand is therefore higher. Since the cities may be considerable distance apart, they do not need frequent stopping. Power demand may range anywhere from 3 MW to 4 MW. The power requirement for a conventional railway traction stations for these trains can be supplied from 69kV, 115 kV or 220kV systems.

2.1.1.3.Very High Speed Trains

The TGV trains in France are one of the fastest trains in the World. The TGV trains run up to 330 miles per hour top speed and therefore require much higher power. The TGV trains, in France, operate with 5 minute headway at peak hours. The system has been designed to operate with 4 minute headway. SNCF, the French Railway, uses a single phase 25kV, 50 Hz system for their conventional railway system but uses a +/-25kV auto-transformer arrangement for the very high speed, TGV trains. The power to the Traction Power Substation is supplied by EDF, the French National Grid, and this traction load of the TGV or major commuter system is fed only from the high voltage systems at 275kV or 400kV. This provides added reliability and reduces power quality problems to their other customers. The electrical system is designed for loss of a substation.

2.1.1.4.Freight Trains

The freight trains have much higher power demands. The freight trains run slow (less than 80 MPH), but use much higher tractive power. The train sets for freight trains are very different from one country to another country. The freight trains in most of the countries in Europe or rest of the World are run on the same electrified railway tracks as the commuter trains or the inter-city trains. The power needs are between 4 to 8 MW. The freight trains in US are hauled by 4 to 6 diesel

locomotives. The US freight rails use double stack freight wagons compared to single stack in Europe and other parts of the World. The freight trains use longer train-sets (100 wagons or more per freight train) requiring much greater power from 18 to 24 MW.

Railway electrification loads and systems required for light rails, commuter trains, and fast high speed trains, and of course for the freight trains are all different. The power demands for these different rail systems are very different. Selection of an appropriate electrification system is therefore very dependent on the Railway system objectives. The typical power demand for each of these classified railway traction systems are shown in Table 2.1. (Bhargava, 1999)

Table 2.1 Power demand for different railway trains (Bhargava, 1999)

Rail System	**Power Demand**	
Light Rail	Less than a MW	Low
Commuter Trains	About 3-4 MW	Medium
High Speed Inter-city Rails	About 4-6 MW	Medium
Very Fast Commuter Trains	About 8-10 MW	High
Freight Trains in Europe	About 6-10 MW	High
Freight Trains in US	From 18-24 MW	Very High

2.2.SIMULATION

2.2.1.Early In The Planning Stage

The need for train performance related simulations arises at several stages in the genesis of a railway:

- early in the planning stage, basic flow models of passenger throughput related to train size, headway and scheduled speed are required;
- Once the station to station distances are known and the basic size of trains and the headway known, detailed assessments of competing traction packages are required. Single train constant voltage performance calculations are used to give station to station runtimes and energy consumption.

- With most of the basic parameters settled, studies of the whole system operation can be examined using an interlinked simulation program which combines the traction performance calculation with the solution of the complete power supply network. It is essential to include power supply network into simulation for accurate modeling of voltage dependent traction.

Before basic parameters for the railway can be laid down, estimates of passenger flows must be made. These can be met with large trains at infrequent intervals or small trains at frequent intervals. Passengers prefer short time intervals (headways) and also the capital cost of the permanent way and stations are reduced for smaller trains.

A further very basic parameter is the average speed the trains achieve on an end-to-end journey. This clearly cannot be too low as the journey times will exceed what is regarded as acceptable to passengers and be poor in comparison with other forms of transport. Furthermore, there is an advantage in increased speeds in that the fleet size to achieve a certain headway service is reduced. A plot of the minimum number of trains needed to run a two-minute service on a 20 km line for various speeds is shown attached in Figure 2.1

Increased scheduled speed is very expensive in terms of energy consumption. The power required to run the same service is superimposed on the fleet-size curve. It can be seen immediately that the curve is very steep. Increased power implies increased capital costs of line side and train-borne equipment as well as increased running costs throughout the life of the railway. The consequence of specifying certain scheduled speeds in terms of energy consumption can vary considerably with the choice of traction motor characteristic and operating philosophy.

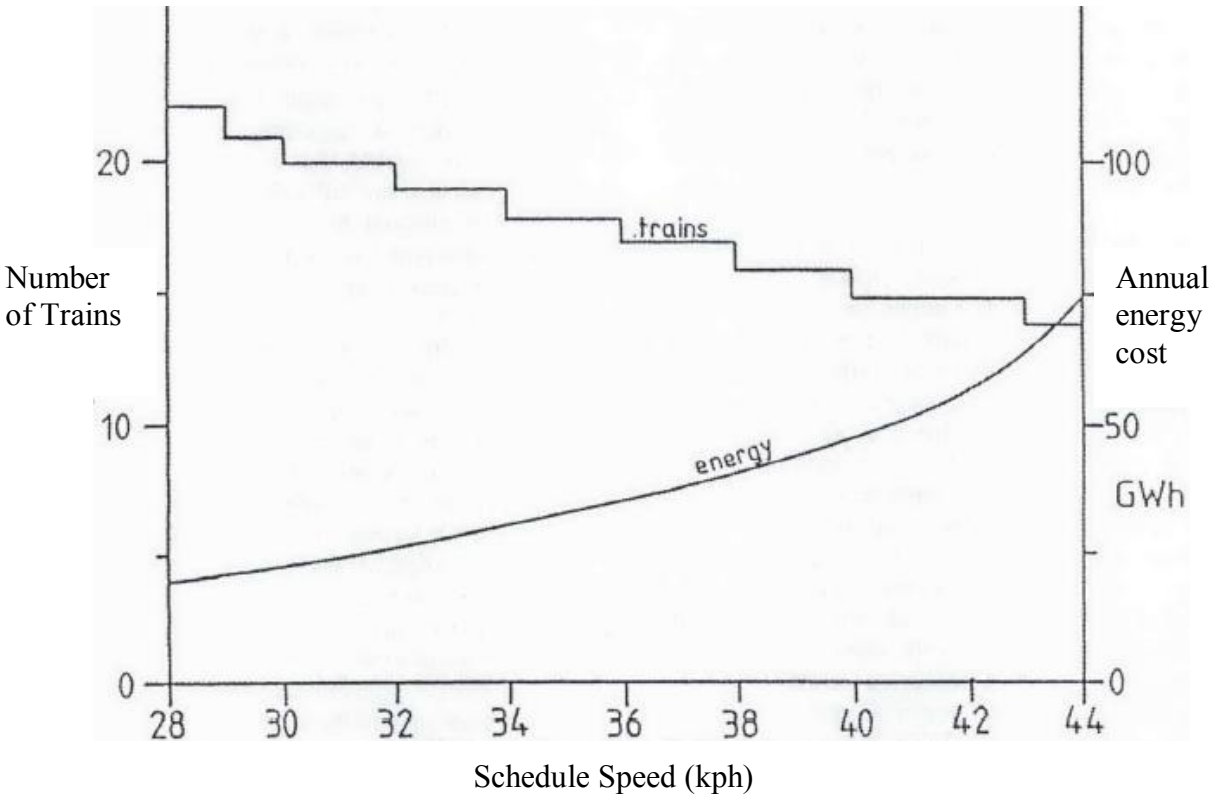

Figure 2.1 Fleet size and energy cost variation with schedule speed (Goodman, 2006)

2.2.2.Exploring Factors That Affect Runtime And Energy Consumption

The following comments discuss some of the fundamental issues relating to the specification of traction drives that can be quantified by the use of train performance simulation methods. The interplay of runtime and energy consumption is most apparent in metro systems and thus the comments largely refer to these.

2.2.2.1.Train Weight

Clearly, the lighter the train, the less energy will be used in a given run. Apart from small shifts in the relative significance of the different terms in the drag equation, for a given run profile, the energy consumption will vary with the weight linearly. Thus it is common to quote energy consumption in Wh/t-km (Watt hours per ton-kilometer) when comparing the effect of other factors in the design. However,

this should not be used to obscure the basic fact that reducing weight is an important element in overall energy reduction techniques. Some operators quote energy on kWh/car-km for this reason.

The specific energy consumption is sensitive to a wide range of parameters, but for the station spacing and scheduled speeds typical of metro systems the overall energy consumption will usually lie in the range 40 to 180 Wh/t-km.

2.2.2.2.Scheduled Speed

Figure 2.2 shows the motoring and braking energies for a train with fixed acceleration and braking rates of 1.2 m/s^2 and 1.0 m/s^2 respectively, a dwell time of 20 s and an assumption regarding the shape of the motor characteristic where the minimum field strength is taken as 40% of the full field strength. The key factors which are allowed to vary on the diagram are the station separation, in the range 500 m to 2000 m and the motor peak power expressed as kW/t and in the range 4 to 20.

The most obvious feature of these results is the very great sensitivity of the energy consumption to the scheduled speed. This is particularly so for short station-to-station spacing. For a typical metro, the average spacing is around 1 km and thus a reasonable scheduled speed of 38 kph will require about 11 kW/t and use 85 W/t-km for motoring. With regenerative braking a potential saving of about 30 W/t-km is available giving a net consumption of 55 W/t-km. Clearly, the results shown in Figure 2.2 are calculated for fixed values of many parameters, only a few of which are explicitly mentioned above. Other major assumptions are that the train is on tangential track and not affected by speed restrictions. It is obviously necessary to perform exact simulations for final confirmation of equipment performance. (Goodman,

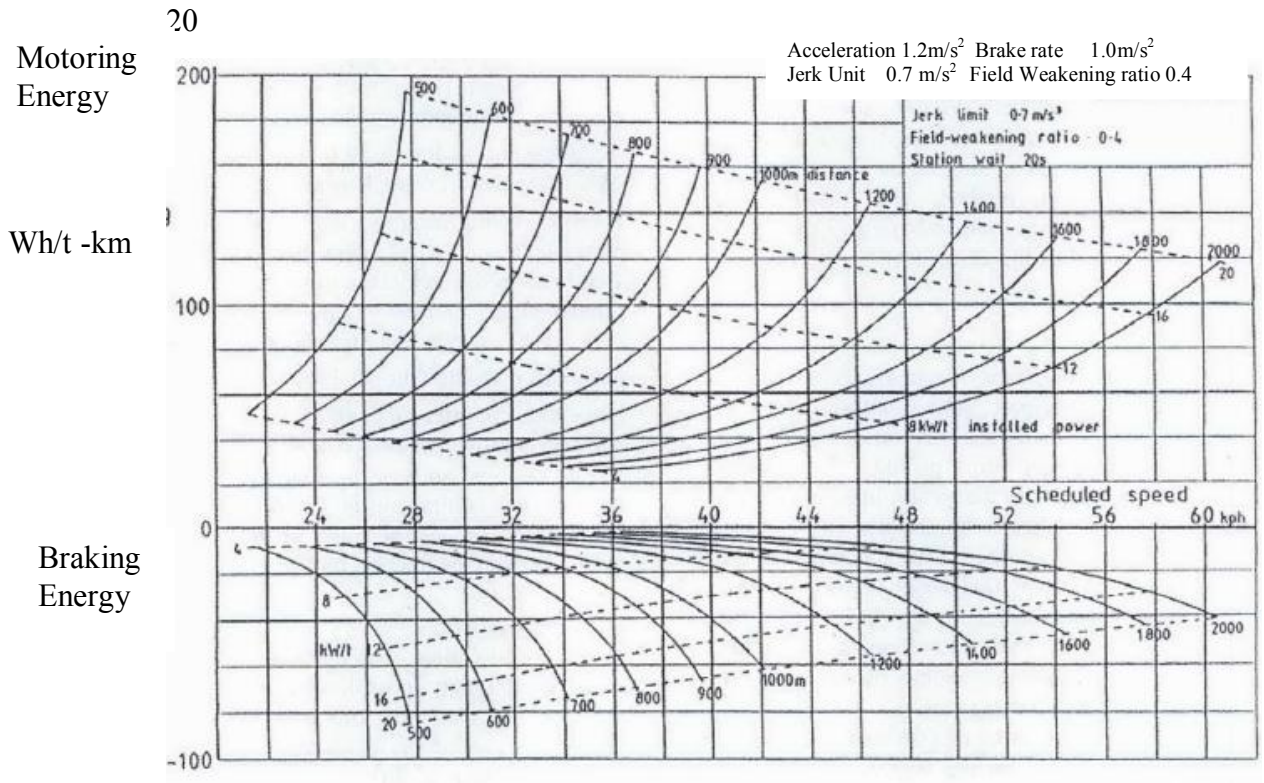

Figure 2.2. Specific energy consumption vs. schedule speed for various distance and installed powers (Goodman, 2006)

2.2.2.3.Proportion of Motored Axles

Basically the number of motored axles determines the starting acceleration because of adhesion limits. The influence of initial acceleration on energy consumption is evident from Figure 2.3

Accelerations as low as 0.6 m/s are characteristic of *25%* axles motored stock whereas the higher figure of 1.4 m/s would usually require 67% or 75% axles motored. The effect is again due to reducing the peak speed required to achieve a given runtime.

Similar considerations suggest a high brake rate will also save energy by reducing peak speed. The generalized results shown here are based on 1.0 m/s^2 brake rate, but rates up to about 1.3 *m/s*^{2} are used. With non-regenerative control equipment, the influence of brake rate is only via the peak speed. When regenerative

equipment is fitted, the best policy is much less obvious because of the limited braking available from the traction motors. (Goodman, 2006)

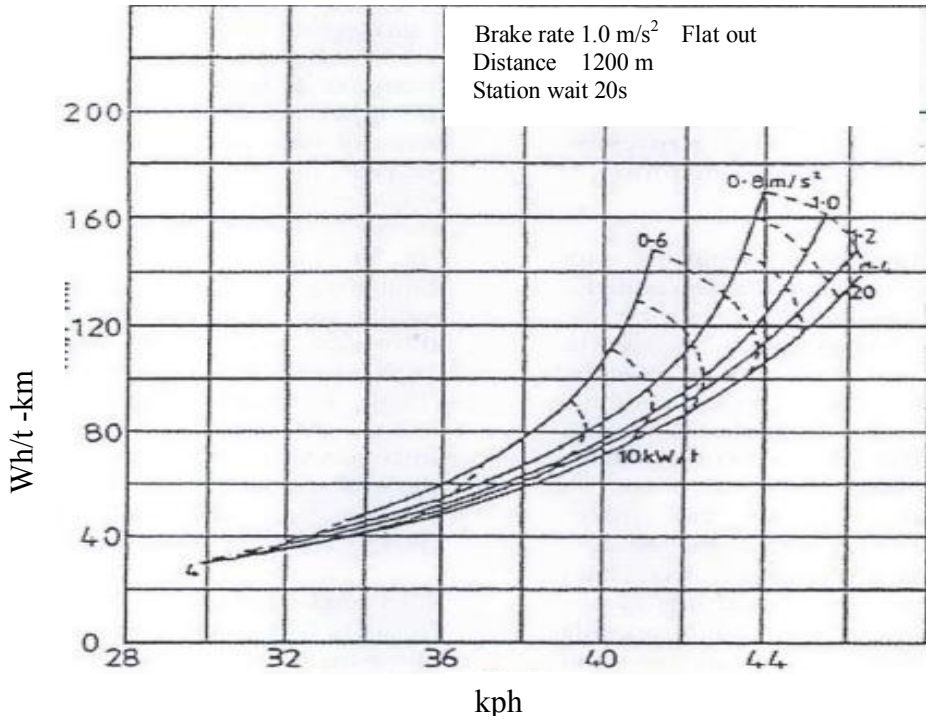

Figure 2.3 Reduction of energy consumption by using high initial acceleration (Goodman, 2006)

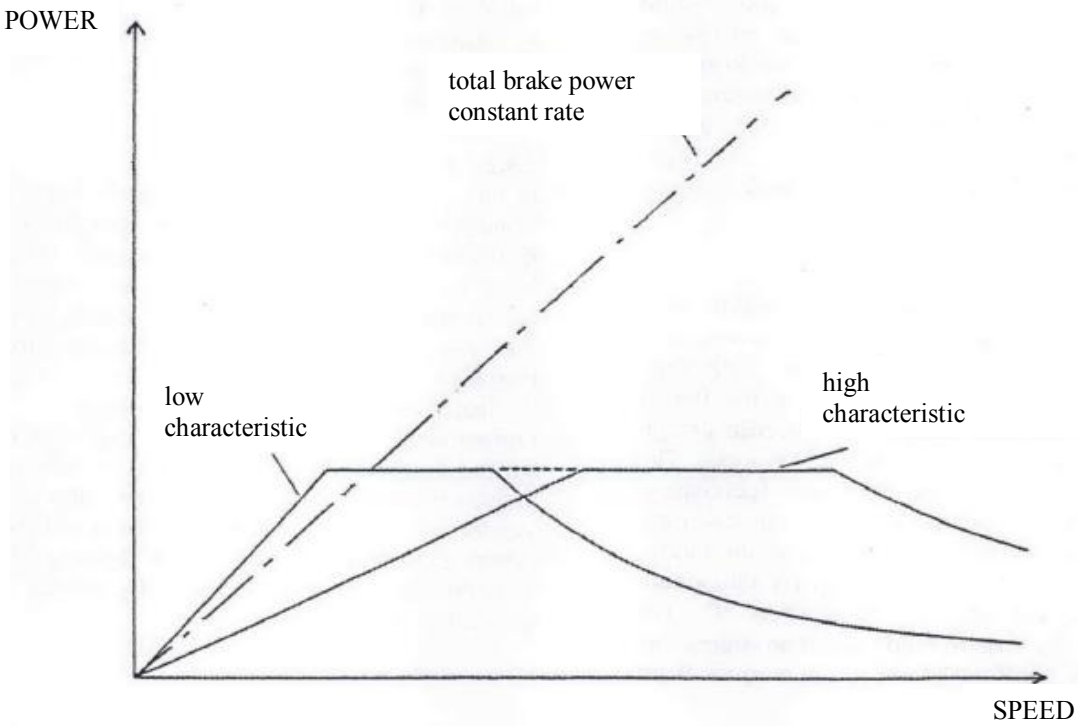

Figure 2.4 Match of low and high motor characteristics to required brake power at constant brake rate (Goodman, 2006)

2.2.2.4. Peak Power.

It is not possible to maintain the initial acceleration up to the design speed limit for the vehicles. By changing the gear ratio and/or motor design, the end of the constant torque region can be adjusted to occur at different speeds; if at a relatively low fraction of top speed (e.g. 25-30 kph on a 90 kph top speed train) it is referred to as a low characteristic motor, if at a relatively high fraction (e.g. 40-45 kph) then it is referred to as a high characteristic motor. The general appearance of these curves is illustrated in Figure 2.5. Notice that for the same value of peak power, the low characteristic implies high initial acceleration and vice versa. From the considerations given in the previous sub-section, the low characteristic machine will give the lowest energy consumption in motoring. (Goodman, 2006)

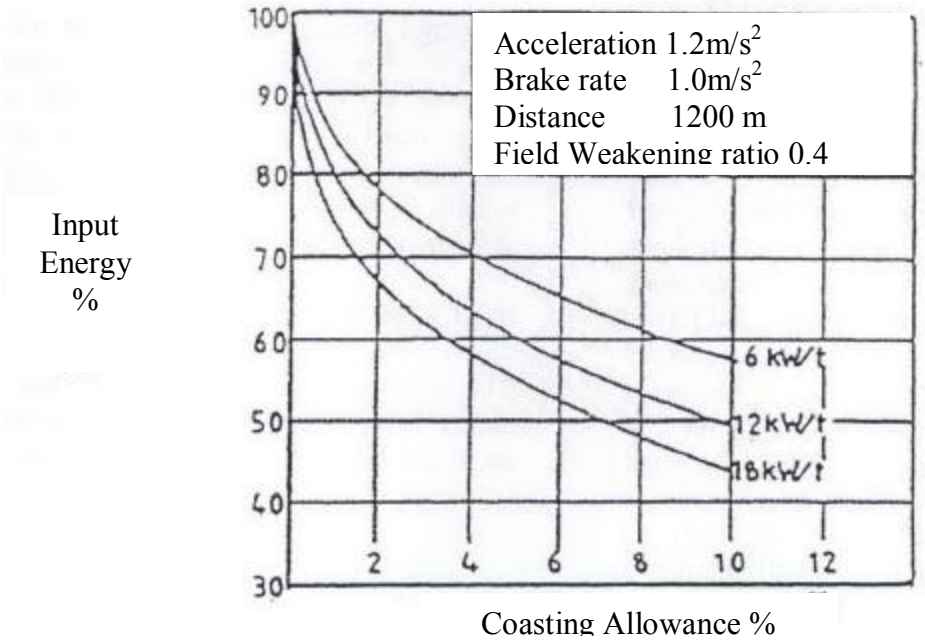

Figure 2.5. Curves showing rapid reduction of energy consumption with small runtime extensions by employing coasting (Goodman, 2006)

2.2.2.5. Motor Characteristics

The considerations of initial acceleration, its relationship to the number of motored axles and the limitations on peak power, combine to prescribe the most energy-efficient motor characteristics, at least in motoring. In essence, sufficient peak power must be installed to achieve a given schedule speed and this power should be used to give a high initial acceleration up to a low base speed, although this will probably require 2/3 or 3/4 axles motored.

Unfortunately, in the braking mode this motor characteristic will not give the best regenerated energy. Generally speaking, operators prefer to use a constant brake rate from any brake entry speed and this means that, at the high-speed end, the motors cannot provide all the brake effort. A blending of electric and mechanical brake is necessary. The match between the required brake power and that which the motors can provide is also illustrated in Figure 2.6

The high characteristic is more favorable for braking as, although it cannot give all-electric brake at low speeds, the lost area between the curves, which represents energy, is less for this case. However, detailed simulations suggest this is

not a good solution overall because of the increased input energy in motoring. It is usually found that measures to reduce input energy are the most successful in reducing net energy because of the 'round-trip' efficiency of the traction equipment; that is to say, for every kWh put into the train, the most that can be got back is about 0.65 kWh. (Goodman, 2006)

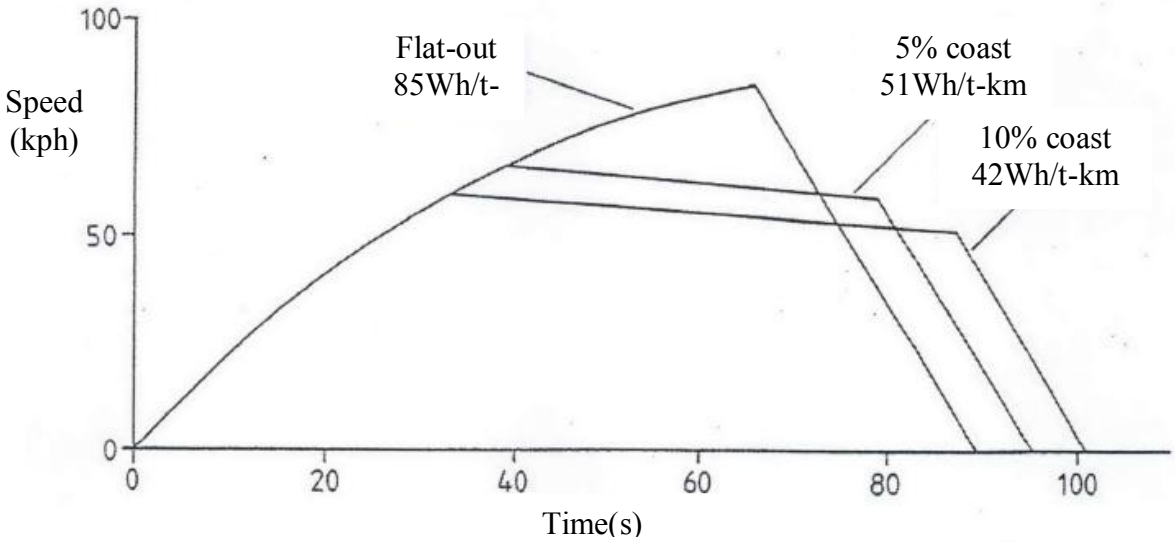

Figure 2.6 Trajectories for various levels of coasting showing the reduction in peak speed and thus energy consumption (Goodman, 2006)

2.2.2.6.Coasting

The use of a period of coasting in the middle of a station-to-station run has long been recognized as a very effective means of saving energy with only modest increases in runtime compared to the flat-out case. Figure 2.5 shows how rapidly the specific energy consumption reduces with coast allowance. The savings up to about 7% coast allowance (percentage increase in runtime compared to the flat-out case) are very attractive, beyond that point the returns diminish.

Coasting is effective because the energy put into a train to accelerate it to a speed ω is $l/2M\ \omega^2$ where M' is the effective mass. For metro and suburban trains the frictional drag is small compared to the tractive effort available for most of the speed range; furthermore the trains spend little time running at speeds anywhere near the

balancing speed (where tractive effort equals frictional drag). Consequently, the dominant factor in the input energy is simply the peak speed reached between stations. Clearly, any technique which reduces the peak speed will save input energy. Furthermore, the effect is sensitive to small changes because the input energy is related to the peak speed squared.

Figure 2.6 shows a simplified set of trajectories comparing the flat out case for a particular station-to-station run with allowances of *5%* and 10% coast allowance. The initial change to *5%* coast saves 34 Wh/t-km (40%), going to 10% a further 9 Wh/t-km (11%). The peak speed in each case is approximately 88 kph, 68 kph and 60 kph. The reductions in the squared values of the latter two speeds compared to the squared value of the first speed are 40% and *52%* respectively, confirming that the energy is almost entirely related to these peak speeds. (Goodman, 2006)

2.2.3.Conclusion Regarding Energy Consumption

In order to reduce energy consumption the following operating characteristics should be given attention.

To reduce input energy

- Reduce train weight
- Use longest runtimes compatible with scheduled speed i.e. reduce waiting times and use coasting
- Use the maximum available power
- Use low characteristic motors which have sufficient axles motored to get high initial acceleration
- Maintain the traction power over as wide a speed range as possible
- Use a high brake rate.

To improve regeneration

In this area of improving regenerative brake the best strategies are not so easily defined. Both the techniques mentioned have cost and weight penalties. On the other hand, improved electric brake can give useful savings on mechanical brake maintenance costs; so much so that some schemes employ rheostatic braking which increases the electric brake but in a way which dissipates the energy rather than saving it.

Furthermore, the usefulness of regeneration does depend on the ability of the supply network to absorb the regenerated energy. This, in turn, depends on the voltage variation at the generating train and the overall system receptivity. It is to address these problems that a multi-train simulation with the power network included is needed (Goodman, 2006)

3.FUNDAMENTAL OF THE TRAIN PERFORMANCE

3.1.Basic Equation of Motion

The obvious starting point is to understand the work that the traction motor needs to undertake. This is determined by the basic equations of motion, along with some limiting factors such as the adhesion (or level of friction) between the wheel and the rail.

Simplistically we need to know how fast the train has to go, and how quickly we want it to get to that speed, i.e. how fast it must accelerate and these details have been already discussed in chapter 2. The acceleration rate will be determined by the Tractive Effort (TE) the motor can provide, while the top speed is governed by the total power available.

$$\text{Force} = \text{Mass} \times \text{Acceleration} \tag{3.1}$$

In the case of traction calculations this can be restated, where

$$\text{Force} = \text{Tractive Effort} = \text{TE}. \tag{3.2}$$

$$\text{TE} = \text{Mass (kg)} \times \text{Acceleration (m/s}^2) \tag{3.3}$$

However it is usual to quote TE in kilo-Newtons (kN) as this leads to easily handled numbers, requiring multiplication by a thousand, or more easily just referring to the train weight in tonnes rather than kilograms. (Nicholson, 2008)

$$\text{TE (kN)} = \text{Mass (tonnes)} \times \text{Acceleration (m/s}^2) \tag{3.4}$$

3.2.Balance Of Forces

Once the tractive effort or braking effort provided by the traction equipment is known, there are two effects which add or subtract from this force before the acceleration or deceleration can be deduced.

3.2.1. Train Resistance

Train motion is opposed by friction of various sorts, principally bearing friction and aerodynamic drag. Bearing friction is mostly characterized by a constant component proportional to weight and a viscous term proportional to speed and weight. Aerodynamic drag also exhibits viscous characteristics but tends to be mostly proportional to speed squared or even cubed. It is very difficult to predict rolling resistance from theoretical calculations and the figures used in calculations are usually based on measurements extrapolated to new rolling stock. The measurements are performed by run-down tests where the natural deceleration of a train on straight, level track on a windless day is measured.Davis Equation is in below.

$$\text{Drag force} = a + b\psi + c\psi^2 \tag{3.5}$$

Where a, b, c are coefficients for particular stock in particular conditions. It is common practice to use different values for open or tunnel situations. A further component of friction is associated with the train passing round curves and referred to as curve resistance. Again it is in reality a complicated effect but is usually assumed to behave as

$$K/R \quad N/\text{tonnes} \tag{3.6}$$

where R is the radius of curvature of the track in meters and K is an experimentally determined constant. For many purposes, curve drag is ignored. (Goodman, 2006)

3.2.2.Gradient

Trains are heavy and require substantial effort to push them up slopes. If a train of mass M is on a slope making an angle α to the horizontal the vertical force Mg (g is the acceleration due to gravity, 9.81 m/s^2) can be resolved into $Mg\sin\alpha$ along the track and $Mg\cos\alpha$ perpendicular to the track, as shown in Figure3.5.

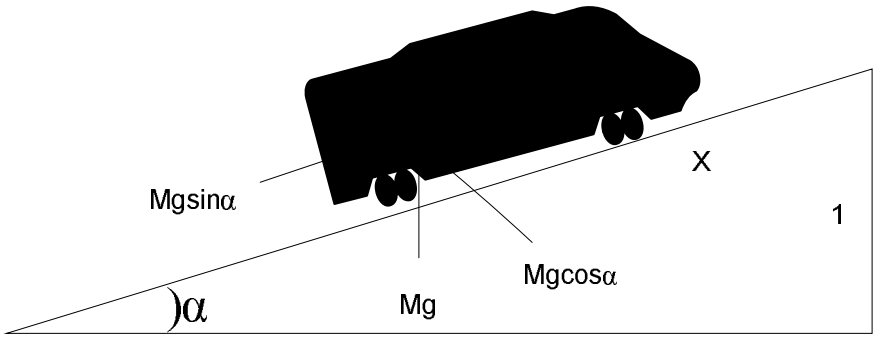

Figure 3.1. Resolution of forces due to train mass on a gradient (Goodman, 2006)

Gradients on railways are small and usually expressed in the form 1 in X, where X is the horizontal distance moved to rise 1 unit. Thus it is sufficiently accurate to take and the force perpendicular to the rails for friction or adhesion calculations can be treated as unchanged from the value on tangent track, Mg. (Goodman, 2006)

$$\text{Sin } \alpha \approx \tan \alpha \approx 1/X \text{ and } \cos \alpha \approx 1 \quad (3.7)$$

$$\text{Hence linear force} = Mg/X \text{ Newton} \quad (3.8)$$

3.3.Effective Mass

When a train accelerates along a track the total mass (tare mass + passenger or freight mass) is accelerated linearly but the rotating parts are also accelerated in a rotational sense. The parts involved are usually the wheel sets, gears and motors, the effect of the latter being magnified by the gear-ratio squared (assuming the motors are geared to rotate faster than the wheels) as in the 'push-and-go toy'. It is usual to express this rotational inertia effect as an increase in the effective linear mass of the train called the 'rotary allowance' and expressed as a fraction of the tare weight of the train.

effective mass = actual tare mass (1 + rotary allowance in p.u.) + passenger or freight load (3.9)

The value of the rotary allowance varies from *5%* to *15%* depending on the number of motored axles, the gear ratio and the type of car construction. (Goodman, 2006)

3.4.Adhesion

The available frictional force between the steel wheels of the train and the steel of the rails is a fundamental physical property limiting the performance of the trains in a very significant way. The coefficient of friction μ, sometimes simply called the adhesion, is the fraction of the perpendicular force on the rails which can be exerted along the rails before slipping occurs. It has a value between *5%* and *50%* depending on conditions, although the range 10% to 30% is more normally assumed for performance calculations. Lower values are assumed for braking (to allow safety margins), perhaps as low as μ = 0.08. EMU and metro consists are usually reckoned to be able to rely on 20% adhesion (i.e. μ=-0 .2) for motoring whereas locomotives are assumed to achieve about 30% adhesion. The friction phenomenon is actually more complicated then simply sliding at a fixed limiting force and if a wheel can be controlled to slip slightly a higher frictional force can be achieved. Many modem locomotives are fitted with this 'creep' control and achieve adhesions in excess of 40%. The upper limit of 50% is sometimes assumed in stress calculations to model a braking train suddenly encountering dry, sanded track.

Evidently, this relatively low (compared to road vehicles) adhesion limits the tractive effort that can be developed and thus the starting acceleration or hill climbing ability. It is the main reason why railway gradients are shallow, especially where locomotive haulage is used. For metro systems, to obtain short station-to-station run-times high acceleration' deceleration is needed and the limited adhesion leads to a need for a high proportion of motored axles. Historically, this is one of the chief reasons for the use of electric traction for surface metro systems. Passenger comfort also provides a realistic limit at about *1.5* m/s2 . (Goodman, 2006)

3.5.Example For Traction Motor Requirements

As a example of the explanations that have been done in previous sections, the calculation of the motor requirement of London Underground tube train shall be given in this part . The equation 3.4 shows us the motion equation for ideal conditions without any losses.

Thus on a level track and assuming that there is no friction or losses, a typical London Underground tube train, where 6 cars are 156 tonnes at tare with a fairly typical starting acceleration (for new trains) of around 1.2 m/s^2

$$TE = 156 \text{ tonnes} \times 1.2 \text{ m/s}^2 = 187.2 \text{ kN} \quad (3.10)$$

However equation (3.10) is optimistic as it does not allow for the rotational inertia of components such as the motors, wheel sets etc. Therefore the amount of the rotating mass needs to be added to the train weight, if the exact amount is not known it is reasonable to assume 10% for the tare weight, the actual value for our notional Lu train is 13.5 tonnes (8.6%). Therefore Equation (3.10) now becomes Equation (3.11).

$$TE = (156 + 13.5) \text{ tonnes} \times 1.2 \text{ ms-2} = 203.4 \text{ kN} \quad (3.11)$$

This deals with moving the train, but to ensure that the timetable can be achieved regardless of the passenger load we want the same performance to be achieved with a full passenger load, what constitutes a full load for design purposes will vary from operator to operator. For our LU train a full passenger load is 800 passengers at 75 kg/passenger, an additional 60 tonnes to move. Equation (3.11) thus develops to Equation (3.12)

$$TE = (156 + 13.5 + 60) \text{ tonnes} \times 1.2 \text{ ms-2} = 275.4 \text{ kN} \quad (3.12)$$

However this is still optimistic as we do not live in a frictionless world. The movement of the train is resisted by several elements, resistance from the bearings on the axle, losses at the wheel rail interface and aerodynamic resistance (only significant at fairly high speeds). The impact of these loses is calculated using the Davis Equation (3.13) or variations thereof.

$$R = A + Bv + Cv2 \quad (3.13)$$

In Equation (3.13) the co-efficients represent the following;

- A represents the static friction
- B accounts for dynamic friction
- C is the aerodynamic coefficient
- v is the vehicle velocity

Most major railways systems, and manufacturers, have their preferred values that they use for a, b & c, often using different values for circumstances such as operation in tunnels. In the case of very large freight trains these values are critical, and can vary widely depending on the type of wagon used, especially the type of axle bearings. For example again the values used by London Underground are shown in Table 3.1, where v is stated in km/h, this gives a typical value in the open at 20 kph of 3.1 kN.

Table 3.1 Typical LV train resistance co-efficients

	A (Newtons)	B (kg/h)	C(kg/km)
open	2900	1.9	0.61
tunnel	2900	8.7	2.3

Figure 3.6 shows the way that train resistance increases with speed, and the appreciable difference between the assumed resistance between running on the surface and running in a (on the Underground, very small) tunnel. At lower speeds the resistance is not really a significant factor, but at higher speeds, especially in tunnels, it does become significant, equal to at least an extra motor.

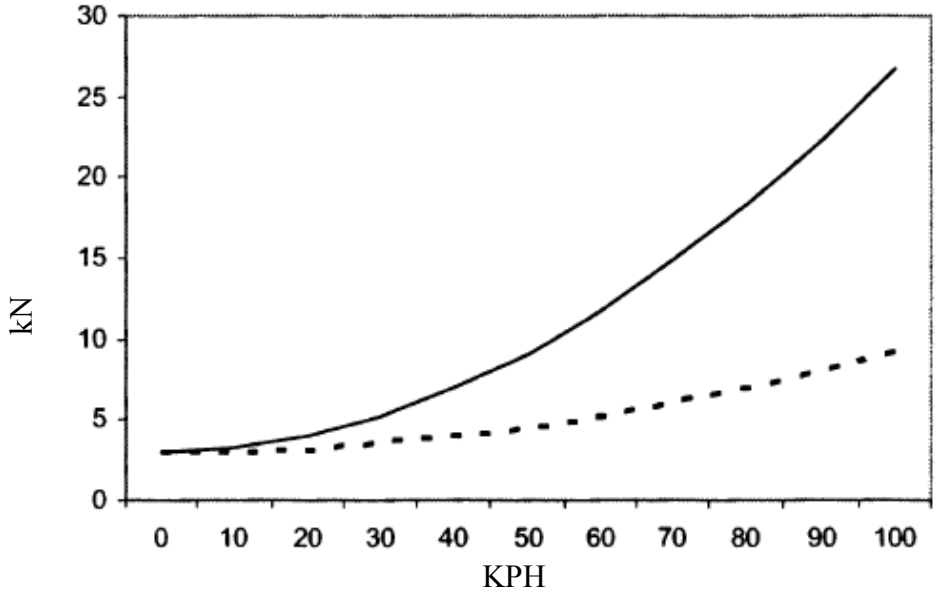

Figure 3.6 Train Resistance vs Speed (---- Open (kN) , Tunbel (kN))

Showing the increased criticality of train resistance in the haulage of very large freight trains the co-efficients are further decomposed and also stated to cover the locomotive alone as well as loaded and empty wagons and typical values are shown in Table 2;

Table 3.2 Typical Resistance Values

Type	Resistance (n/ tonne)
Laden	$0.9+9/W+0.003v+(0.026/Wn)v^2$
Empty	$0.3+9/W+0.003v+(0.026/Wn)v^2$
Loco	$0.9+9/W+0.003v+(0.044/Wn)v^2$

Finally in determining the required size of your motors the worst gradient that the train has to operate over, the ruling gradient (or grade if using American English), has to be determined along with the performance requirements over that gradient.

The force required to overcome the gradient IS given by Equation

$$Fgrad = M\ g\ \sin\alpha \qquad (3.14)$$

Where M = vehicle mass , g = acceleration due to gravity (-- 9.81 m/s^2) α= gradient

Note that in cases where a is small, sin a can be approximated by the gradient express as a percentage.

Thus it can be seen that for our sample loaded tube train used previously significant tractive effort is needed to ensure it does not slow down going up a gradient of 1: 100 or 1% in this case, as shown in Equation (3.15) .

$$TEgrad = 216 \text{ tonnes} \times 0.01 \times 9.81 = 21 \text{ kN} \quad (3.15)$$

Taking all these forces together gives a combined expression that gives the tractive effort required to accelerate a train at a given rate, while overcoming resistance and going up a hill of a given gradient.

$$TE(kN) = R + Mg \sin\alpha + Ma \quad (3.16)$$

Equation (3.16) and combinations thereof determines the sort of levels of tractive effort that are required.

However you also need to understand what sort of power levels will be required, or how fast your top speed is if your power levels are restricted, as is usually the case. Power is the rate of doing work and is best described for our purposes as stated in Equation (3.17).

$$\text{Power} = \text{Force} \times \text{speed} \quad (3.17)$$

Aligning to our previous discussion

$$\text{Power (kW)} = \text{TE (kN)} \times \text{v (m/s)} \quad (3.18)$$

Applying to our standard tube train if we want it to be able to be accelerated at 1.2 m/s^2 , when fully loaded, up a 1% gradient, and sustain that until 20 kph (5.55 m/s) give Equation (3.19) .

$$\text{Power (kW)} = (275 + 3.1 + 21) \times 5.55 = 1{,}660 \text{ kW} \quad (3.19)$$

Therefore if power is limited, as it always will be, the tractive effort available and hence the acceleration, will have to reduce as the speed rises. This leads to the

classic shape of the speed vs. tractive effort curve seen in all rail vehicles shown in Figure 2. (Nicholson, 2008)

4.ELECTRIC TRACTION POWER SUPPLIES

There is a wide variety of electric traction systems around the world, which have been built according to the type of railway, its location and the technology available at the time of the installation. Many installations seen today were first built up to 100 years ago . Due to massive advantages of electric power supply compare to diesel fuel, there has been a gigantic acceleration in railway traction development in the last 20 years.

The main advantage of electric traction is a higher power-to-weight ratio than types such as diesel or steam that carry power generators on board. This was particularly the case when compared to steam engines and diesels of the mid-twentieth century. This results in a higher rate of acceleration and higher tractive effort on steep grades. Electrification is also a more efficient way of transmitting power, especially on the busiest and most heavily trafficked routes where any additional capacity (either through longer trains or more frequent services) will require proportionally less additional energy when it comes from a common source rather than on each train. Electric locomotives can deliver as much as 2½ times the tractive power output of an equivalent diesel.

With electric traction it is also possible to further increase efficiency through regenerative braking, which means that a slowing-down train can use its electric motors as generators and recycle energy back into the system for other electric trains to use. Electric traction offers significantly improved performance when ascending gradients, plus the possibility of using regenerative braking to cost efficiently maintain safety whilst descending.

Other advantages include the lack of exhaust fumes at point of use, less noise and lower maintenance requirements of the traction units. In countries where electricity comes primarily from non-fossil sources, such as Austria and France, electric trains also produce fewer carbon emissions than diesel trains.Electric railways have the potential to be the least environmentally damaging form of traction. Although this depends on how the power is sourced, even the dirtiest

emissions are easier to reduce at a few power stations compared to many hundreds of moving trains.

For passengers the advantages of electric traction includes improved overall performance and less vibration which results in faster, more comfortable, smoother and quieter journeys. The improved acceleration also means that extra stations can be served with less time penalty - this is especially beneficial to users of minor stations which might otherwise have a less frequent service. Experience has shown that the very act of investing in railway electrification also gives passengers greater confidence that the line is 'valued' by the railway operators and therefore has a secure future. The sparks effect is a well proven phenomena whereby passenger numbers significantly increases when a line is electrified.

If most of an existing rail network is already electrified, there are benefits to extend electrified lines to allow through running.

The main disadvantage is the capital cost of the electrification equipment, most significant for long distance lines that do not have heavy traffic. Suburban railways with closely spaced stations and high traffic density are the most likely to be electrified, and main lines carrying heavy and frequent traffic are also electrified in many countries.

Basically the major advantage and disadvantages of electrification can be listed as in below .

Advantages :

- Lower running cost of locomotives and multiple unit
- Higher power-to-weight ratio , resulting in
    - Fewer locomotives
    - Faster acceleration
    - Higher practical limit of power
    - Higher limit of speed
- Less noise pollution
- Lower power loss at higher altitudes
- Lack of dependence on crude oil as fuel

Disadvantages :

- Upgrading brings significant cost ,
    - Especially where tunnels and bridges and other obstruction have to be altered for clearance
    - Alteration or upgrades will be needed on the railway signaling to take advantage of the new traffic characteristics.
- Increased maintenance cost of the lines (although reduced maintenance cost and multiple units)

Power is transmitted to electric railway locomotives and vehicles using DC or AC networks. The parallel development of traction technology in the industrialised countries has led to a plethora of different electrification systems, Table 1 exemplifying the geographical extent of the various voltages and frequencies in use in Europe. For new railways, the type of network is influenced by technical considerations such as:

- operational requirements (for urban metro, high-speed passenger or heavy-haul freight)
- physical route characteristics (such as gradients, and bridge and tunnel clearances)
- proximity of generating plant and utility or railway-owned power networks
- available traction technology (converters, traction motors and regenerative capability).

DC networks with trackside rectifiers and transmission voltages between 600 V and 1,5 kV are standard for urban and regional lines up to about 100 km long, although there are extensive 3 kV DC main line systems dating from the 1920s and 1930s. The original advantage of DC power supply was the simplicity of the vehicle-mounted traction equipment. DC series motors, wound at the full line voltage, could be started and run under resistance control by switching from series to parallel connection as speed increased. DC supply is still advantageous with modern power electronic traction control due to the compact size and weight of chopper and inverter drives.

AC distribution of electrical power to trains is economic for high-speed and heavy-haul railways. The high catenary voltage implies lower currents and smaller power losses, so fewer substations are required compared with the lower voltage DC traction networks. (Hill , 1994)

All electric traction power supplies, whether they are using AC or DC for the final supply to the trains via some form of conductor system along the track, supply the power to the track from regularly spaced track-side substations. In almost all cases, this power will be derived from the industrial utility supply at a level within the grid system that is appropriate to the power being drawn i.e. at 11 or 33 kV for metros and light rail and at 132, 275, or even recently at 400 kV for mainline. It is important to appreciate that modern power electronic control equipment makes it equally feasible to use AC or DC traction motors on the vehicles irrespective of whether the train is collecting AC or DC current. For the moment ignoring history, which actually has a tremendous bearing in railway systems, the fundamental choice between AC and DC transmission to the train is related to:

- safety, principally the obvious dangers posed by high voltage exposed conductors
- transmission efficiency, whereby the higher the voltage, the lower the current and the less copper is needed
- economics of the conductor system, the substations and the on-board controllers

These issues will be referred to again shortly, but it is useful to examine the existing systems before discussing how they have come about.(Goodman ,2006)

4.1.DC Railway Electrification Supply System

Railway electrification has in the past been dominated by overhead contact wire and D.C. third , fourth conductor rail electrification systems. The historical reasons for this have been the success of the D.C. traction motor and the necessity of a D.C. supply. Mercury arc rectifiers were originally used to provide rectification at substations with the D.C. power being transmitted to the traction equipment by the

conductor rail or overhead wire. Success in producing mercury arc rectifiers capable of being operated on board the railway vehicle enabled railway A.C. electrification system to become a reality in the 1950/60's.

It should be noted that DC is still the most common form of railway electrification system in the world. (White, 2008)

Most silicon rectifiers on traction systems use a three phase 50 Hz national or railway supply intake. Three phase rectification arrangement is used to reduce harmonic distortion at the point of common coupling and to reduce harmonic content in the DC supply. Where the mercury arc rectifier have been replaced by a silicon rectifier the double star transformer with inter phase transformer is employed. The advance of the silicon rectifier makes more simple arrangements of design. (White, 2008)

In this part the DC supply works , why we use it , the equipment of DC system and the different types of application in the world will be explained

DC system can be divided into two main parts.

1. Voltage Level

   There are some standard levels for application : 600V , 750V , 1500V , 3000V etc…

2. Feeding Conductor Type

   Overhead Line System , Third Rail , Fourth Rail , Overhead Rigid Conductor etc…

4.1.1.Rectifier Design

The function of the rectifier is to convert the three-phase current into direct current. In the past, mercury arc rectifiers have been used, however it is now normal to install naturally ventilated silicon rectifiers. This has become possible with the increase in area of the silicon wafer and has created what is practically a short circuit proof rectifier. Natural ventilation of the rectifier means that there are no moving parts and therefore an increase in reliability, economic benefits and minimum maintenance. Silicon diode rectifiers are very robust, efficient (low on state losses)

and able to sustain large fluctuations in temperature, high over current and over voltage rating (reverse).

The use of capsule/disc construction permits a wide range of the mean forward current and allows a minimum number of devices to be connected in parallel in each arm. The voltage level of the supply system and the transformer rectifier arrangement will give the characteristic DC voltage. The DC system voltage should be such that it complies with the train operating requirements whether 650V/1500V or 3000V DC. (White, 2008)

The pulse characteristic of the supply system is primarily defined by the transformer winding and converter arrangement. A number of simple arrangements of the transformer windings may be chosen with a 3 phase AC supply system to provide 6, 12, 18, and 24 pulse DC output voltage. Other ripple frequencies may be achieved using two converters and windings, which are phase displaced or wound in an alternative star/delta configuration.

A 12 pulse rectifier therefore can be obtained by connecting two separately fed phase displaced, 6 pulse systems in series or parallel. The arrangement will provide the necessary 30° displacement of the supply to provide a twelve pulse ripple when the respective bridges are connected in series or parallel. (White, 2008)

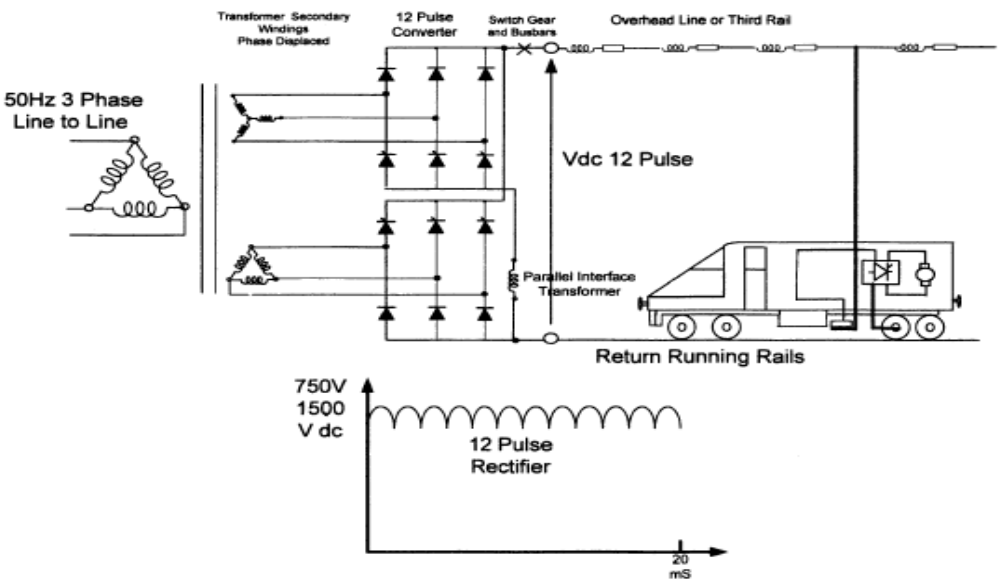

Figure 4.1. 12 pulse parallel bridge converter

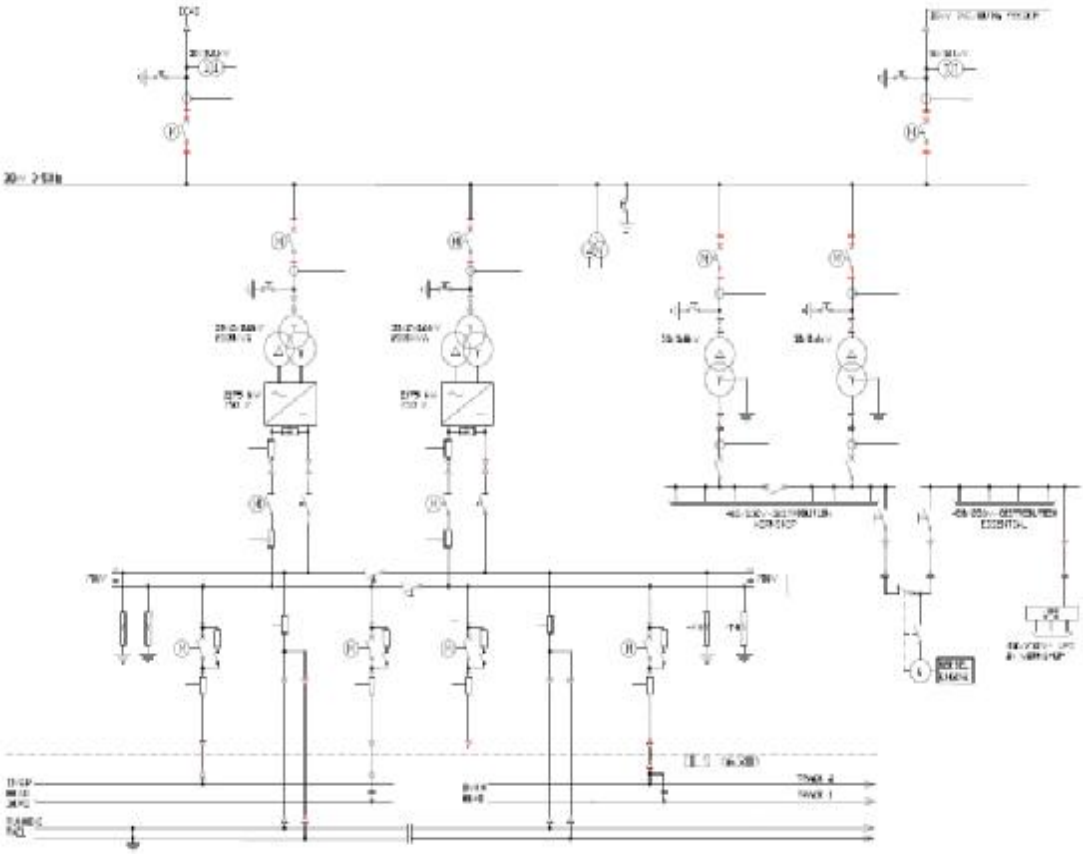

Figure 4.2. A typical circuit diagram of the traction substation (Adana LRTS substation one)

4.1.2.D.C. Conductor Rail Systems

With the lower D.C. systems voltages, it is usual to have the traction power feeding arrangement at either track level [light rail heavy metro systems] or via an overhead line [street running trains].

Third rail system is usually cheaper for surface lines insulation problems, the system voltage is 600/750 V on the third rail.

In fourth rail system the positive conductor is at a potential of +400 V and the negative or fourth rail at -230 V, this is a 630 V system. Underground systems use a fourth rail to carry the return current to minimize stray traction leakage currents. Without the fourth rail these leakage currents would cause corrosion of buried water and gas pipes by electrolytic action. The centre earth system minimizes the voltage

of system voltage to earth, thereby reducing the risk of injury to electric shock. (White, 2006)

4.1.3.D.C. Overhead Contact Systems

The use of electric power for traction purposes naturally involves the transmission of power over considerable distances; obviously this can best be achieved by the use of a high voltage. When the contact system is placed overhead, the voltage can be increased and the danger to personnel is greatly reduced. A greater substation spacing is possible, together with an improved system efficiency due to the copper losses being reduced [e.g. if the voltage is doubled then for a given power the current is halved and hence the copper losses are reduced to one quarter]. (R.D White , 2006)

4.1.4.Positions of the Lineside Traction Sub-Stations

A detailed analysis is needed to establish the correct positions of sub-stations on the railway system. Having established the working voltage 600V, 750V, 1500V or 3000V the exact position of the substation has to be decided. This decision is made on the technical performance of the power system, however it is also necessary to take into account other factors which will determine the final choice, availability of land, position of junctions and crossovers, the provision of road access up to the main door of the building in order to facilitate the transport of spare items of plant and any necessary maintenance test equipment.

The most economic distance between substation is:

- 600V D.C. is 3-4km
- 750 V D.C. *5-6km,*
- 1500V D.C. is 8- 13kmn
- 3000V D.C. is 20- 30km

The distribution voltage for D.C. overhead Metro and Mainline systems is typically 1500V, 3000V and therefore requires less isolation and clearance than for A.C. electrification. The mechanical strength of the overhead line conductor becomes

the main factor in overhead design making the conductor sizes not dissimilar between 1500 V D.C. and 25 kV A.C. Where the power requirements exceed the capability of the overhead catenary it is necessary to include parallel feeds along the overhead masts. Connections are made at regular intervals to the catenary to ensure good current sharing.

The 3000 V system is applied almost entirely to the main line system in order to maximize substation spacing, with 750 V and 1500 V D.C. supplies predominantly chosen for urban mass transit or light rail systems.

Factors Influencing Substation Spacing :

- Maximum Permissible Voltage Drop
- System Loading
- Conductor Section
- Circuit Breaker Tripping Current (White, 2008)

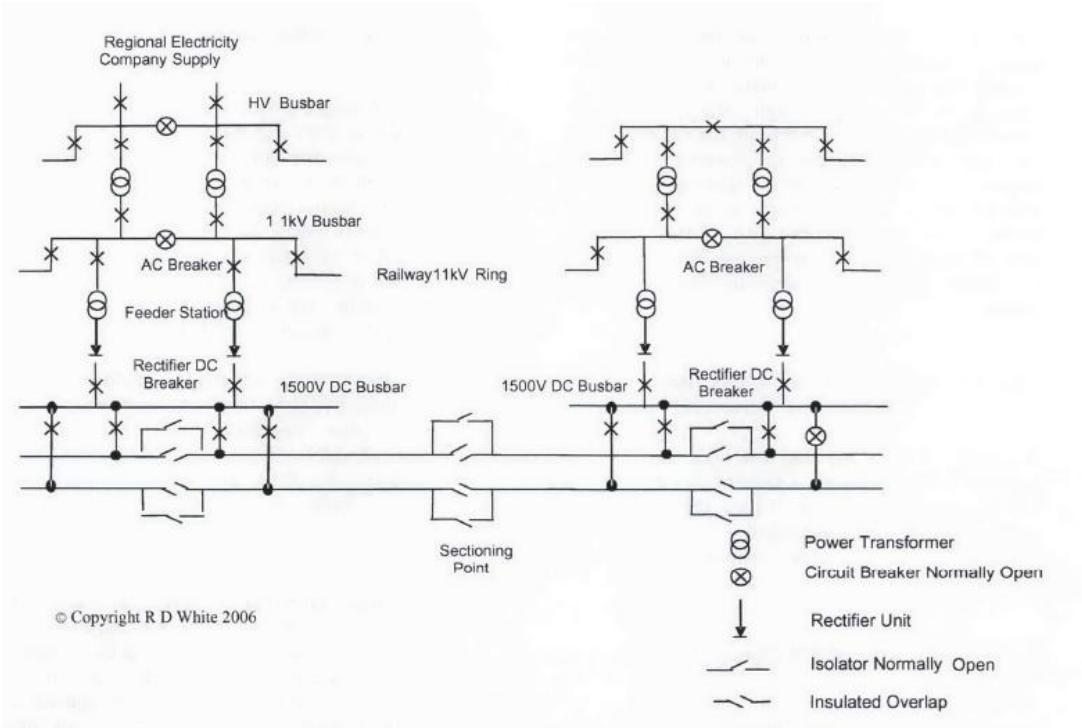

Figure 4.3. Typical Feeding Arrangement 1500V D.C. Electrification System

4.2.AC Traction Power Suppliy Systems

AC distribution of electrical power to trains is economic for high-speed and heavy-haul railways. The high catenary voltage implies lower currents and smaller power losses, so fewer substations are required compared with the lower voltage DC traction networks.

Standard AC distribution equipment and switchgear is used. Three-phase AC transmission, normally the most efficient means of distributing high-power electricity, would be advantageous for traction due to the inherent regenerative capability of three phase induction motors. However, it has not been widely applied because of the difficulty of power collection by moving locomotives.

A number of systems were tried in the early 1900s on mountain railways in Italy, Switzerland and USA. The last major line, from Genova to Torino, was converted from three-phase at 3.6 kV, 1 62/3 Hz to 3 kV in 1964.

In the early 20th century, low-frequency single-phase traction networks were established to combine the economies of high-voltage AC transmission with the advantages of using AC commutator motors. In Europe, the 15 kV, 16 2/3 Hz networks are very extensive and have been expanded despite the need for frequency converters or special generating stations. In the USA, some sections of the 12 kV, 25 Hz electrification system in the New York area have been converted to 60 Hz, facilitated by the ready availability of dual-frequency traction equipment.

Nowadays, the standard supply for main line systems is 25 kV single-phase AC at 50 or 60 Hz. The system was first widely exploited in France in the early 1950s. The economy of high-voltage transmission is combined with the compatibility of national utility electric grid networks. The development of rectifier locomotives with DC traction motors and tap changers, using mercury arc rectifiers, semiconductor diodes and finally thyristor phase control, ensured the success of the 25 kV system. New lines at 25 kV, 50/60 Hz have been constructed adjacent to existing 3 kV DC networks in, for example, France, Russia and South Africa. 25 kV remains the standard voltage although since 1980 some freight railways in North America and South Africa have been electrified at 50 kV, 50/60 Hz.(R.J.Hill 1994)

There are lots of different applications of AC system electrification . We can divide into three part AC systrm as in common use.

- Low Frequency AC System
- Polyphase AC System
- Standart Frequecy
-

4.2.1.Low Frequency AC System

The low frequency electrified railway system has been in operation for over a century in Sweden, Germany and other European countries. With the modern day power electronics technology available for frequency conversion, and the high power quality demanded by the utility power customers, the low frequency system is likely to make the railway electrification system more affordable and desirable.

Frequency conversion is not only possible, but is becoming an economically attractive alternative. The frequency conversion is being used for accurate speed control, energy and power savings in several industrial processes. The cost of power frequency conversion is dropping and the reliability is constantly improving. Modern day control systems are making the conversion very precise and efficient. Frequency conversion systems can be applied to the railway electrification systems to obtain the advantages of industrial frequency for power generation and the low frequency system for power distribution on the catenary. The 60 Hz frequency can be converted to 15 or 20 Hz for railway electrification. When converting the frequency, the low frequency system can be operated as a single phase system. The frequency conversion can be done using a cyclo-converter, or it can be done using an AC/DC/AC system conversion. The AC/DC/AC conversion is used extensively in Adjustable Speed Drives. This would solve multitudes of problems related to power quality, reduce the cost of electrification, etc.

A low frequency system decreases the cost of electrification by increasing the distance between two successive substations, and reducing civil engineering modication costs by enabling lowering the catenary voltage from the 25 kV voltage commonly used in the U.S. to 16.5 kV at 15/20 *Hz.* Such a system would enable paralleling the catenaries between two substations on the secon- side, thus increasing the capabilities of the catenaries and reducing the power quality and unbalance voltage problems. The various advantages that can be derived from low frequency operation are: (B. Bhargava , 1996)

4.2.1.1.Advantages Of A Low Frequency

4.2.1.1(1) Longer Substation Beat/Less Substation Installations:

A lower frequency system will reduce the inductive voltage drop in the catenary. A 15 Hz system would have approximately one fourth the inductive voltage drop as compared to a 60 Hz system, thus it would enable the substations to be located at 3 to 4 times the distance compared to a 60 Hz system based just on the

voltage drop criterion. The number of substations required could be reduced to 30-40 percent.

4.2.1.1(2) Parallel Operation of Catenary From Adjacent Substation:

The catenaries of the traction system can be all in phase. They can be paralleled on the secondary side. Paralleling the secondaries will enable the power to be drawn from two or more substations, thus decreasing the voltage drop further in the catenary and also distributing the load on two or more substations. There will be a smoother transition of load from one substation to the other as the train moves along.

4.2.1.1(3) Reduced Voltage Operation at 15-16.5 kV:

Since the substation beat can be increased because of a lower frequency and parallel operation of the catenary system, lower catenary voltage could be used and substantial savings are achieved in civil engineering modifications by reducing the electrical clearance requirements at the reduced voltage level. The lower voltages have been used in Germany and Sweden with success. Reducing the voltage level; however, would increase the current in the catenary and would increase losses which may require a higher size catenary conductor or an additional feeder circuit.

4.2.1.1(4)Lesser Electrical Clearances And Civil Engineering Requirements:

Lower voltages will result in lower clearance requirements. This could be useful where bridges have to be raised, tracks have to be lowered or when the tunnels do not permit adequate clearances for the 25 kV system.

4.2.1.1(5) Reduced Substation Voltage Capacity Or Better Utilization Of Substation And Catenary Capacity:

With the 25 kV single-phase, 60 Hz system, each substation has to be designed to provide full power for the trains within the substation beat and half the

adjacent substation. By paralleling the traction system on the secondary side and sharing the loads among the adjacent substations, it is quite possible to reduce the substation capacity or to provide larger train frequency.

4.2.1.1(6) Reduced Unbalance Voltage Problem:

The traction load, as explained earlier, is one of the worst kinds of load as it is often supplied from one or two phases of a power system. The single phase load creates voltage unbalance and other power quality problems. With a low frequency traction system, the load will appear as a balanced load on the utility system. There would be little unbalanced voltage or current problems. The frequency conversion system would also separate traction load from the rest of the customers.

4.2.1.1(7) Reduced Harmonics into The System:

With the low frequency system, harmonics would be generated in the conversion equipment. Appropriate filtering can be provided doing with the conversion equipment to limit the harmonics to acceptable levels. The modern day electric locomotives have onboard power factor correction and harmonic filtering. The frequency conversion equipment filters on the system would further reduce the harmonics generated from the locomotives and reduce the harmonics entering into the utility system.

4.2.1.1(8) Lower Voltage Utility Substations:

The unbalance voltage caused by the trains can become the single most important factor which will dictate the selection of the substation primary voltage. Adequate short circuit duty and voltage levels are required to limit the voltage unbalance and the harmonics at the substation. (B. Bhargava , 1996)

4.2.2.Polyphase AC System

Three-phase AC transmission, normally the most efficient means of distributing high-power electricity, would be advantageous for traction due to the inherent regenerative capability of three phase induction motors. However, it has not been widely applied because of the difficulty of power collection by moving locomotives. A number of systems were tried in the early 1900s on mountain railways in Italy, Switzerland and USA. The last major line, from Genova to Torino, was converted from three-phase at 3.6 kV, 16 2/3 Hz to 3 kV in 1964.(R.J.Hill , 1994)

This was abandoned in the 1960's because of the complexity of the current collection, especially at points and crossings. (Goodman, 2006)

There were some railways that used two or three overhead lines, usually to carry three-phase current to the trains. Nowadays, three-phase AC current is used only on the Gornergrat Railway and Jungfraujoch Railway in Switzerland, the Petit train de la Rhune in France, and the Corcovado Rack Railway in Brazil; until 1976 it was widely used in Italy. On these railways the two conductors of the overhead lines are used for two different phases of the three-phase AC, while the rail was used for the third phase. The neutral was not used.

Some three-phase AC railways used three overhead wires. These were an experimental railway line of Siemens in Berlin-Lichtenberg in 1898 (length: 1.8 kilometers), the military railway between Marienfelde and Zossen between 1901 and 1904 (length: 23.4 kilometers) and an 800-metre-long section of a coal railway near Cologne, between 1940 and 1949. (Web)

Figure 4.4. Three Phase pantograph on a Corcovado Rack Railway train in Brazil.(Web)

4.2.3.Standart Frequency 25kV 50Hz Electrification Supply System

Only in the 1950s after development in France did the standard frequency single-phase alternating current system become widespread, despite the simplification of a distribution system which could use the existing power supply network.

The first attempts to use standard-frequency single-phase AC were made in Hungary in the 1930s, by the Hungarian Kálmán Kandó on the line between Budapest-Nyugati and Alag, using 16 kV at 50 Hz. The locomotives carried a four-pole rotating phase converter feeding a single traction motor of the polyphase induction type at 600 to 1100 volts. The number of poles on the 2,500 HP motor could be changed using slip rings to run at one of four synchronous speeds.

Today, some locomotives in this system use a transformer and rectifier that provide low-voltage pulsating DC current to motors. Speed is controlled by switching winding taps on the transformer. More sophisticated locomotives use thyristor or IGBT transistor circuitry to generate chopped or even variable-frequency AC that is then directly consumed by AC traction motors.(Web)

The 25 kV A.C. 50 Hz electrification system has been developed specifically for railway traction purposes. The main feature that separates this system from the conventional three-phase and neutral HV distribution network of the public supply authority is that the railway system is a single-phase system with one pole earthed. (White, 2009)

The 25kV rail network has been designed to meet the needs of a fast, intercity, multi-track railway network carrying a variety of trains at frequent intervals. This operation requires an overhead system that is inherently safe for employees and passengers, reliable and provides a high degree of security of the supply to the traction units. This security will ensure that the electrification supply system is able to provide the required power levels to fulfill the performance of the traction units. It should be recognised that if the service or loads are increased the performance of the electrification system should be reviewed. (White, 2009)

The average distance between substations ranges from 20 - 40 miles. It subjects the utility with high voltage and current unbalances, flicker and harmonics. The other disadvantages are that the phases between adjacent substations cannot be paralleled. It requires high short circuit duty substations and thus a strong utility network. It also requires redundant substation capacity to feed power for substation outages. (Bhargava, 1999)

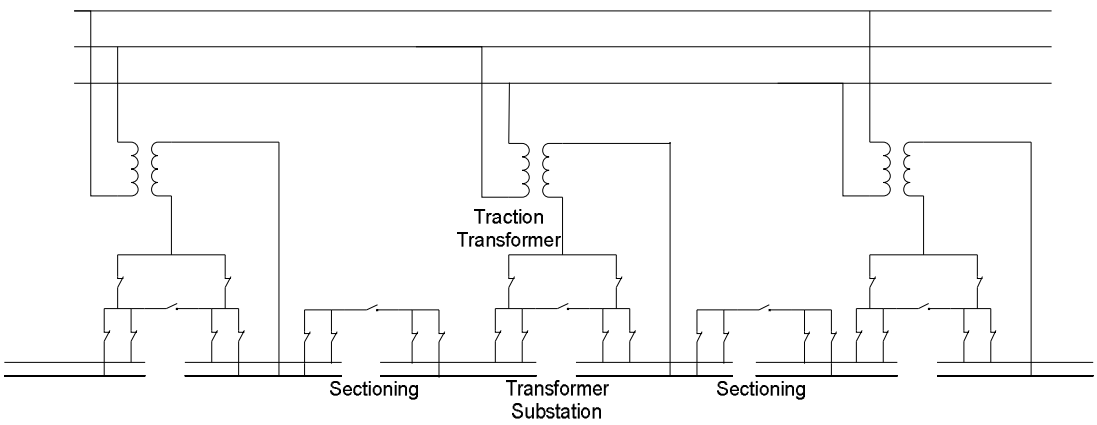

Figure 4.5 Center fed AC railway catenary fault isolation arrangement

This system is quite economical, but it has its drawbacks: the phases of the external power system are loaded unequally, and there is significant electromagnetic interference generated, not to mention acoustic noise.(Web)

The practical details of AC power feeding are concerned with maintaining the quality of the supply. On the traction side, catenary feeding systems using booster transformers and auto transformers feeding have been developed to improve transmission efficiency and system regulation and to reduce earth. (Hill, 1994)

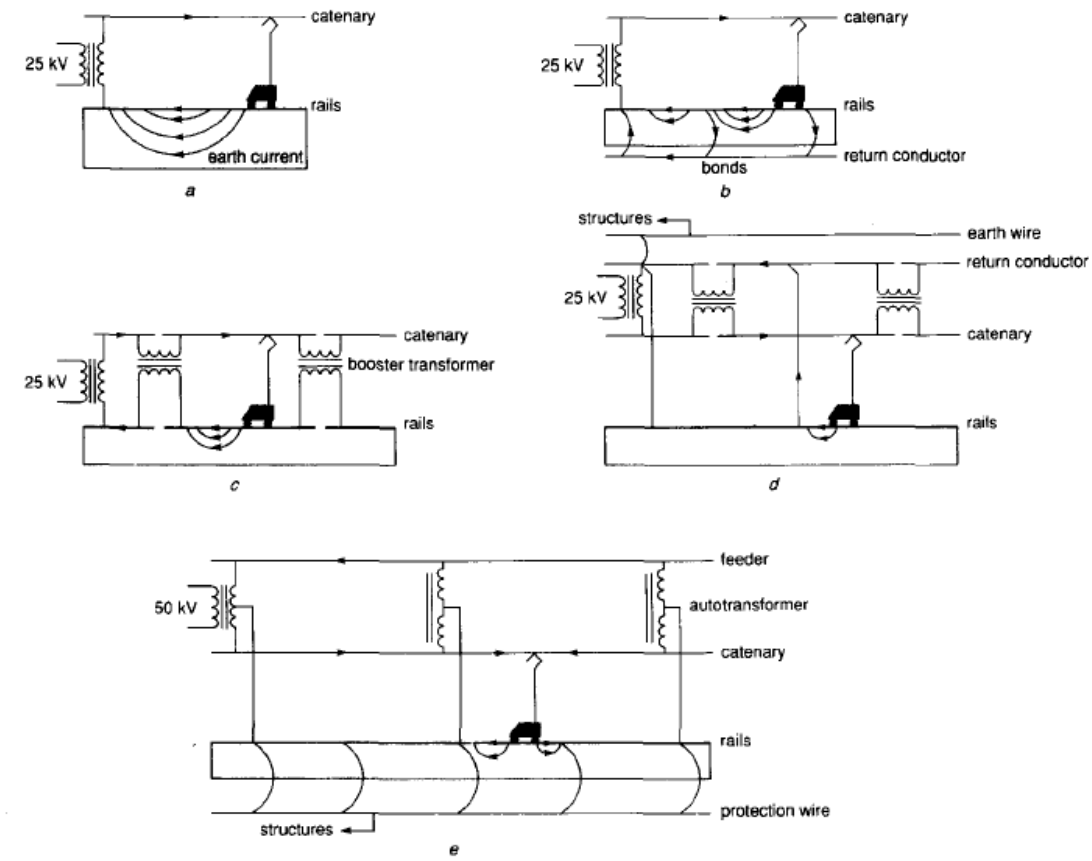

Figure 4.6 AC railway feeding system

4.2.3.1.Booster Transformer Feeding System

The least capital-intensive way of feeding power is by direct connection of the traction feed transformer secondary to the catenary and rails at each substation

(Fig.4.6.a). The disadvantages are high feeding impedance with large losses, high rail-to-earth voltage (a potential safety hazard) and the production of earth currents which can cause interference in adjacent telecommunications circuits.

The addition of a return conductor connected to the rails at regular intervals, typically 5 or 6 km, provides a lower impedance traction current return path (Fig.4.6.b). By its screening effect, it can also reduce inductive interference in parallel telecommunications cables by about 30%.

Booster transformers (BTs), rated at about 150 kVA, were first used on the Tokaido Shinkansen (Japan) in 1964. They are placed along the catenary at 3-4 km intervals and represent a further improvement in the feeding circuit. The BT primary is connected across a gap in the contact wire and the secondary across an insulated rail section (Fig.4.6.c). The turns ratio is unity and traction return current is forced from the rails and earth to flow through the transformer secondary to equalize the Ampere-turns in the core set up by the primary current. The preferred configuration is to incorporate a conductor in parallel with the rails for the return current, as shown in (Fig.4.6.d) (Hill, 1994)

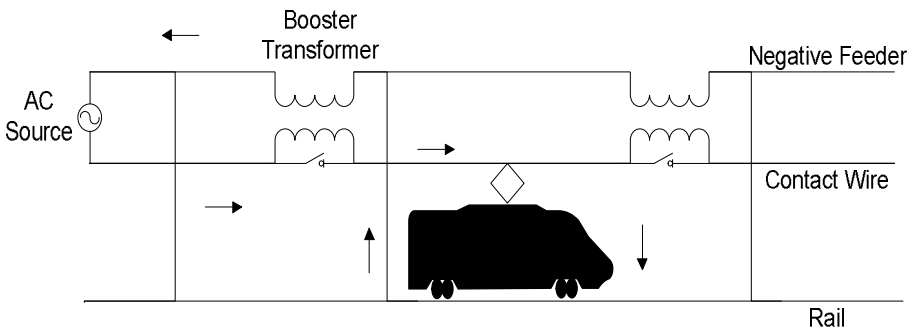

Figure 4.7 BT feeding system.

Figure 4.7 shows the composition of a BT feeding circuit. A BT is installed every 4 km on the contact wire to boost the return circuit current on the negative line .This design minimizes the inductive interference on telecommunication lines because the current flows to the rail only in limited sections.

In particular, when an electric car passes a BT section, a large arc is generated in the section , and a large load current can cause a very large arc that can damage

the overhead line . Consequently, capacitors are often inserted in the negative feeder to compensate for the reactance and reduce the amount of current intercepted by the pantograph, thereby reducing arcing, and also helping to prevent voltage drop. (Oura,1998)

In high-voltage AC traction networks, the line impedance is the most significant part of the total feeding impedance. The impedance at power frequency is dominated by the physical layout of the circuit and mounting the negative feeder on the mast close to the catenaries minimizes the circuit inductance.

Fig.4.8 shows the current paths in a BT system and the form of the feeding circuit impedance curve. The feeding transformer impedance is typically between (0.5 and j3.0) and (1.2 + j7.6)Ω, depending on rating, and the line impedance is about (0.2+j0.6) Ω /km. The inherent slope of the curve is given by the contact-wire return-conductor short-circuit impedance and the vertical represents the BT series impedance. When the short-circuit load is to the right of the BT, the impedance is low since return current is forced to flow through the BT winding rather than the rails. In a practical system, the BT series impedance is made approximately equal to the feeding impedance between BTs. If the rail leakage to ground admittance is minimized, the total feeding section impedance increase will be limited to about %25.

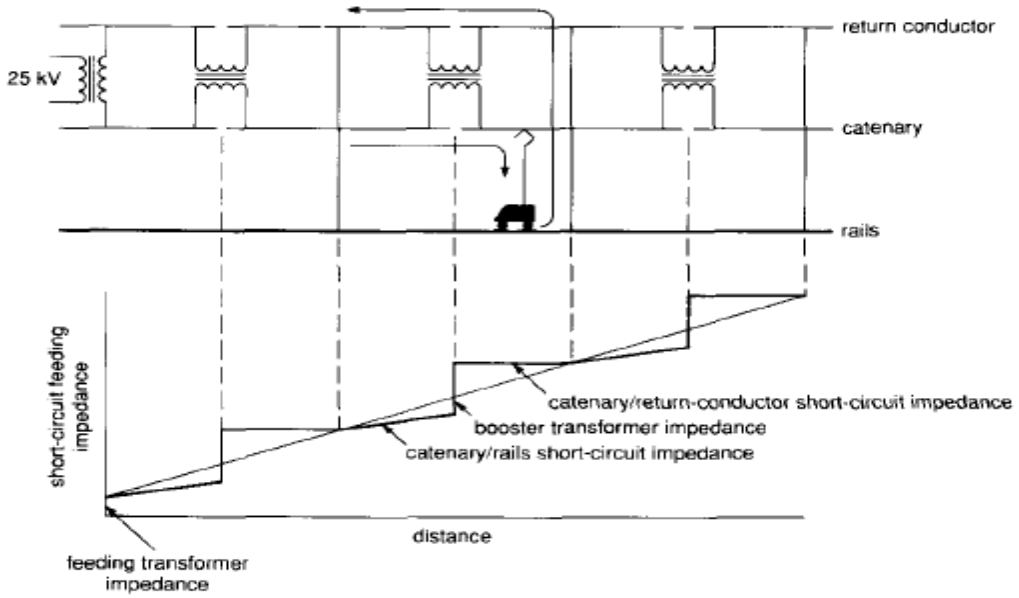

Figure 4.8 BT with return conductor feeding system (Hill, 1994)

Allowing the traction current to return through this distributed earthing system to the feeder transformer is liable to cause an excessive amount of electromagnetic interference into adjacent telecommunications circuits. To minimise this the current is constrained to return to the feeder transformer in return conductors positioned near to the 25 kV overhead line and in such a way as to reduce the level of interference. The return current is constrained to flow in the return conductor by booster transformers [current transformers] which have their primary connected in series with the 25 kV line and their secondary connected in series with the return conductors and the rail return. These booster transformers are positioned at approximately 3 km intervals, one booster is required for each 25 kV overhead track feed. (White, 2009)

Earthing in BT systems requires a grounded neutral at the feeder station, with one of the running rails bonded to a separate earth wire which is also connected to other metallic structures such as the masts. Return current in occupied BT sections is shared between the rails and earth according to the value of the earth-rail leakage admittance. The BT magnetizing current return path also flows through the rails and earth. The earth current will be high at BT locations and minimum at the rail/return-conductor bonds, producing a voltage rise between the rails and remote earth. To minimize this rail voltage, a total earth impedance of less than about 1Ω must be maintained with the mast earth resistance limited to approximately 2OΩ. (Hill, 1994)

4.2.3.2.Autotransformer Power Feeding System

In railways, the electric current is taken from the catenary conductor to the locomotive, where the energy is used by electric motors and fed to the earth connected rails, which are part of the return circuit. In a two-phase fed catenary system, the rail and the earthed return conductor are connected to the midpoint of the catenary autotransformer. One pole of the autotransformer is connected to the catenary phase, and the other pole to the negative phase conductor. With this connection, the power is fed to the locomotive with double voltage compared to the

voltage of the locomotive itself. This means that the phase currents are reduced to half and the feeder losses to the fourth part compared to the single-phase feeder. The task of the autotransformers along the catenary line is to balance the voltages between the catenary and the earth, and the negative phase conductor and the earth, and then distribute the return current evenly between the two phases.

The advantages that are obtained with this connection compared with single-phase feeding and booster transformers are among the following, depending on the objectives:

- Lower losses due to higher voltage
- Longer distance between catenary feeder substations
- Better collection of returning stray currents
- Reduced interference for communications (ABB Railway Transformers)

Autotransformer (AT) feeding combines the advantage of higher-voltage power transmission, hence increased substation spacing, with the convenience of using standard 25 kV traction equipment. The principle is shown in Fig. 1e. The AT winding is connected between the catenary and an auxiliary feeder, with the rails tied to an intermediate point. In 25 kV traction systems, the winding has a 1:1 ratio with a 50 kV supply centre-tapped at the rails. (Hill, 1994)

AT's were first used for railway electrification design in 1913 when the New York, New Haven and Hertford railway electrification was extended to New Haven. The design by Professor Scott was introduced to reduce the line loss and the inductive interference on the 11kV 25Hz electrification system. [Scott was also the inventor of the Scott connected transformer] (White, 2009)

Subsequently it ceased to be used and returned to the scene only in 1972 when Japanese Railways used it on the San Yo line. The main objective is to limit interference generated by traction, while avoiding the problems of current collection which booster transformers with an equivalent role had created on the Tokaido new line.

It was the electro-technical aspect in the form of reduction of losses on lines which was attractive firstly in 2 x 25 kV power feed; the first application was in 1981 on the new Paris - Lyon high speed line; this made it possible to avoid costly

construction of high voltage lines to connect sub-stations to the national grid distribution network.

At the end of 1992, in France, 12 869 km of the track subgrade had been electrified. 6970 km were electrified to 25 kV with 107 sub-stations, 1570 km of which were 2 x 25 kV with 25 sub-stations and 5400 km of which were 1 x 25 kV with 82 sub-stations. (C. Courtois ,1993)

Autotransformer has been introduced in a number of countries including in Australia [Blackwater and Gregory Coal line], Chinese Railways [Datong to Qinhaungdao], Russia [Vjaz'ma to Orsha], Japan [Bullet Train], France [TGV Lines], Spain, Belgium [TGV Lines], Hungarian State Railway [Lake Balaton] and New Zealand [North Island line]. (White, 2009)

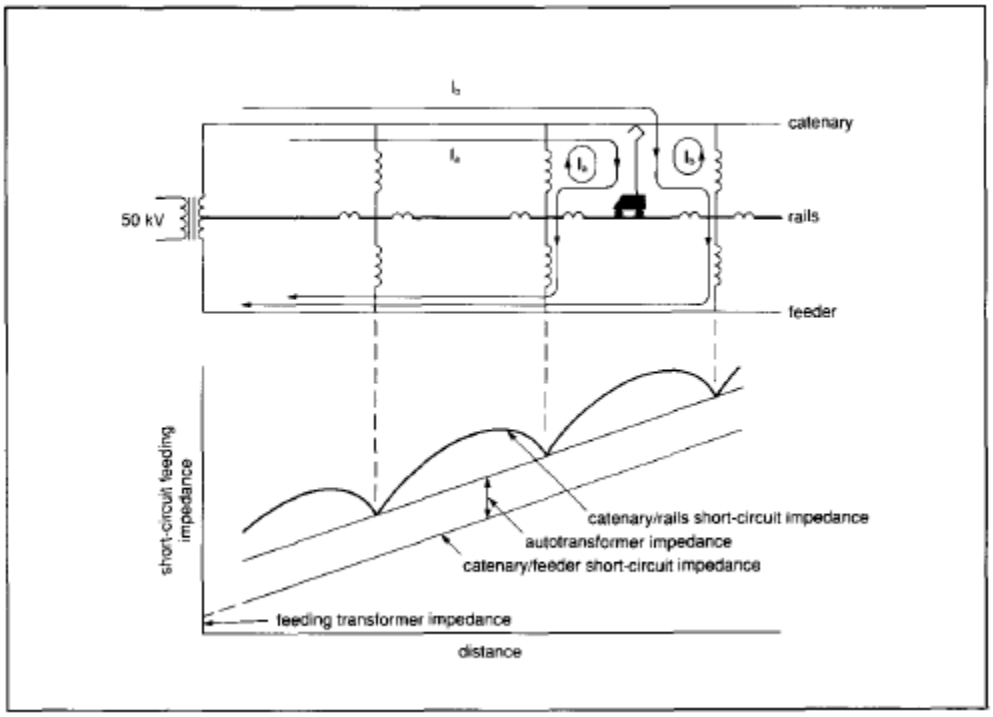

Figure 4.9 AT feeding system principle (Hill, 1994)

The principle of AT operation is illustrated in the simplified model of Fig.4. 9 The train draws current from two adjacent ATs, the total supply current being half the train current. Rail currents flow through the AT windings as shown in order to maintain Ampere-turn balance in the cores. In contrast to BT current balancing, the AT system operates by balancing voltages. For ideal ATs, no current will flow in the

rails of unoccupied sections, and since the AT midpoints are grounded, the earth current will be maximum at some point between the train and each AT, and minimum at the AT locations. (Hill, 1994)

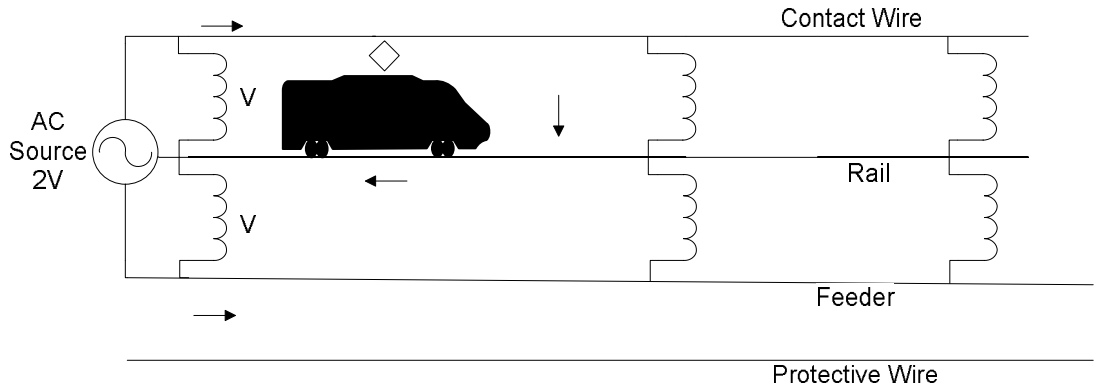

Figure 4.10 AT feeding system

To minimize the feeding impedance, the size of the catenary / return feeder loop is reduced by mounting the feeder physically close to the catenary at the top of the mast. The protection wire, clamped high on each mast, is connected to the rails at regular intervals including at all AT locations and midway between them. It is bonded to all metal masts, fences and earthed foundations, and at critical locations, such as stations and bridges, to an earthed buried cable giving a total ground resistance less than 1Ω. Other equipment may be connected to the protection wire by surge diverters or 3 kV spark gaps for over voltage protection.

AT`s are rated at 5 or 10 MVA (with 5minute 100% overload and 15 minute 50% overload capacity) and the windings can withstand a 2.5 kA short circuit. Magnetizing current and leakage impedance cause departures from idealized operation. The former produces a no-load current in the catenary and return feeder which lowers system efficiency. The leakage impedance is typically about (0.1 + j0.4) Rand reduces the AT output voltage, causing load current to be drawn from remote ATs with associated rail and earth currents. These earth currents may cause induced interference voltages in trackside cables, although for long lines an AT system will generally produce less interference than a BT system.

Although the absence of additional BT series impedance and the higher transmission voltage improves the voltage regulation in AT systems, the feeding impedance is modified. Fig.4.9 shows the form of the AT system short-circuit input impedance in a single-end-fed section, which has been calculated from circuit analysis knowing the self and mutual impedances of and between the catenary, rails and feeder. The curve is composed of the source impedance, the catenary to return feeder short-circuit impedance, the AT leakage impedance and the contact wire to rails short-circuit impedance. The maximum within each AT section is significant in determining the system voltage regulation. A typical average value for the feeding impedance isjO.12 Ω/km. (Hill, 1994)

4.3.Power Distribution Systems of ElectrifiedRailways

4.3.1.Overhead Line System

An electric railway takes its power for the electric motor, lights, air conditioning etc., from the overhead line using the pantograph on the roof.

The pantograph is in constant contact with the overhead line (contact wire) located about 5 m above the rails whether the train is moving or not. Therefore , the overhead line must always be located within the pantograph range, and the pantograph must always maintain contact with the overhead line to supply uninterrupted, good-quality power at all times .To meet these requirements , the overhead equipment is generally designed bearing the following in mind :

- Must have characteristics meeting above rail to speed and current requirements.
- Must be uniform height above to rail optimize pantograph power collecting characteristics , so entire equipment must have uniform spring constant and bending rigidity
- Must have minimum vibration and motion to ensure smooth pantograph passage during high speed operation or strong winds.
- Must have strength to wind stand vibration, corrosion, heat, etc. while maintaining balance with reliability and operation life span.

Figure 4.2 compares the catenary equipment for high speed trains in different countries. In Japan, compound catenary equipment coasting of three longitudinal wires is used for shinkansen, while simple or stitched catenary equipment is used in Europe. The Italian high-speed line uses twin catenary equipment to supply the large current for 3kV dc electrification .Table 4.1 compares the constants of these various catenary systems. (Oura, Mochinaga, 1998)

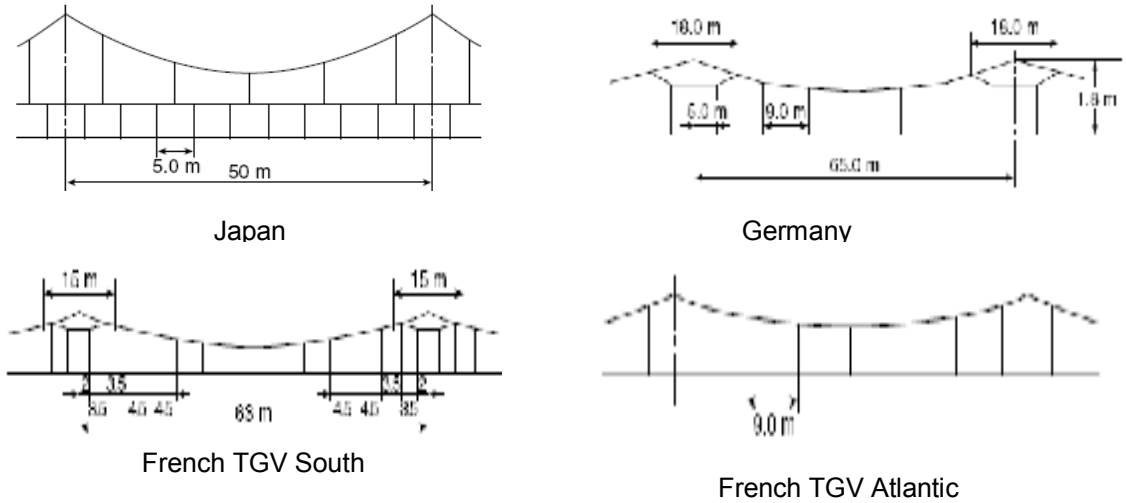

Figure 4.11. OLS of World High Speed Railways (Oura, Mochinaga, 1998)

4.3.1.1.Construction

To achieve good high-speed current collection it is necessary to keep the contact wire geometry within defined limits. This is usually achieved by supporting the contact wire from above by a second wire known as the messenger wire (UK & Europe) or catenary (US & Canada). This wire is allowed to follow the natural path of a wire strung between two points, a catenary curve, thus the use of catenary to describe this wire or sometimes the whole system. This wire is attached to the contact wire at regular intervals by vertical wires known as droppers or drop wires. The messenger wire is supported regularly at structures, by a pulley, link, or clamp. The whole system is then subjected to a mechanical tension.

As the contact wire makes contact with the pantograph, the carbon surface of the insert on top of the pantograph is worn down. Going around a curve, the

"straight" wire between supports will cause the contact wire to cross over the whole surface of the pantograph as the train travels around the curve, causing an even wear and avoiding any notches. On straight track, the contact wire is zigzagged slightly to the left and right of centre at each successive support so that the pantograph wears evenly.

The zigzagging of the overhead line is not required for trolley-based trams or trolleybuses.

Depot areas tend to have only a single wire and are known as simple equipment. When overhead line systems were first conceived, good current collection was possible only at low speeds, using a single wire. To enable higher speeds, two additional types of equipment were developed:

- Stitched equipment uses an additional wire at each support structure, terminated on either side of the messenger wire.
- Compound equipment uses a second support wire, known as the auxiliary, between the messenger wire and the contact wire. Droppers support the auxiliary from the messenger wire, and additional droppers support the contact wire from the auxiliary. The auxiliary wire can be constructed of a more conductive but less wear-resistant metal, increasing the efficiency of power transmission.

Dropper wires traditionally only provide physical support of the contact wire, and do not join the catenary and contact wires electrically. Contemporary systems use current-carrying droppers, which eliminate the need for separate wires. For tramways there is often just a simple contact wire and no messenger wire.

4.3.1.2.Overhead Line Conductors

The selection of the OLE conductors is a key system design requirement and is affected by considerations of mechanical strength, electrical characteristics, physical and metallurgical properties as well as economic and environmental considerations.

Hard Drawn Copper as a material in its simplest form has provided good service over many years and is still specified for many modem systems. Work hardening during the production process provides good mechanical strength and the pure elemental material has excellent conductivity. The current rating of the wire is determined by its thermal properties (although system considerations such as available balance weight travel can also apply) and a maximum temperature of 80°C can be accommodated prior to the onset of annealing and loss of strength. Silver copper (CuAgO.I) provides a modern alternative with virtually identical strength and conductivity characteristics but the benefits of a higher annealing temperature of -150°C and improved low temperature creep performance.

Higher mechanical strength and improved wear performance can be achieved at the expense of electrical conductivity by alloying with Cadmium (CuCdO.7). More recently environmental considerations have led to the use of tin as an alternative alloying element which provides very similar properties. For very high mechanical strength Copper Magnesium alloys have been developed. Stranded conductors are used for catenary and auxiliary wires due to their ease of handling but the contact wire must have a solid profile to allow for wear due to the passage of pantographs. Wires are available in standard sizes, with the most common being 100/107mm^2, 120mm^2 and 150mm^2 although other sizes are also encountered.

In rigid beam solutions, the main conductor comprises of a rigid aluminium extrusion into which a conventional contact wire is inserted.

The contact wire has a grooved profile to allow it to be gripped by dropper clips and registration arms without interfering with passing pantographs. (Warburton ,2009)

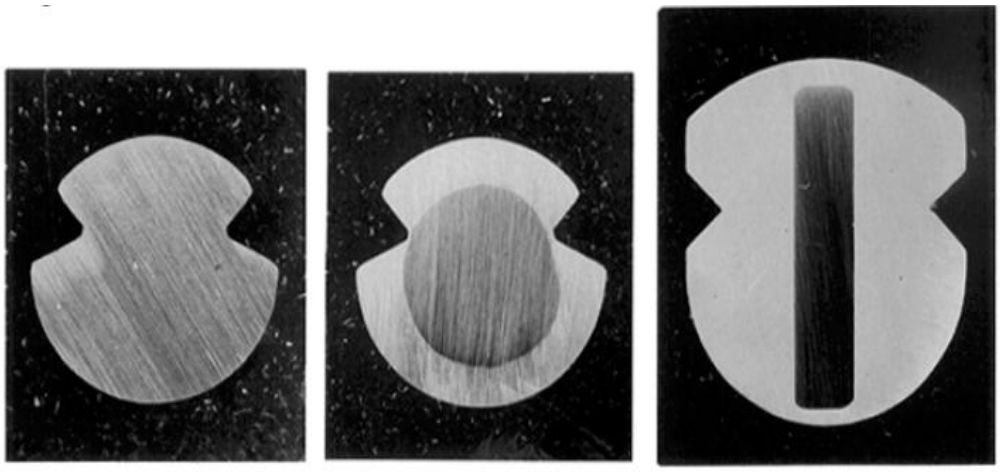

Figure 4.12.Cross sections of contact wires (Oura, Mochinaga, 1998)

4.3.1.3.Pantographs

Current is collected from overhead lines by pantographs. Pantographs are easy in terms of isolation you just lower the pan to lose the power supply to the vehicle. However, they do provide some complications in other ways. Since the pantograph is usually the single point power contact for the locomotive or power car, it must maintain good contact under all running conditions. The higher the speed, the more difficult the maintenance of good contact.

Pantograph contact is maintained either by spring or air pressure. Compressed air pressure is preferred for high speed operation. The pantograph is connected to a piston in a cylinder and air pressure in the cylinder maintains the pantograph in the raised condition. (Railway Technical Web Pages)

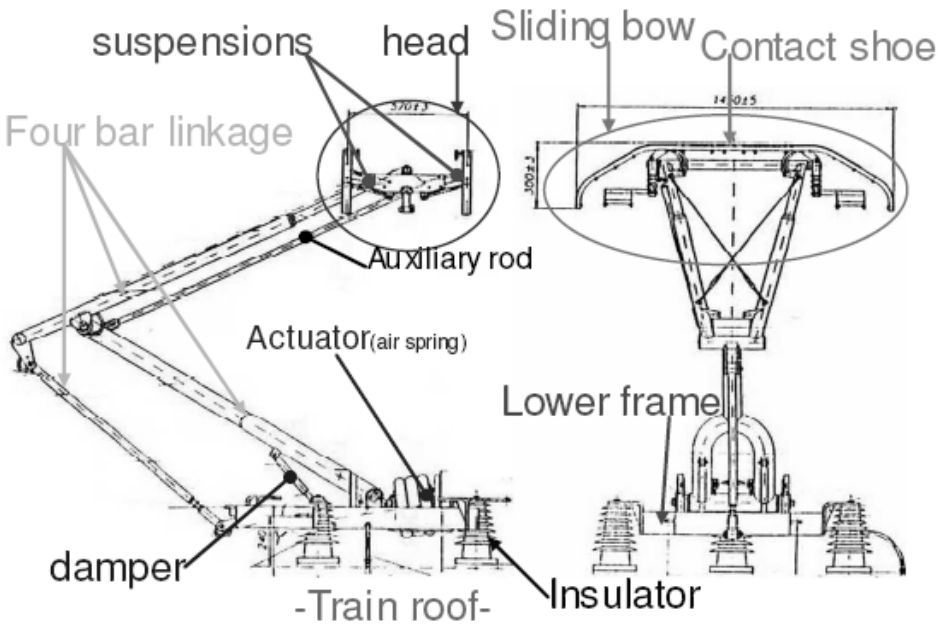

Figure 4.13.Commercial pantograph (schunk WBL85) and its main components (Allotta, Pugi, Bartolini, 2008)

The design of the pantograph is such that it must ensure a good electrical interface between the conducting head and the contact wire, at speed, under a range of operational and weather conditions. The contact wire represents an elastic medium and so the pantograph must be able to move vertically to maintain contact. More fundamentally, the contact wire height varies significantly to accommodate the requirements of bridges/tunnels and level crossings, necessitating associated vertical movements of the pantograph. Typically a pantograph requires a vertical range of movement of up to 2m and the design must be such that the pressure or force at the contact wire interface must be kept as uniform as possible over this range, and of course at speed as this range is traversed.

From a horizontal perspective, the contact wire occupies a lateral zone in its static/no wind situation and the width of the pantograph must be designed to suit this. On tangent track the contact wire is required to be registered on alternate sides of the track centreline to ensure that it laterally traverses the pantograph head, thus ensuring that no groove is worn in the interface carbons. This would cause 'snatching' and unacceptable performance. On curved track, the combination of the track curve and hence pantograph trajectory with the straight wire under tension (from a plan view

perspective) ensures that the wire will traverse the head of the pantograph. The effect of wind must also be accounted for in this analysis and becomes in fact a key parameter for determining OLE support distances on mainline applications.

The allowable movement range/position of the contact wire relative to the projected track centreline is termed the permissible displacement (or deviation). This value is determined from the pantograph half width, pantograph sway and track tolerances as well as providing for a safety distance from the pantograph edge. The predicted contact wire displacement, calculated from the wire and track geometry, the wire tension, aerodynamic characteristics and span length must be less than this value.

Unfortunately, a wide pantograph head which may assist displacement considerations, has a detrimental impact regarding mechanical and electrical kinematic effects. Furthermore, the mass of the pantograph as a whole must be kept as small as practicable to provide good dynamic performance. (Warburton, 2009)

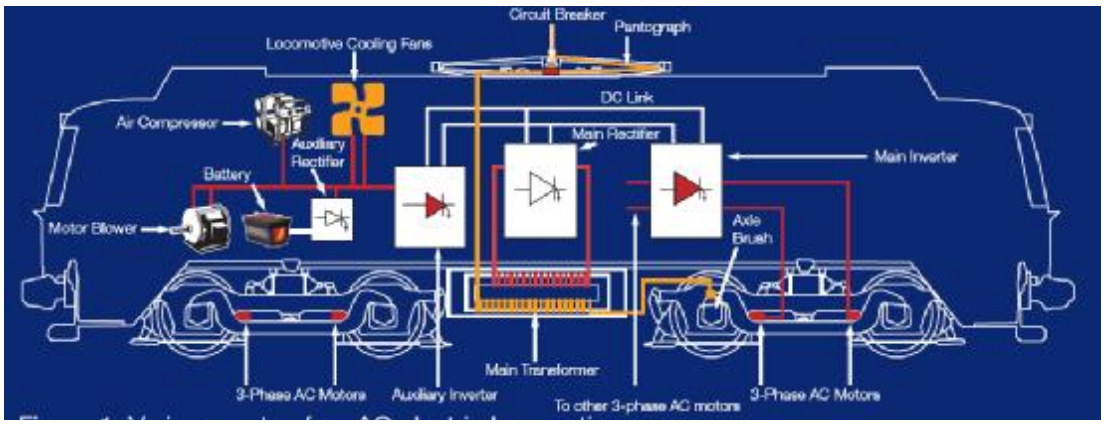

Figure 4.14. Various parts of an AC electric locomotive (LEM traction catalogue, 2001)

4.3.2.Conductor Rail System :

For suburban railways or metro systems, the trend is to use a low-level conductor rail system. It provides a reliable way of distributing power to a large number of trains in a small geographical area, and gives a good-looking result as well. When in tunnel, a conductor rail allows a smaller diameter than would be the case with overhead, and this can produce a significant saving in overall cost of the

railway. For this reason most recent urban metro systems have been developed using third rail current collection. (Hartland, 2008)

4.3.2.1.Third Rail

A third rail is a method of providing electricity to power a railway through a continuous rigid conductor alongside the railway track or between the rails. It is used typically in a mass transit or rapid transit system, which has alignments in own corridors, fully or almost fully segregated from the outside environment. A list of lines or networks equipped with a third rail is provided further below. Third-rail systems generally supply direct current to power the trains. In the early 1900s the third-rail system was used to power early roller coasters such as the Rough Riders in Coney Island, New York. (Web)

Third rail systems represent a low-maintenance power distribution network, and are suitable for voltages up to 1500V - above this figure the insulator sizes required become impractical. There are a number of possible arrangements. (Hartland, 2008)

4.3.2.1.(1.)Top-Running Systems

Top-running systems use a conductor rail mounted directly onto insulators on the sleeper ends. As such they provide a simple, robust design, well suited to higher speeds, and the maintenance is straightforward. Network Rail in Great Britain has over 4000km of system, with a maximum speed of 1 60kmlhr, extending for 150 km from London.

There are also extensive systems in New York, Paris, Beijing and several Russian cities using similar arrangements.

One fundamental difference between overhead and third rail systems is that the third rail is not continuous alongside the railway. Gaps must be provided at turnouts, and to ensure a continuous supply of current to the train, several sets of shoe gear must be fitted. This leads to quite complex studies of train and point work interaction at areas of complex point work; for there is the ever-present possibility

that the ramp gaps at turnouts will coincide with the shoe gear positions to produce that undesirable effect of a 'gapped' train - with not one shoe in contact with the third rail. Careful design of turnout position is required, especially in depots and complex junctions to avoid stranding trains.

In this regard the top-running system has advantages, for the proximity of the conductor rails to the running rails allows the conductor rails to extend well into the turnout areas, so minimising the actual gaps between ramps.

The great disadvantage with top-running rails is the difficulty with debris falling on the contact surface, and the formation of ice, which can dramatically affect current collection and disrupt the service if the ambient temperature hovers around freezing for any length of time. (Hartland, 2008)

4.3.2.1.(2.)UNDER-RUNMING SYSTEMS

The conductor rail in this system is hung from brackets along the lineside, with the contact surface underneath. This provides protection against ice and debris, and allows for the fitting of an overall cover to guard against accidental contact by staff or others on the line. The height of the rail means that gauge considerations force it to be located well outboard - this means that ramp gaps at turnouts are larger and train gapping can be quite serious in complex point work areas. Nevertheless, it has been the choice for much of European cities, and in recent years the emerging metro systems in East Asia have all used this system of electrification. (Hartland, 2008)

4.3.2.1.(3.)Side Running Systems

Although less common that the other types, the side running system provides definite benefits of train pickup - because the rails can be mounted continuously through turnouts, train gapping may be virtually eliminated.

A major user of side running conductor rail is the Vancouver Sky train system. This is a fourth rail system, which gives the added benefit of freedom from stray currents. (Hartland, 2008)

4.3.2.2.Technical aspects

The third rail is usually located outside the two running rails, but occasionally runs between them. The electricity is transmitted to the train by means of a sliding shoe, which is held in contact with the rail. On many systems an insulating cover is provided above the third rail to protect employees working near the track; sometimes the shoe is designed to contact the side (called side running) or bottom (called bottom running) of the third rail, allowing the protective cover to be mounted directly to its top surface. When the shoe slides on top, it is referred to as top running. When the shoe slides on the bottom it is not affected by the build-up of snow or leaves.

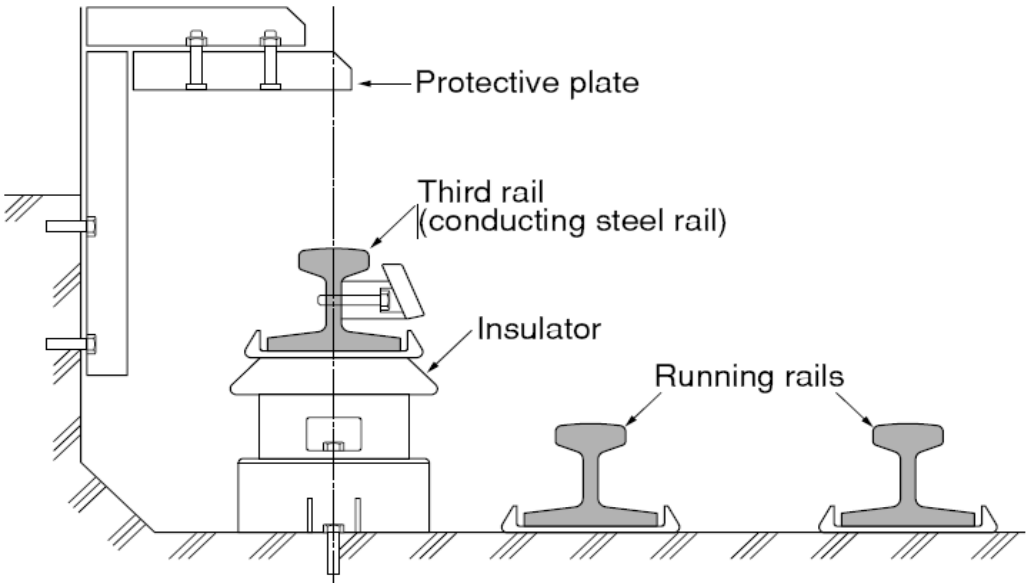

Figure 4.15. Third Rail (Oura, Mochinaga, 1998)

4.3.2.3.Advantages of Third Rail

4.3.2.3.(1.)Cost

Third-rail systems are cheaper to install than overhead wire systems, less prone to weather damage (other than flooding and icing, which cause major problems), and better able to fit into areas of reduced vertical clearance, such as tunnels and bridges. In many countries they were perceived as key means of reducing construction costs of tunnels, hence their popularity at underground railways

4.3.2.3.(2.)Visual Appear

Third-rail systems cause less visual intrusion: they do not need overhead lines, which some people perceive as unsightly.

4.3.2.3.(3.)Robustness

Third-rail systems are more robust than overhead line systems, as the conductor rail is able to take higher mechanical forces than the contact wire of an overhead line system. The shoegear on a train is designed to shear off if it hits the conductor rail too hard, but as a train has many sets of shoegear, it is able to continue its journey. By contrast a pantograph is more likely to get tangled up in the overhead wires and not be able to continue its journey.

4.3.2.3.(4.)Maintenance Access

Because it lies near the ground within easy reach, instead of many feet up in the air, a third rail system allows easy maintenance.

4.3.2.3.(5.)Compatibility

Many railways use a third rail and DC power, even where overhead lines would otherwise be practical, due to the high cost of retrofitting. Every expansion of such system must cope with the problem of compatibility. It usually leads for the choice of already existing technology.

4.3.2.4.Disadvantages of Third Rail

4.3.2.4.(1.)Safety

An unguarded electrified rail carrying more than 50 volts is a safety hazard, and some people have been killed by touching the rail or by stepping on it while attempting to cross the tracks. However, such incidents are usually the result of carelessness on the part of the victim. The principal hazard is probably associated with level crossings. While their number on third rail lines is normally reduced to none, they still occur at some systems, particularly on rural and suburban portions of the network

4.3.2.4.(2.)Limited Capacity

A relatively low voltage is necessary in a third-rail system otherwise, electricity would arc from the rail to the ground or the running rails but the resulting higher current (sometimes upwards of 3,000 amperes) causes more proportional voltage drop per mile, meaning that electrical feeder sub-stations have to be set up at frequent intervals along the line (generally no more than 10 miles (16 km) apart), increasing operating costs.

4.3.2.4.(3.)Infrastructure Restrictions

Junctions and other point work make it necessary to leave gaps in the live rail at times, as do level crossings. This is not usually a problem, as most third-rail rolling stock has multiple current collection shoes along the length of the train, but under certain circumstances it is possible for a train to become "gapped" — stalled with none of its shoes in contact with the live rail. When this happens, it is usually necessary for the train to be shunted back onto a live section either by a rescue locomotive or another service train, although in some circumstances it is possible to use jumper cables to temporarily hook the train's current collectors to the nearest section of live rail. Given that gapping tends to happen at complex, important junctions, it can be a major source of disruption.

4.3.2.4.(4.)Inefficient Contact

Fallen leaves, snow and other debris on the conductor rail can reduce the efficiency of the contact between the conductor rail and the pickup shoes, leaving trains stalled because of the lack of power.

4.3.3.Fourth Rail

The London Underground is one of the few networks that uses a four-rail system. The additional rail carries the electrical return that on third rail and overhead networks is provided by the running rails. On the London Underground a top-contact third rail is beside the track, energised at +420 V DC, and a top-contact fourth rail is located centrally between the running rails at -210 V DC, which combine to provide a traction voltage of 630 V DC. The same system was used for Milan's oldest underground line ; the more recent lines use an overhead catenary.

4.3.4.Coaxial Cable Feeding System

As shown in Figure 4.16., the coaxial cable feeding system features a coaxial cable laid along the track. Every several kilometers, the inner conductor is connected to the contact wire and the outer conductor is connected to the rail. The cable itself is very expensive but the conductor layout is simple, making it ideal for use where space is limited. Japan is the only country that uses this system (the Tokyo sections of Tohoku Shinkansen and Tokaido Shinkasen)

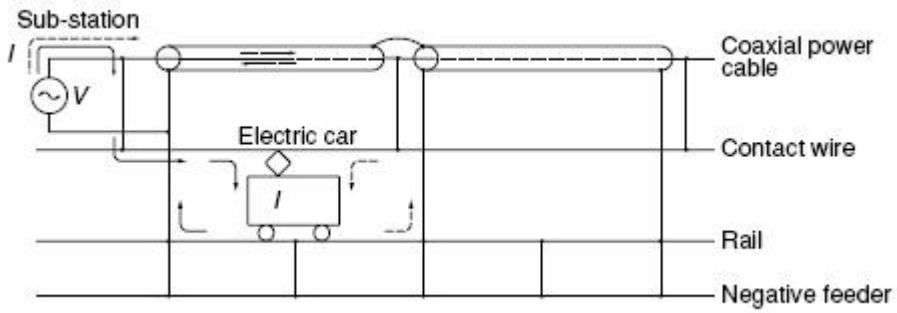

Figure 4.16. Coaxial Cable Feeding System (Oura, Mochinaga, 1998)

In comparison to the overhead line , the coaxial power cable has an extremely small round-trip impedance . Therefore , the load current is boosted in the coaxial power cable the connection with the overhead line . This results in all current distribution similar to that of the AT feeding system , significantly reducing the inductive interference in telecommunication lines. (Oura, 1998)

5.TRACTION MOTORS

5.1.Introduction

Railway systems have a simple goal to move people and material from A to B. In the Newtonian world in which we live a force must be applied to the object it is desired to move.

On the railway this force can be generated in one of two ways, via an engine of some form mechanically coupled in some way to the driving wheels, or using an electric motor coupled to the driving wheels.

As systems and technology have developed so has the use of electric traction motors become more prevalent. The use of electric motors is an obvious solution when the power source for the locomotive or train is itself electricity delivered by either overhead catenary or a third (and sometimes fourth) rail. (Nicholson, 2008)

5.2.Electrical Traction Machines

Having considered the fundamental physical basis for the selection of machines for traction, the next consideration is to choose the topology of the machine and design its characteristics for economy and efficiency. At this point it should be noted that in addition to infrastructure limitations (such as maximum line current) the requirements of the customer affect the situation, for example through the necessity of frequent start-stop operation as in inner suburban duty or high maximum speed as in an inter-city train. (Hill, 2006)

5.2.1.Traction Motor Types

The function of a traction motor is to propel a vehicle at variable speed within the traction duty cycle loading constraints. Electrical machines for traction must respect:

- limitations on space for physical installation
- requirement for economy in operation
- limits on dielectric stress of machine insulation

- maximum thermal loading of conducting and insulation materials
- harsh environment -including vibration , shock, temperature and humidity
- limitations on weight for axle/wheel loading.

Continuous improvement of machines over time has resulted in effective machine designs being produced without the need for significant over dimensioning. The following types of motors have suitable characteristics for traction:

- DC series commutator motor
- Separately-excited commutator motor(for continuous or pulsating current DC)
- Low-frequency AC commutator motor
- Three-phase AC synchronous motor
- Three-phase AC cage induction (asynchronous) motor.

Although large numbers of traction vehicles are still operating with low-frequency commutator motors and DC series motors, the separately-excited commutator motor and the three-phase cage induction motor are considered the best for traction. In addition, the synchronous machine is successfully utilized in France and elsewhere for locomotive and high-speed train drives. (Hill, 2006)

5.2.2.Physical and Thermal Considerations

In selecting a traction motor, the important characteristics to be considered are

- mechanical: the torque and speed characteristics
- electrical: voltage, current and power levels
- physical: dimensions, volume and weight
- thermal: permitted temperature rise.

The installed torque and power of a given machine must be optimized with respect to the traction duty cycle and axle load. At the same time, the maximum physical size of the motor depends on the space available within the vehicle bogies or body. During operation, thermal factors are important, particularly with respect to short-term ratings. (Hill, 2006)

5.3.DC Motor

DC motors have been utilized for traction for over one hundred years and were originally chosen because of their inherent compatibility with traction power supplies and ease of mounting within locomotive bogies. Their operating voltage, current, speed and torque levels are consistent with the dynamic and kinematics traction duty cycle requirements.

Fig. 5.1 shows a schematic of a DC machine. The DC field coils on the stator generate flux that passes through the air gap, the rotor teeth, armature winding, the rotor core and the stator yoke. The DC armature is a closed winding residing in longitudinal slots in the iron rotor core. At one end, connections are made to the bars of a copper commutator. Carbon brushes make a sliding contact with the commutator, thus enabling armature current to be fed into or extracted from the armature winding.

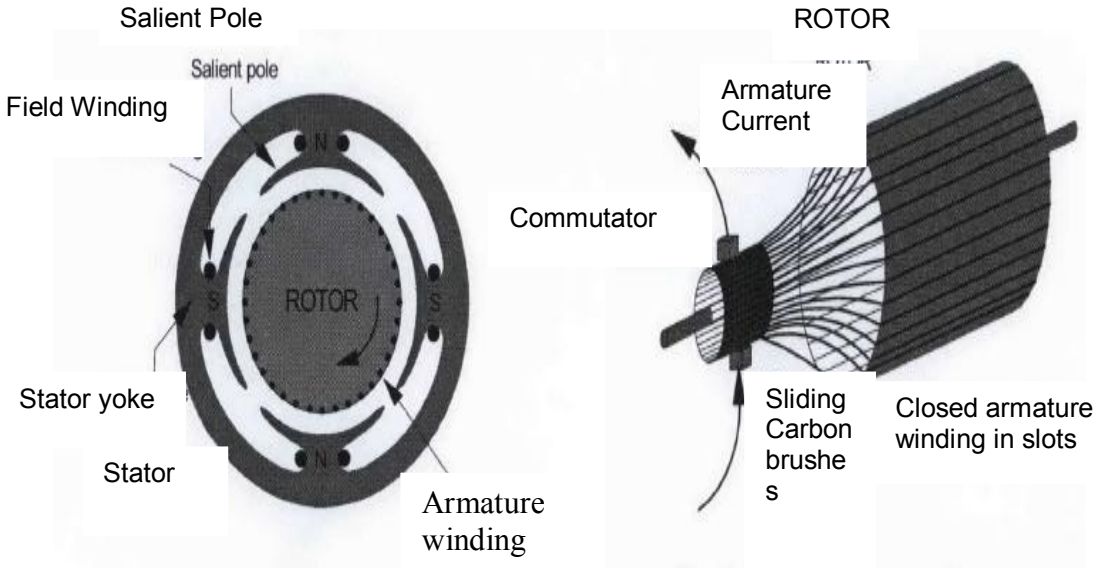

Figure 5.1. DC Traction motor schematic (Hill, 2006)

DC traction motors may have series or separately-excited fields. Following, the steady state operation of both types of motor will be examined, with the objective of deriving characteristic curves relating the machine torque and speed to the terminal voltage and current.

The basic electromechanical machine equations relate the back EMF and torque to magnetic flux, speed and armature current. The back EMF is

$$Ea = k\phi\omega \quad (5.1)$$

where the parameter k is a machine constant ($pZ/2\pi a$, with p the number of poles, Z the number of conductors in the armature and a the number of parallel paths in the windings), ϕ is the magnetic flux per pole, obtained by integrating the field flux density over the pole pitch, and ω is the rotational speed. The torque is where la is the total DC armature current. (Hill, 2006)

$$T = k\phi\ Ia \quad (5.2)$$

5.3.1.Series Motor

In the series motor, there is a single armature and field winding. The field flux is therefore a function of armature current. From the equivalent circuit of Fig.5.2 , the motor voltage is

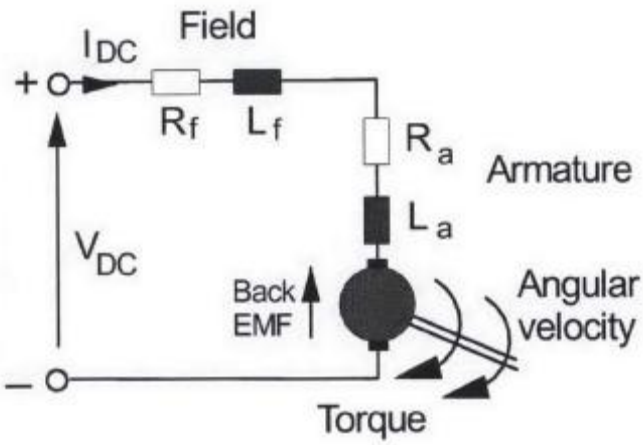

Figure 5.2 DC series motor equivalent circuit (Hill, 2006)

$$V = Ia(Ra + Rf) + Vb + Ea \quad (5.3)$$

where Ra is the armature resistance, Rf is the field resistance, Vb is the brush voltage drop and Ea, is the motor back EMF. Because of the magnitude of armature current, the field winding has a small number of turns with a large wire diameter to reduce its resistance. (Hill, 2006)

Using the basic machine equations, the terminal voltage becomes ;

$$V = T / (k\phi)(Ra + Rf) + Vb + k\phi\omega \quad (5.4)$$

To solve this equation exactly, the relationship between the flux $k\phi$ and armature current I, is required. Since this is non-linear, a numerical technique involving, for example, a polynomial curve fit is necessary for an exact solution.

Obtaining an approximate solution for the torque-speed curve is, however, possible by representing the magnetisation characteristic by simple analytic functions in two regions of operation. The resulting equations are applicable to low armature current where flux is proportional to the current

$$\omega = \frac{V - Vb}{k_2\sqrt{T}} \tag{5.5}$$

and for high armature current where the flux is almost constant.

$$\omega = (V\text{-}Vb) / k_3 - T(Ra + Rf)\, k_3^2 \tag{5.6}$$

These equations define the limits of the torque-speed characteristic. This characteristic is, in fact, ideal for traction since the machine develops a high starting torque, following which the ωT product representing the mechanical power output is approximately constant. Furthermore, since machine cost is closely related to power, rather than torque or speed alone, it represents a very economical solution through efficient motor utilisation.

The motor works because, simply put, when a current is passed through the motor circuit, there is a reaction between the current in the field and the current in the armature which causes the armature to turn. The armature and the field are connected in series and the whole motor is referred to as "series wound".

A series wound DC motor has a low resistance field and armature circuit. Because of this, when voltage is applied to it, the current is high. The advantage of high current is that the magnetic fields inside the motor are strong, producing high torque (turning force), so it is ideal for starting a train. The disadvantage is that the current flowing into the motor has to be limited somehow, otherwise the supply could be overloaded and/or the motor and its cabling could be damaged. At best, the torque would exceed the adhesion and the driving wheels

would slip. Traditionally, resistors were used to limit the initial current. (railway technical web site)

The particular advantage of the series motor is that control of only one variable, the armature current, is necessary. Speed control can be achieved by varying the terminal voltage, adjusting the series resistance, or changing the field. (Hill, 2006)

5.3.2.Separately-Excited Motor

In the separately-excited motor, the field excitation is obtained using a power supply independent from that of the armature circuit, Fig.5.3. The circuit equations are:

$$If = \frac{Vf}{Rf} \text{ and} \tag{5.7}$$

$$Vt = Ea+IaRa+Vb \tag{5.8}$$

The open-circuit magnetisation characteristic, giving the back EMF as a function of field current at constant speed, defines the motor flux through the relationship

$$\frac{Ea}{\omega} = k\varphi \tag{5.9}$$

since the curve of kϕ as a function of field current can be obtained by plotting Ea/ω against field current. The speed for a specific torque can be determined iteratively with a correction to allow for lost torque at each particular speed. The speed torque curve is obtained as

$$Vt = k\varphi\omega + \frac{TRa}{k\varphi} + Vb \tag{5.10}$$

or $$\omega = \frac{Vt - Vb}{k\varphi} - \frac{TRa}{(k\varphi k^2} \tag{5.11}$$

This equation is nonlinear since the motor flux is a function of field current,

which is dependent on the machine iron saturation characteristics. The speed control characteristics are shown in Fig.5.4, from which speed variation may be achieved by either:

- varying the terminal voltage : If armature resistance is small, the speed is then independent of load torque (a typical value for the speed regulation from zero to full load is 5%), or
- varying the field current and hence flux : The minimum value of field resistance is that of the field winding itself. As field current and hence flux decrease, the torque for constant armature current will decrease.

The separately-excited motor is suitable for traction because it may be controlled to produce high torque at low speeds, and yet fully utilize its rated power at high speeds. (Hill, 2006)

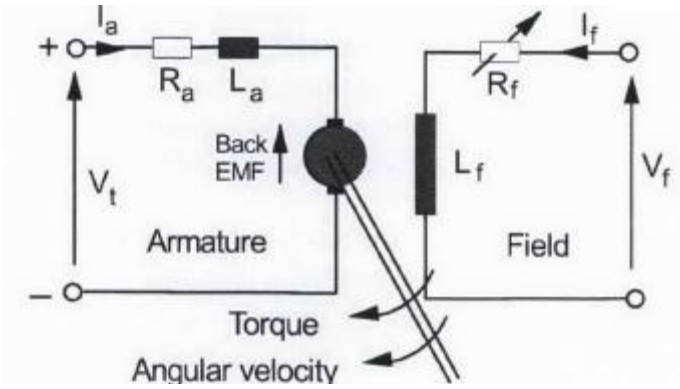

Figure 5.3.DC separately-excited motor equivalent circuit (Hill, 2006)

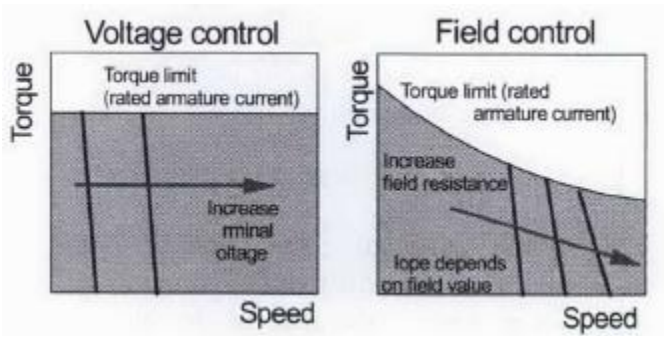

Figure 5.4.DC separately excited motor speed control by armature voltage and field current (Hill, 2006)

5.4.AC Motor

5.4.1.Three Phase AC Motor Construction

The motor is formed from two parts, the fixed outer frame the stator, and the internal rotating element - the rotor. Unlike the DC motor where commutation caused by the rotation of the armature is used to create the rotating magnetic field, the necessary rotating magnetic field is naturally caused in the static stator by the three-phase currents.

The stator is formed from a stator core and stator windings. The stator core is comprised of thin laminations of cast iron or aluminium which are clamped together to form a hollow cylinder. The laminations are punched to provide slots to take the windings once the core is assembled.

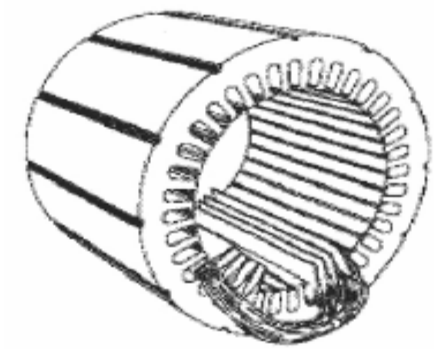

Figure 5.5 AC machine stator core (Nicholson, 2008)

Coils of insulated copper bar are then inserted into these slots. The arrangement of the windings is designed to produce pairs of poles, with the number of pole pairs and the frequency of the supply determining the rotation speed of the motor.

The rotor is formed from a main shaft around which is fitted a rotor core. The rotor core is formed of thin laminations of cast iron or aluminium, punched to the required pattern and then clamped together on the main shaft. The windings are then placed into slots in the core and all connected together at each end by welding to a shorting ring or plate. The rotor windings are angled to prevent rotor lock and run more quietly by reducing magnetic hum and slot harmonics.

Other than that there is not much more to say about squirrel cage AC motor construction. Add a bearing at each end of the shalf, put some bell housing at each end of the stator formation, bolt it all together and you have a motor. When compared to complexity of the DC motor armature you can easily see why AC motors have generally become the motor of choice. (Nicholson, 2008)

5.4.1.1.AC Motor Operation

The torque speed curve of the ac motor is significantly different from a dc motor, and its natural characteristics are not ideally suited to traction applications without manipulation

The toque produced at the rated motor speed, also called the synchronous speed, is zero. Hence to be of use and produce a torque the motor much be run at some speed lower than the synchronous speed, hence why they are call asynchronous motors.

The synchronous speed of the motor is determined by equation :

Equation

$$Ns = 120 \times f/P \tag{5.12}$$

Where

Ns = the synchronous speed of the motor in rpm

f = the supply frequency in hertz

P = number of pole pairs

However in practice the rotor is always 'chasing' the stator field, therefore running at a slower speed - the base speed. The difference between the synchronous speed and the base speed is the slip, is defined in Equation (5.10).

$$\% \text{ slip} = (Ns - Nb)/Ns \times 100 \tag{5.13}$$

where

Ns = the synchronous speed in rpm

Nb = base speed in rpm

As the load on the motor increases the % slip increases, as the load on the motor decreases the % slip decreases. In general an operating slip of around about 5% is typical.

From the above it can seen that if a constant torque needs to be developed across a range of speeds then the supply frequency applied to the stator needs to be changed. Hence the control of the motor needs to be able to supply a variable frequency three phase supply hence the need for the switching devices and complex electronics that will be discussed by others.

So, as with many things in life, although the asynchronous AC motor is much simpler to construct and maintain that a DC motor, this has to be traded off against the much greater complexity of the require control equipment. (Nicholson, 2008)

5.4.2.Synchoronous Traction Motors

The synchronous machine is an important electromechanical energy converter. Synchronous generators usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers. For these applications synchronous machines are built in large units, their rating ranging from tens to hundreds of megawatts. For high-speed machines, the prime movers are usually steam turbines employing fossil or nuclear energy resources. Low-speed machines are often driven by hydro-turbines that employ water power for generation. Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers.

Synchronous machines can also be used as motors, but they are usually built in very large sizes. The synchronous motor operates at a precise synchronous speed, and hence is a constant-speed motor. Unlike the induction motor, whose operation always involves a lagging power factor, the synchronous motor possesses a variable-power-factor characteristic, and hence is suitable for power-factor correction applications.

A synchronous motor operating without mechanical load is called a compensator. It behaves as a variable capacitor when the field is overexcited and as a variable inductor when the field is under-excited. It is often used in critical positions in a power system for reactive power control. (Chan, 2004)

Synchronous motors are three-phase AC motors which run at synchronous speed, without slip. (In an induction motor the rotor must have some “slip”. The rotor speed must be less than, or lag behind, that of the rotating stator flux in order for current to be induced into the rotor. If an induction motor rotor were to achieve synchronous speed, no lines of force would cut through the rotor, so no current would be induced in the rotor and no torque would be developed.) (LLC, 2004)

Synchronous machines operate from AC power and rotate in synchronism with the frequency of the applied current. Although earlier attempts had been made to utilise synchronous machines for traction, it was the advent of variable-frequency converters using power electronic devices in the 1980s that made the use of synchronous traction motors feasible. Such traction machines tend to be of large diameter so are suitable for mono-motor bogies. (Hill, 2006)

Synchronous motors have the following characteristics:

- A three-phase stator similar to that of an induction motor. Medium voltage stators are often used.
- A wound rotor (rotating field) which has the same number of poles as the stator, and is supplied by an external source of direct current (DC). Both brush-type and brushless exciters are used to supply the DC field current to the rotor. The rotor current establishes a north/south magnetic pole relationship in the rotor poles enabling the rotor to “lock-in-step” with the rotating stator flux.
- Starts as an induction motor. The synchronous motor rotor also has a squirrel-cage winding, known as an Amortisseur winding, which produces torque for motor starting.
- Synchronous motors will run at synchronous speed in accordance with the formula:

Synchronous RPM = (120 x Frequency) / Number of Poles (5.14)

Example: the speed of a 24 -Pole Synchronous Motor operating at 60 Hz would be:

120 x 60 / 24 = 7200 / 24 = 300 RPM (LLC, 2004)

Figure 5.8 shows a schematic of a synchronous machine with the winding arrangements shown in simplified form. Two air gap fields are generated. The stator

winding when excited with three phase currents gives rise to a field sinusoidally distributed in space and time, rotating within the air gap at the synchronous speed determined by the supply frequency. A DC winding on the rotor produces a steady field that rotates at the rotor frequency. If the rotor moves at synchronous speed, the two fields will be stationary with respect to each other and a net torque will be produced with value depending on the magnitude of the armature and field currents and their relative angle.

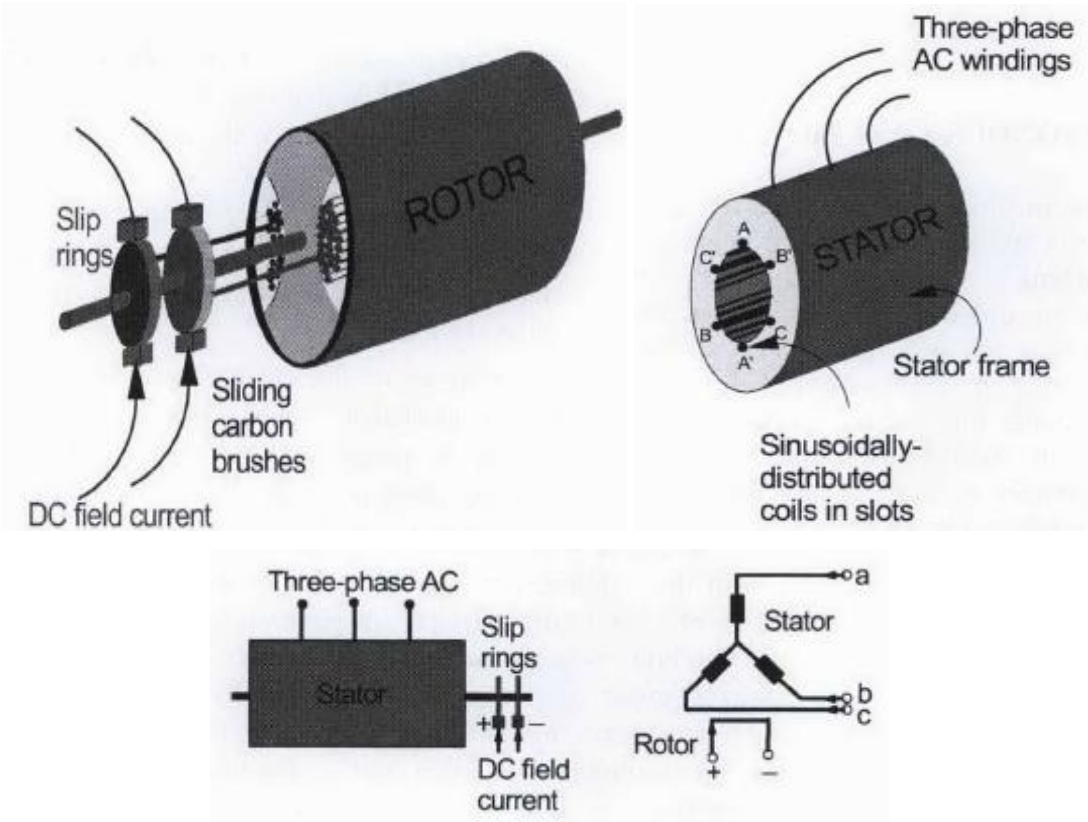

Figure 5.6. Schematic representation of rotor and stator windings of synchronous machine (Hill 2006)

If the rotor moves at any other than the synchronous speed, the net torque will be zero.

In a synchronous machine, an EMF is present even with zero stator current so provided the machine is rotating it can be controlled by a naturally-commutated converter. The synchronous machine is thus a self-commutated machine similar in some respects to a DC motor: in the DC motor, switching of current is achieved by

the commutator, whereas in the self commutated synchronous machine, conmmutation is governed by the voltage or rotor position of the machine itself.

Synchronous traction motors are fed from current source inverters. The terminal voltage must be variable from zero to maximum and the voltage frequency ratio maintained constant to retain optimum machine flux. Therefore, at least during the maximum torque acceleration period, the machine must be overexcited. (Hill, 2006)

Two methods are commonly utilized for the application of the direct current (DC) field current to the rotor of a synchronous motor.

- Brush-type systems apply the output of a separate DC generator (exciter) to the slip rings of the rotor.
- Brushless excitation systems utilize an integral exciter and rotating rectifier assembly that eliminates the need for brushes and slip rings. (LLC, 2004)

5.4.2.1.Advantages of Synchronous Motors

The initial cost of a synchronous motor is more than that of a conventional AC induction motor due to the expense of the wound rotor and synchronizing circuitry. These initial costs are often off-set by:

- Precise speed regulation makes the synchronous motor an ideal choice for certain industrial processes and as a prime mover for generators.
- Synchronous motors have speed / torque characteristics which are ideally suited for direct drive of large horsepower, low-rpm loads such as reciprocating compressors.
- Synchronous motors operate at an improved power factor, thereby improving overall system power factor and eliminating or reducing utility power factor penalties. An improved power factor also reduces the system voltage drop and the voltage drop at the motor terminals.

5.4.3.Induction Traction Motors

The majority of traction motors being installed in rail vehicles today are AC motors, usually a three-phase asynchronous motor, also known as a 'squirrel cage' motor.

As will be seen later the squirrel cage motor has some fairly fundamental benefits over the standard DC traction motor. It is simpler to construct, easier to maintain and has a better power/size and power/weight ratios. However to use these advantages a variable frequency three-phase AC supply has to be available on the train - and this in the past has been difficult from a dc or single phase ac supply as is customarily used.

However the advent of modern power electronics, along with massively more, and cheaper, processing power has made the ability to produce variable frequency three-phase supplies much more practical.(Nicholson, 2008)

5.4.3.1.Basic Construction and Operating Principle

Like most motors, an AC induction motor has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two. Virtually all electrical motors use magnetic field rotation to spin their rotors. A three-phase AC induction motor is the only type where the rotating magnetic field is created naturally in the stator because of the nature of the supply.

Two sets of electromagnets are formed inside any motor. In an AC induction motor, one set of electromagnets is formed in the stator because of the AC supply connected to the stator windings. The alternating nature of the supply voltage induces an Electromagnetic Force (EMF) in the rotor (just like the voltage is induced in the transformer secondary) as per Lenz's law, thus generating another set of electromagnets; hence the name – induction motor. Interaction between the magnetic field of these electromagnets generates twisting force, or torque. As a result, the motor rotates in the direction of the resultant torque. (Parekh, 2003)

The stator is made up of several thin laminations of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in Figure 5.8 . Coils of insulated wires are inserted into these slots.

Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created. (Parekh, 2003)

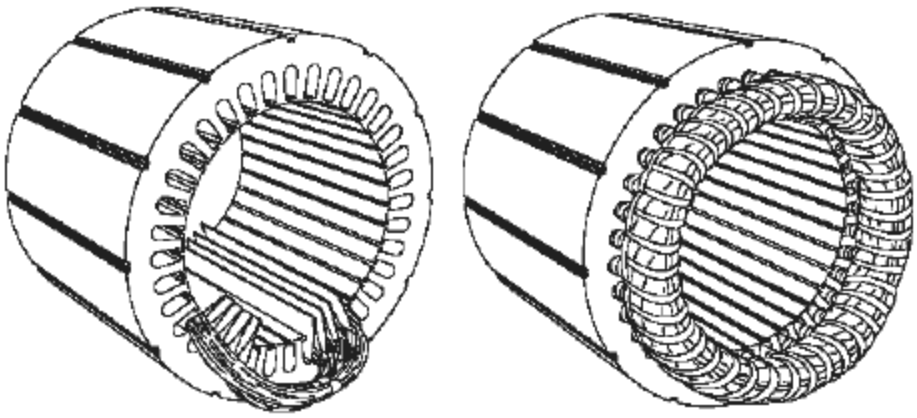

Figure 5.8.A Typical Stator (Parekh, 2003)

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the periphery. In the most popular type of rotor (squirrel cage rotor), these bars are connected at ends mechanically and electrically by the use of rings. Almost 90% of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings, as shown in Figure 5.9. This total assembly resembles the look of a squirrel cage, which gives the rotor its name. The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons.

The first reason is to make the motor run quietly by reducing magnetic hum and to decrease slot harmonics.

The second reason is to help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic

attraction between the two. This happens when the number of stator teeth are equal to the number of rotor teeth. (Parekh, 2003)

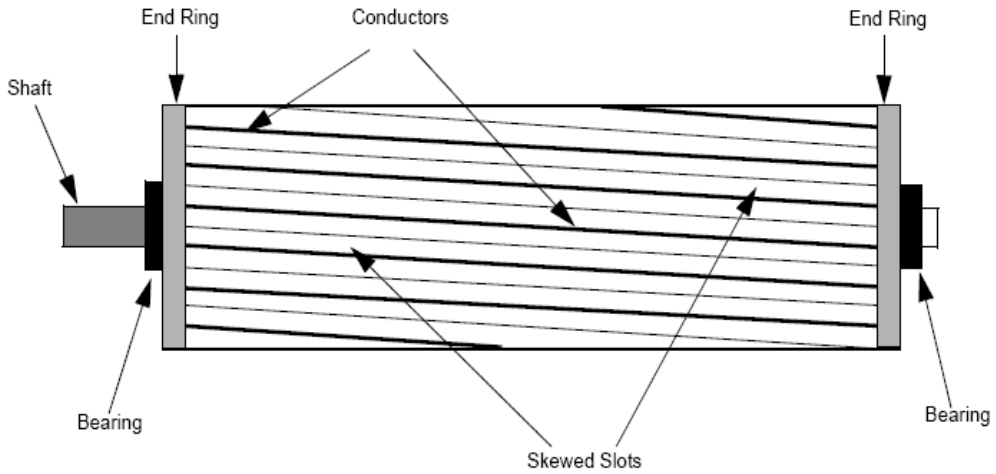

Figure 5.9 A Typical Squirrel Cage Rotor (Parekh, 2003)

The cage induction (asynchronous) machine operates from AC current but does not require a separate rotor supply. Figure 5.10 shows an induction machine rotor and stator in schematic form. The stator comprises a symmetric set of sinusoidally distributed windings and the rotor is a cage of parallel conducting bars. The rotor cage forms a closed set of windings in which circulating currents can be induced from the stator currents. There are no brushes or slip-rings requiring conducting current transfer to the rotor conductors.

Torque production in the machine arises from the magnetic field set up by the three-phase currents in the stator windings. This creates a rotating flux vector in the air gap , moving at the synchronous angular frequency, which induces currents in the rotor conductors that in turn set up an opposing air gap flux moving at the rotor frequency. Interaction between the rotor currents and the resultant air gap flux wave creates torque.

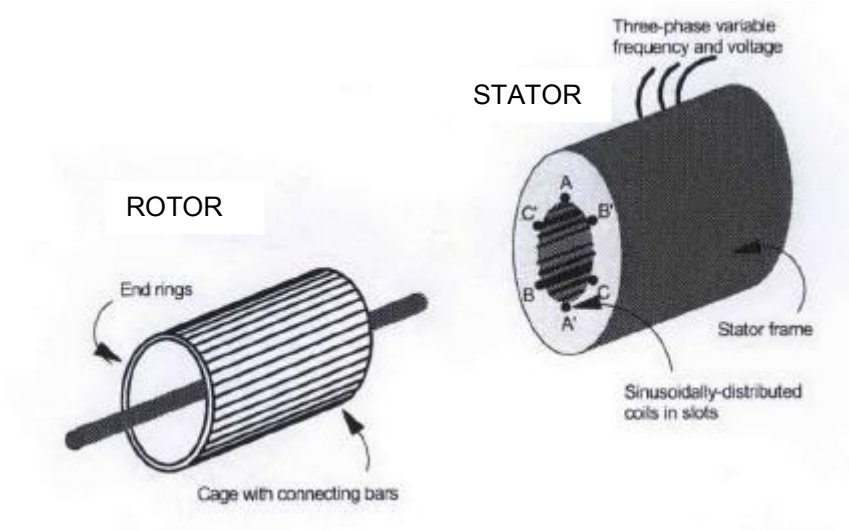

Figure 5.10 Asynchronous (induction) traction motor schematic (Hill, 2006)

Detailed consideration must be given to the frequencies of the various flux waves and currents. If the rotor moves at angular speed ωr , the induced EMF in the rotor coils is at angular frequency (ωs-ωr) with respect to the rotor coils, so the rotor currents will also be at this frequency. The rotor and stator flux waves are both at frequency co, with respect to the stator and torque is therefore produced provided they are not coincident in space. Thus if the rotor moves at synchronous speed (ωs=ωr) no torque will be produced.

The part of the rotor flux density wave that does not cancel the stator flux density leaves a core flux in the air gap. This is equivalent to the magnetising flux in a transformer core, except that electrical power is converted to mechanical motion by a moving secondary winding rather than extracted as electrical power by a stationary winding. (Hill, 2006)

Compared with DC series or separately excited machines, cage induction motors have the following advantages for traction:

- high maximum speeds robustness and reliability with a low maintenance requirement
- simple cooling arrangement with enclosed frames
- high uniform torque with inherent overload management
- high power/weight ratio

- low cost/power ratio
- high-voltage operation
- inherent regenerative braking capability
- steep torque-speed characteristics
- stable operation with parallel connection.

In a three-phase cage IM, the stator is a symmetric set of sinusoidally-distributed windings and the rotor is a closed set of parallel conducting bars in which induced currents can flow. There are no brushes or slip-rings requiring conducting current transfer to the rotor conductors. The magnetic field set up by the three-phase currents in the stator windings creates a rotating flux vector in the airgap. This rotating flux induces currents in the rotor conductors, which in turn set up an opposing airgap flux. Interaction between the rotor currents and the net airgap flux wave creates torque.

In general, inverter-fed IMs must be designed to accommodate extra power losses and torque pulsations from the effects of stepped voltage waveforms. There are several additional issues when considering the use of inverter-fed IMs for railway traction. The achievable maximum wheel/rail adhesion limits the installed power per axle, so traction inverters are usually required to drive several motors in parallel, with implications for the control system design. The design of drives must also take into account the severe thermal loading and harsh environmental conditions found in traction including vibration, shock, temperature and humidity. (Hill, 1994)

5.3.3.2 Utilisation for Traction

The induction motor torque-speed characteristic given by the basic equation indicates that the variables available for speed control are the terminal voltage, stator field frequency, number of poles and rotor circuit resistance. Of these, the last two are not used in inverter-fed drives where traction control involves variation of the terminal voltage or current and the stator frequency.

The maximum torque-speed envelope of an induction motor traction drive is of the form. Within this constraint, the motor is controlled within four regions of operation as shown in Figure 5.11 and summarised below.

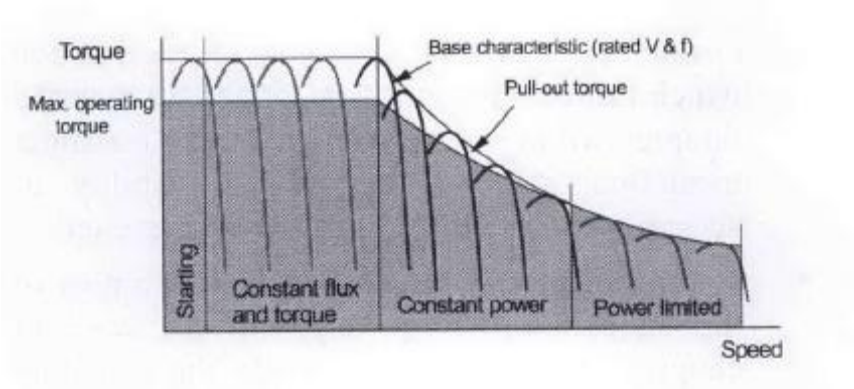

Figure 5.11 Traction characteristics with induction motor drive: motor characteristics (Hill, 2006)

- Constant torque. The motor base characteristic corresponds to operation at rated voltage and frequency. Below this speed, the machine is operated with constant air gap flux by maintaining the machine magnetising current (Ima) constant. If the following conditions are satisfied ;

  $[Rs + (R'r/S)] << \omega s L_L$ (5.15)

  $(Va/\omega s)=k_2$ (5.16)

  where the parameters k_1, and k_2 are constants for a particular machine, then the torque will be constant. The first of the above three equations holds above very low speeds and the second is satisfied below the base speed since the characteristic curves are parallel with constant breakdown torque. Control up to the base speed is achieved by increasing the voltage and frequency together such that their ratio is unchanged, as in the third equation. The torque is thus constant and power increases linearly until at the base speed it is at the rated value, limited only by the line or inverter power supply. Constant torque operation also applies with negative torque, so a traction load may be decelerated by regenerative braking merely by reduction of the inverter frequency.

- Starting. At very low speeds, the stator resistance Rs becomes large in comparison with the reactance ωsL_L and linearity between torque and machine flux no longer holds. The stator impedance voltage drop increases and the ratio Va/ωs must be increased to compensate for the consequent reduction in air gap flux. The machine, however, can always be started at maximum torque.
- Constant power. Above the base speed, the motor terminal voltage and current are maintained at their rated values.

$$T=k_3/S\omega s^{3} \tag{5.17}$$

The torque is with the parameter k_3 constant.

$$\omega mecT\approx\omega sT=(k_3 / S\omega s^{2}) \tag{5.18}$$

The power is which will be constant if the product $S\omega s^{2}$ invariant. The torque will then be inversely proportional to motor speed. As speed is raised, the motor slip will increase until the working torque is equal to the breakdown torque. The constant power region is thus a transition region above the base speed where the ratio Va/ωs, and hence the machine flux, decreases due to increasing frequency. The controller must increase the slip to achieve constant power. In addition to the decreasing breakdown torque on the individual characteristics, the characteristics broaden slightly because the product Sωs is no longer constant.

- Reduced power. The maximum breakdown torque at rated frequency is found by differentiation. The torque has an inverse square relationship with frequency and the power is inversely proportional to frequency. Motor speed increase is thus obtained by increasing frequency and maintaining the output torque at the breakdown torque, which requires a reduction in the stator current. The torque is also inversely proportional to stator inductance which implies that voltage drop due to stray inductance limits the high-speed performance.

Figure 5.12 shows the torque, power, voltage and current of the machine during each region of operation. Up to the base speed, power is mainly expended in accelerating the mass of the vehicle. Beyond that point, power-limited acceleration occurs. At high speed, in the torque and power limiting region, the load torque characteristic is eventually balanced by the available propulsion torque to give the maximum operational speed. In normal operation, a torque margin must be provided. Typical manufacturers' characteristics give a working torque in the constant torque region of 55% of the pull-out torque. The constant power region ends at 175% and max speed is 250% of the base speed.(Hill, 2006)

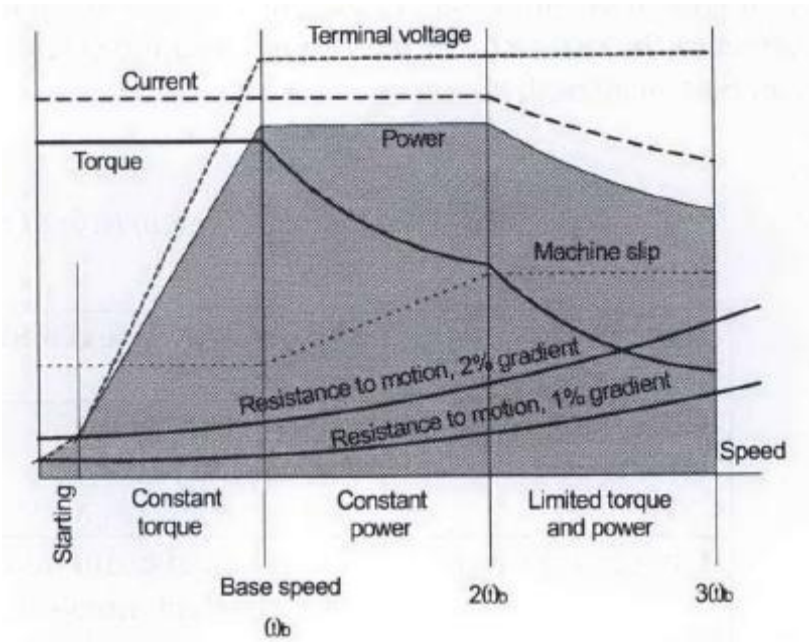

Figure 5.12. Traction control regimes (Hill, 2006)

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5.5.Power Electronic Controllers

The widespread proliferation of power electronics and ancillary control circuits into motor control systems in the past two or three decades have led to a situation where motor drives, which process about two-thirds of the world's electrical power into mechanical power, are on the threshold of processing all of this power via power electronics. The days of driving motors directly from the fixed ac or dc mains via mechanical adjustments are almost over.

The marriage of power electronics with motors has meant that processes can now be driven much more efficiently with a much greater degree of flexibility than previously possible. Of course, certain processes are more favourable to certain types of motors, because of the more favourable match between their characteristics. Historically, this situation was brought about by the demands of the industry. Increasingly, however, power electronic devices and control hardware are becoming able to easily tailor the rigid characteristics of the motor (when driven from a fixed dc or ac supply source) to the requirements of the load. Development of novel forms of machines and control techniques therefore has not abated, as recent trends would indicate.

It should be expected that just as power electronics equipment has tremendous variety, depending on the power level of the application, motors also come in many different types, depending on the requirements of application and power level. Often the choice of a motor and its power electronic drive circuit for application are forced by these realities and the application engineer therefore needs to have a good understanding of the application, the available motor types, and the suitable power electronic converter and its control techniques. Table 33.1 gives a rough guide of combinations of suitable motors and power electronic converters for a few typical applications. (Rahman, 2007)

5.6.History of Traction Drives

As shown in Table 5.1., drive systems for electric railcars have been developed in response to needs for energy saving, high adhesion, light weight and lower level of noise features, as supported by the development of power electronics.

For DC electrical railcars, a field chopper control systems, which is a combination of the conventional cam shaft control systems and regenerative brake function has been developed in 1967 and used for commuter railcars which are operated for relatively long distances between stations. On the other hand, subway railcars, which require frequent starting and stopping due to the short distance between stations, employ armature choppers. They have replaced the cam shaft

control unit with thyristor choppers and are capable of contactless control during power running and the effective use of regenerative brakes for stopping.

In the late 1970s, traction motors were changed from DC motors to induction motors. As a result there was an increasing need for VVVF (Variable-Voltage Variable Frequency) inverter control of induction motors to improve maintenance-free features by eliminating brushes and to achieve a higher adhesion.

Compared to chopper control, inverter control can eliminate most contacts except for circuit breakers in the power supply systems, but requires a larger number of power electronics devices. To solve this problem, GTO thyristors with a self-commutation function have been developed for larger capacity, and VVVF inverter systems are being used in commercially applicable stages. (Nakamura, 1993)

Table 5.1. Historical trends of drive systems for electric railcars (Ohmae and Nakamura, 1993)

1960	1970	1980	1990	2000
	Energy saving	High adhesion	Light weight	Low noise
	Dc MOTOR			Ac MOTOR
DC Railcar	CAM Shaft Control	Chopper Control	Inverter Control	
	Resistor	Thyristor	GTO	IGBT
AC Railcar	DIODE	Thyristor	GTO	
	Rectifier	Phase controlled converter	PWM Converter	
ANALOG BASED CONTROL CIRCUIT			Microcomputer	

Modem power electronics and the associated microprocessor based control electronics make it equally feasible to control AC or DC traction motors from AC or DC supplies. All four possibilities are substantially represented on the world's railways, although there is a clear trend with new builds to use AC motors (usually induction motors, but some use of synchronous machines). The chief reasons for this are the elimination of the commutator that is a feature of the DC machine, increased power density in the machine itself and the possibility of a 'sealed-for-life' motor that should require almost zero maintenance. Against this, the requirement for a variable-

voltage, variable-frequency supply makes the power electronic converter more complicated (especially when working from an AC supply) and arguably less reliable and more expensive.

However, the latest generation of power electronic inverters (i.e. providing a 'vvvf supply) based on IGBT's (insulated-gate bipolar transistors) are simpler, more compact and more reliable than the previous generation based on GTO's (gate-turn-off thyristors) and are now able to control all but the largest drives without excessive use of series-parallel grouping of the switching devices.(Goodman, 2006)

All power electronic controllers convert electrical power from one form (e.g. AC) to another (e.g. DC), using some type of high-power silicon switches and diodes.
There are two basic methods of obtaining voltage control using switch action:-

- With an AC supply, a device like a thyristor is gated at some delay angle with respect to the start of the mains supply cycle and thus only part of the sine wave gets applied to the load. Since the mains reverses each cycle, even in an inductive load the current will naturally fall to zero some way into the negative half-cycle and the thyristor will be commutated off. This is known as phase-angle control.
- With a DC supply, a device such as an IGBT is needed as this can be turned off as well as on via the gate. With this capability, it is possible to use Pulse-Width Modulation (PWM), in which a series of rectangular pulses, usually at constant frequency and amplitude, have their widths adjusted to deliver the required average voltage to the load. With a high carrier frequency (say 1 kHz) and variation of the pulse-widths in sympathy with a modulation frequency representing the output AC frequency required, this same basic technique enables an AC output to be derived from a DC supply. To get both polarities of output voltage and three phases a bridge of six switches and six anti-parallel diodes is in fact required. .(Goodman, 2006)
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5.7.Traction Drives for DC Motors

The majority of railway traction drives in use today utilize commutator machines. For many years, most drives used series or separately-excited motors on DC-supplied railways with resistance control, and universal motors on low-frequency AC railways with tapped transformer and rectifier control. In the 1970s, DC-DC chopper control was developed for both series and separately excited motors, with the latest technology using gate turn off (GTO) thyristors. Separately-excited motors have been used for power frequency AC railway rectifier drives from the 1950s and, with naturally commutated thyristor converters, represent cost-effective, mature technology.

The DC machine produces or absorbs torque by the interaction of a DC field with a DC armature current. Traction motors operate from an unsmoothed rectified power supply and thus have to withstand large ripple currents and dynamic stresses. The high power density requirement means that, except for small motors used in tram and light rail systems, DC traction motors are open and must be cooled with forced ventilation. The maximum permitted temperature rise is 240 ^{0}K for ambient temperatures between -1 0 and +40 ^{0}C.

5.7.1.DC-DC chopper converter traction drives

Chopper converters supply a variable voltage DC load from a fixed voltage source (Fig.5.10). Power flow in both directions between source and load is possible with combined step-up/step-down circuits. The advantages of choppers in traction are:

- energy saving during starting
- smooth, steeples control of tractive effort
- rapid response to change of control conditions
- convenient to program duty cycle with target velocity, acceleration and jerk values
- possibility of regenerative operation
- reduced maintenance requirements compared with electromechanical equipment.

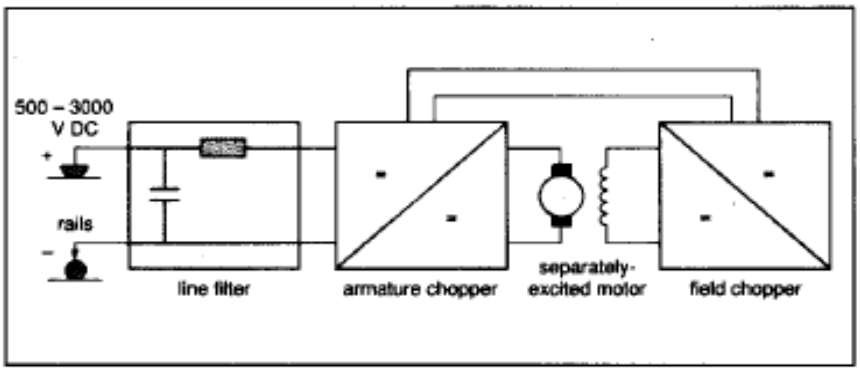


Figure 5.7 DC-DC chopper converter traction drive schematic (Hill, 1994)

The economics of chopper-controlled traction in terms of energy and reliability was thought to be marginal with force commutated thyristor converters in the 1970s, but became very favourable with gate turn-off (GTO) thyristor converters in the 1980s. The major application area of chopper-controlled traction is on DC transit railways where the presence of other accelerating vehicles can produce significant energy savings through regeneration. On new railways in Japan, full exploitation of chopper regenerative capabilities includes the provision of regenerative substations to absorb excess energy not required by nearby accelerating trains. The introduction of chopper-controlled trains on existing railways, however, does require careful prior engineering analyses to be made to determine the system receptivity for regenerative operation.

Choppers are used extensively in metro and light rail systems and have also been developed for high-power locomotives. Fig. 6 shows the power circuit of a chopper-controlled light rail vehicle. Each articulated vehicle is supplied by a pair of 150 kW traction motors with a starting torque of 40.7 kN (1 6.3 kN at 31.9 km/h). The line

5.8.Induction Motor Drives

Fig. 5.11 shows the main types of converter fed traction drives with three-phase motors. In DC-fed railways, IM`s can be fed from either a voltage-source inverter or current source inverter. The VSI is a variable voltage, variable frequency (VVVF) circuit and, as it does not normally need a fixed voltage DC source, it can

deal with large variations in traction line voltage which can be as much as -50% and +20%. The exception to this is on 3 kV DC railways where a preconditioning DC-DC chopper converter is necessary to limit the reverse voltage on the inverter power devices if a two-level VSI is used. CSI`s always require a chopper preconverter to maintain the link current constant.

AC-fed converter drives with three-phase motors were developed some time after the DC-fed versions. A line converter is required to rectify the AC for the DC link feeding the VSI. The first drives, introduced in Japan, used a phase-controlled rectifier providing for dynamic braking only. Later drives use a four-quadrant pulse converter controlled by PWM which maintains near unity power factor and enables regeneration of power. A second-harmonic filter is required for this circuit in the DC link. For completeness, a high-power CSI-fed synchronous machine traction drive which is in service in France on the TGV Atlantique is also shown in Fig. 13. One advantage of this drive is the self commutation of the inverter devices which can therefore use standard thyristors.

All the regenerative drives also incorporate dynamic braking through a chopper controlled resistor for situations when the traction line is not receptive to regenerated energy.

5.8.1.DC-Fed Current-Source-Inverter Traction Drives

A CSI is ideally supplied from a DC source having a constant current capability. For traction, a chopper preconverter is necessary to maintain the source current in the DC link constant, the exact current demand being satisfied through the chopper duty cycle. The chopper does not require fast response thyristors and has good short-circuit protection capabilities since a fault current will have a long rise time, enabling converter shutdown to be initiated before the link current can rise to a dangerous level. Because the circuit operates using natural (line) commutation, the power semiconductors must be able to withstand reverse voltage, requiring the use of conventional rather than GTO thyristors. However, power losses are low and the starting torque is high.

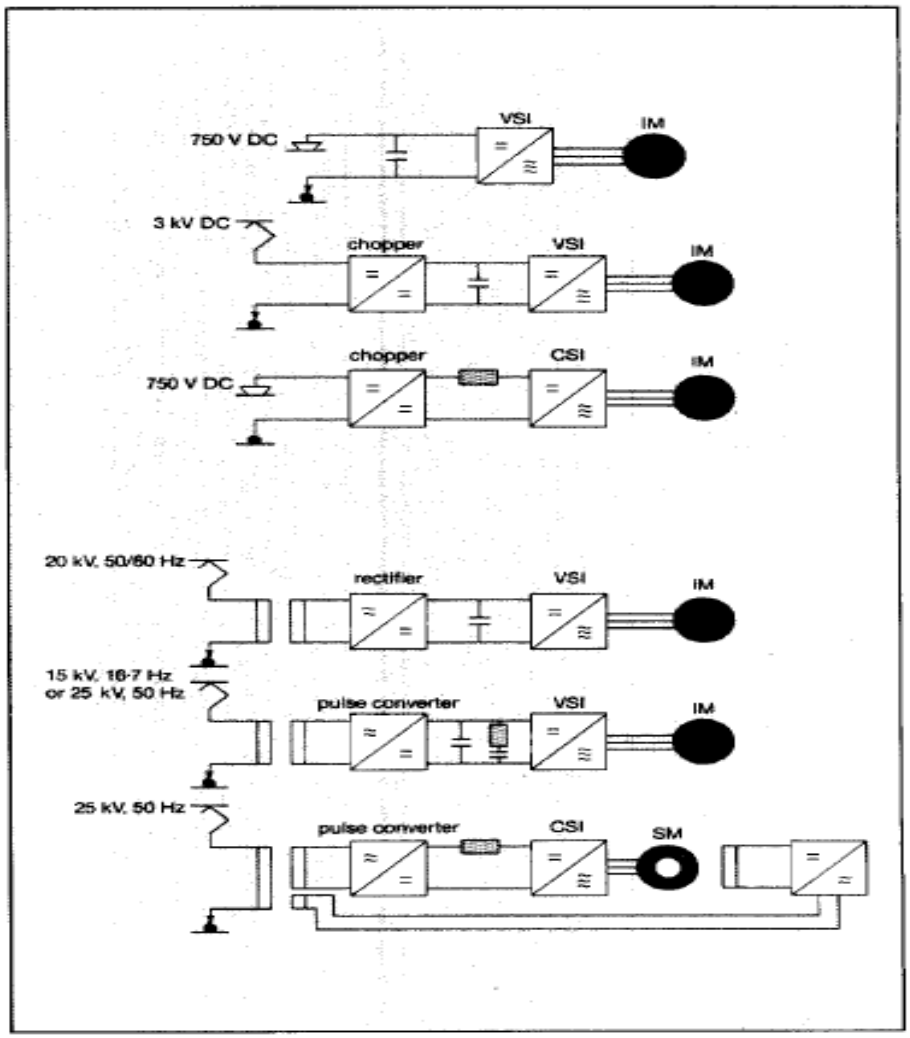


Figure 5.8 Traction drives with-three phase motor(Hill, 1994)

6.POWER QUALITY

6.1.Introduction

What exactly is power quality? This is a question with no fully accepted answer, but surely the response involves the waveforms of current and voltage in an ac system, the presence of harmonic signals in bus voltages and load currents, the presence of spikes and momentary low voltages, and other issues of distortion. Perhaps the best definition of power quality is the provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully, without interference or interruption. A broad definition of power quality borders on system reliability, dielectric selection on equipment and conductors, long-term outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply, and many other areas. A narrower definition focuses on issues. (Masoud, 2004)

Why is power quality a concern, and when did the concern begin? In the last 50 years or so, the industrial age led to the need for products to be economically competitive, which meant that electrical machines were becoming smaller and more efficient and were designed without performance margins. At the same time, other factors were coming into play. Increased demands for electricity created extensive power generation and distribution grids. Industries demanded larger and larger shares of the generated power, which, along with the growing use of electricity in the residential sector, stretched electricity generation to the limit. Today, electrical utilities are no longer independently operated entities; they are part of a large network of utilities tied together in a complex grid. The combination of these factors has created electrical systems requiring power quality. (CRC Press, 2002)

The difficulty in quantifying power quality concerns is explained by the nature of the interaction between power quality and susceptible equipment. What is “good” power for one piece of equipment could be “bad” power for another one. Two identical devices or pieces of equipment might react differently to the same power quality parameters due to differences in their manufacturing or component

tolerance. Electrical devices are becoming smaller and more sensitive to power quality aberrations due to the proliferation of electronics. For example, an electronic controller about the size of a shoebox can efficiently control the performance of a 1000-hp motor; while the motor might be somewhat immune to power quality problems, the controller is not. The net effect is that we have a motor system that is very sensitive to power quality. Another factor that makes power quality issues difficult to grasp is that in some instances electrical equipment causes its own power quality problems. (CRC Press, 2002)

Power quality is an important issue in all manufacturing and process control environment. Voltage surges, sags, and momentary outages that last for less than one 60 Hz cycle to about 10 seconds have caused serious problems for many power consumers. Many of these problems are due to normal transients when equipment or factories go on-line or shut down. Others are caused by lightning strikes and faults on the transmission and/or distribution system. Electronic equipment has especially become much more sensitive than its counterparts 10 or 20 years ago. An important article triggering the interest in power quality appeared in Business Week in 1991. The article cited an estimate that "power-related problems cost U.S. companies $26 billion a year in lost revenue." (Yin, Lu, 2001)

The quality of the electric power supply is currently an important issue in relation to public electricity systems. Poor power quality causes unnecessary disturbance leading to malfunction of plant and even loss of load. Therefore commercial pressures to ensure adequate power quality and there are international standards in place to define the maximum permissible disturbance levels. On systems having an open energy market the regulator, who may be perceived to be the ally of the consumer, often sets power quality.

One function of a power quality standard is to fix a target disturbance limit that is acceptable to the equipment user and manufacturer and also the energy supplier. Different conditions exist on private networks which are used by a restricted set of loads. In these systems it is not appropriate to use standards intended for public supplies since many of the normal loads connected to public systems may not be present. (Morrison , 2001)

Among the important problems taken into account in railway electrification studies, the evaluation of the mutual influence between traction loads and three-phase power supply public networks is of a basic importance. (Capasso, 1998)

The railway electrification load is one of the worst kinds of load for an electrical utility to supply. The only load which gives more challenge to the utility is arc furnace load. The railway electrification load is highly intermittent, irregular, low load factor and poor power factor. The railway electrification load creates system voltage and current unbalance, generates harmonics and results in voltage flicker. Because of the above characteristics, the railway electrification load generally requires oversized substation facilities. It stresses the electrical utility equipment more and also causes interference with other customer loads and often complaints from the other utility customers, etc. The railway electrification load is fed on single or two phases of the electrical utility system. This load has always been a challenge to utility engineers and results in increased electrification cost to the railways. Some recently electrified railroads and the utilities are using extremely tight power quality standards to maintain acceptable power quality to other customers. Some of the common power quality characteristics of the loads are discussed in this paper . (Bhargava, 1996)

With the rapid development of electrical railway, the train speed continuously improving, the electric locomotive traction power also increase exponentially. The electric locomotives in operation, in addition to the absorption of main frequency power from the power grid, also inject the harmonic and negative sequence current into the power grid. Research shows that the harmonic and negative sequence has a negative impact to the power system.

At present, the electrification of the rail traction power supply system, recognized with the following characteristics:

- Electric Railway traction power supply system uses two-phase power supply, and produce the negative sequence component in power system;
- Using electric traction Rectifier electric locomotive (AC - DC), the locomotive pantograph in the locomotive with frequently speed-level

adjustment, switching and sliding flow will generate electric arc due to offline, the system will generating high harmonics mainly based 3, 5, 7 order;

- Electric Railway traction load is a moving load, with shock characteristic, the electric locomotive frequent started and passed quickly in the electricity supply arm area, load current fluctuations greatly, the difference between the peak load and the valley is magnificently;
- Power supply of power supply circuit switching or Electric locomotive through the area without electricity, traction transformer will have a larger inrush current because of the no -load switching.

Therefore, electric railway will have an impact on the power grid system, the main ones are:

- power quality decline;
- have additional loss, vibration increases large and the heat increase, in the internal of the rotation motors and the transformer .and generators in particular;
- increase system power loss, interfere the normal operation of telecommunications equipment;
- caused frequent start or lose the lock of the relay protection containing negative sequence components or composite voltage components, may causing the malfunction of phase-difference High-frequency protection and the protection of generator negative sequence current;
- harmonics may also trigger system inductors, capacitors resonance, and amplified the resonant, threat the security of power grid. (Wang, 2008)

Electrical engineers have been paying a special attention, since the 1950's , to this technically complex problem in studies for railway electrifications with the 25 kV, 50 Hz single-phase a.c. system, because of the need of limiting the disturbances due to primary power supply network, much more constraining than in d.c. electrification system . It can be said that the benefit of cost reduction for the fixed installations, associated to the a.c. electrification option, could be fully achieved, only when the primary network ability to feed the traction load, satisfying power

quality requirements without special equipment in traction substations or the need of traffic limitations, were demonstrated.

It is well known that a.c. traction loads are fed by single-phase transformer substations. The primary winding of the transformer is connected (phase -to-phase) to a high voltage three-phases network, and then gives rise to the flow of negative sequence currents and therefore to the presence of unbalanced system voltages in three phase network.

There has been for many years an almost universal adoption of transformer tap changers and diode rectifiers bridge (before) and thyristor converters (after) for the traction power units in a.c. locomotives, in order to allow the utilization of direct current traction motors. The currents absorbed by trains flowing in the contact lines and in the primary network branches are then non-sinusoidal and distort the system voltages both in single phase traction system and in three phase network. Phase-angle control of thyristors produces in addition poor power factor during acceleration phase.

Modern locomotives, using pulse-width modulation are capable of guaranteeing almost unity power factors through their speed range. The harmonic disturbance is also much more reduced because of the disappearance of low frequency characteristic harmonics. However, even if problems will tend to come down as a consequence of the technological development of the locomotives, we must consider that the lifetime of the locomotives is about 30-40 years, and then the old generation locomotives will be on duty long.

The need of predetermining the conducted disturbance in the early design stage, in order to verify the feasibility of a 25 kV single-phase railway electrification, produced in the last 30 years researches and studies, which contributed to the knowledge development in the power quality field .

Less attention has been given in the past to disturbance problems in the d.c. traction system, which form the other main railway electrification typology. The major source of disturbance is the harmonic distortion caused by the a.c./d.c. converters located in the traction substations. However in the past the problem has not produced special constraints in railway electrifications, mainly because the power demanded by single converter substations was maintained, as a rule, under 5-10 MW.

The grow of the electric power demand necessary to face the increase both in speed and in weight hauled by single trains, as well the traffic increase along the main lines, made the harmonic pollution aspect more significant than in the past. The constraints imposed by power standards together with the increasing attention given to the power quality aspects have recently determined, for d.c. electrification feasibility studies too, a careful analysis of the technical solutions adequacy as far as concerns disturbances in the public network.

Moreover, it is important to underline that the electrification of a d.c. 3kV (or 1.5 kV) line involves, in comparison with an a.c. line, the realization of a higher number of traction substations with a smaller unitary power. Therefore, while the a.c. electrified traction systems are fed, as a general rule, by HV three-phase networks with high short circuit levels, the d.c. systems are often supplied by means of relatively weak HV grids and MV distribution networks as well. It is then evident that the disturbance caused by d.c. electrified traction systems, even if smaller, is much more distributed in the power grid so that not negligible power quality problems can arise in case of modernization and development of existing lines supplied by networks having low short circuit levels. Furthermore for both electrification systems the sudden changes in traction power demand may cause voltage fluctuations and flicker. (Capasso, 1998)

The growing complexity of the AC and DC traction systems in terms of both new technologies and automation requires a careful control of the Power Quality disturbances they cause.

In particular, the AC traction systems can cause in the three-phase supply network:

- Voltage unbalances at fundamental frequency, as a consequence of different active and reactive phase powers absorbed at substation terminals;
- voltage and current distortions, due to the AC traction locomotives which use controlled converters;
- slow voltage variations, due to the time-varying nature of the phase-powers.

The DC traction systems can cause in the three-phase supply network

- voltage and current distortions, due to the AC/DC static converters of the traction substations;

- slow voltage variations, due to the time-varying nature of the phase-powers.

In addition, inside the traction systems there are voltage and current distortions due to the controlled-converters aboard the locomotives and, in case of DC traction systems, due to the AC/DC substation converters. (Battistelli, 2004)

6.2.Power Quality Problems In Electric Railway

6.2.1.Voltage Unbalance

The most restrictive criteria among voltage unbalance, voltage flicker or harmonics is the voltage and current unbalance. Voltage unbalance in an electrical utility system is caused by unbalanced load or the untransposed transmission system.

Since electrified trains are single phase loads inherently, connection of these time varying (as much as they are high speed) unbalance (as much as they are high power) loads to three phase power system will lead to huge power unbalance. (Bhargava,1996)

The traction loads are supplied by two phases of the three phase power system through dedicated substations operating at industrial frequency. The degree of voltage and current unbalances depends of the train motion, load condition and power system supply configuration.

The analysis of the problems regarding unbalance covers two aspects :

- the influence upon the operation characteristics of the plants supplied by unbalanced voltages;
- the influence on the economical and technical indicators of the transmission and distribution network, as well as on the generator systems.

In the first case, the utility must ensure to the customer the agreement of the voltage unbalance indices within the standardized limits. The customer is interested to monitor the supplying voltage for obtaining the information regarding unbalance and the agreement with the stipulated limits.

In the second case, the customer must ensure the correspondence of the produced disturbances within the allocated limits, established by the utility, as condition for power quality assessment to others customers in the electrical network. The utility is interested to survey the electrical currents of the customer and to verify the correspondence of the unbalance within the allocated limits.

The unbalances affect the operation of the supply system and of various equipments connected to it. The induction motors, fed by an unbalanced system of voltages, present lower efficiency, overheats and increase the real power losses, so a significant loss of the life duration. The voltage unbalance produces also high frequency pulsation torques and consequently vibrations and noises during operation. Moreover, the influence of the voltage unbalance upon the operation conditions of the generators present in the power system is very important for limiting the overheating of the rotor windings. Voltage unbalance may also cause the undesired tripping of relays, influences converters and PWM drives operation due to the amplitude or phase angle unbalance. The capacitor banks, connected to a power system with unbalanced voltages contribute itself to the aggravation of the unbalance. In fact, on the phase with the smallest phase voltage amplitude, the smallest reactive power is associated and so the smallest improvement of the power factor. (Golovanov, 2005)

Allowing for 1 percent ambient unbalance from other sources, the voltage unbalance from the railway electrification load will have to be limited to 1 percent. Some utilities may allow higher ambient voltage unbalance. Also some utilities have reported consumer complaints when 2 percent imbalance was use. While designing substations and the electrification system for railway electrification, it is always desirable to measure the ambient voltage unbalance over a period of a couple of days. Also the unbalance should be compared with the short circuit duty available to actually calculate the load in the MW causing this ambient voltage unbalance.

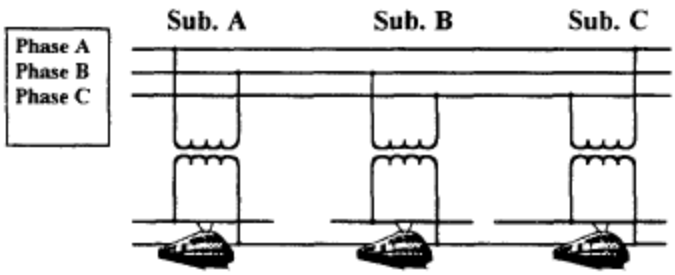


Figure 6.1. Power Distribution System For Adjacent Substation E.R(Bhargava,1996)

The typical load fed from a railway electrification substation was estimated to be about 60 - 100 MVA. This would allow about four trains within the substation beat. Assuming that a 100 MVA load has to be fed from two phases of a substation in Fig. 6.1. and also assuming that the ambient unbalance is 1 percent, then the short circuit duty must be more than 10,000 MVA to limit the voltage drop to less than 1 percent imbalance . (Bhargava,1996)

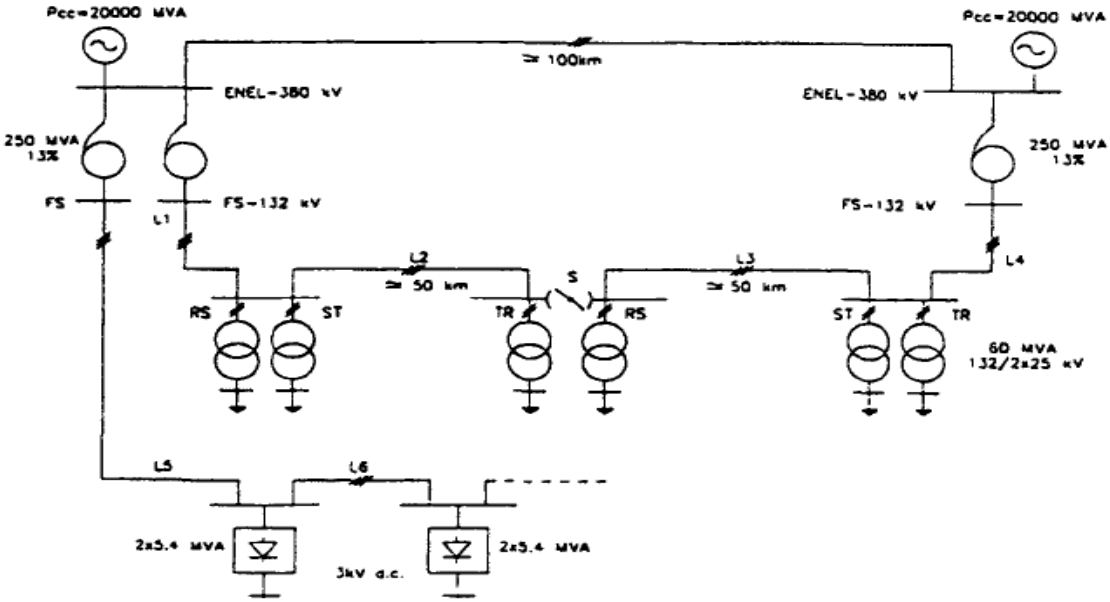


Figure 6.2. Standard configuration of the HV power supply system of the new Italian High-speed Railway Network

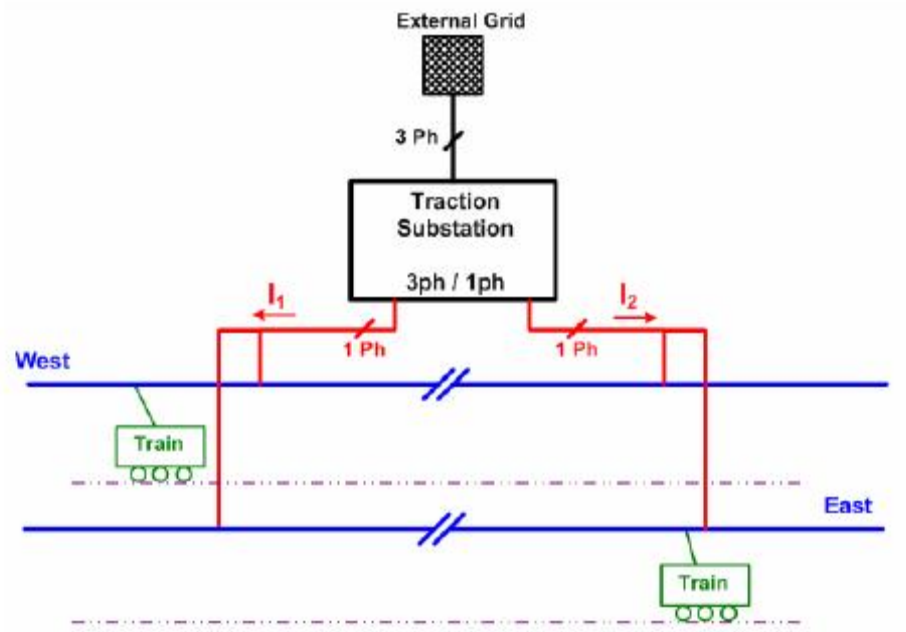


Figure 6.3 AC traction substation feeding two sides of catenary in west and east directions (Farhad, 2005)

The simplified well known formula for evaluating the voltage unbalance factor, K=P/Pcc (where P and PCC are respectively the power in MVA of the single-phase traction load and the three-phase short circuit capacity at the H.V. terminals) is not in general applicable in cases in which more A.C. traction substations are mutually influenced because of the structure of the power supply network. Three-phase load flows are then usually performed. The traction load values for the unbalance calculations are determined selecting the worst likely loading conditions. These are the instants in which the differences in the power absorbed by the three pair of phases are at a maximum. The above calculations can be easily carried out starting from the transformers load diagrams obtained from simulations, once known the connection of the primary winding of the various single-phase transformers to the phase pairs. (Capasso, 1998)

6.2.1.1.Unbalance Limits

In many important a.c. railway electrification studies a limit of 1-1,5 % for the long duration voltage unbalance and up to 2% for time interval shorter than 10

min has been assumed as acceptable . The above mentioned European Standard requires similar compatibility levels. (Capasso ,1998)

6.2.1.2.Unbalance Factor

The maximum voltage unbalance factor should be calculated at the connection points of the main traction substations to the utility network, which is dependant to the loading characteristics of the traction system. This calculation should be done for controlling and limiting the unbalance magnitude and duration. Most utilities around the world use the voltage unbalance factor as a simple measure to limit the unbalance injections at the connection points of the traction substations. Table 6.1 shows the formulate for calculating the voltage unbalance factor injected from the traction substations to the utility grid for some transformer configurations. Possible changes of network configuration, whether it is the changes within the traction supply system due to load transferring or the daily, weekly or seasonal changes in the utility grid, should be carefully considered in the voltage unbalance calculation. (Farhad, 2005)

Table 6.1. Voltage unbalance factor injected from the traction system to the grid at the connection point

Transformer Configuration	Voltage Unbalance Factor
Single Phase	$\varepsilon_V = S_L / S_S$
V-V There Phase	$\varepsilon_V = (S_{L2} + \alpha^2 S_{L1}) / S_S$
Scott , Leblanc	$\varepsilon_V = (S_{L2} - S_{L1}) / S_S$

6.2.1.3.Unbalance Restricting Solutions

In order to minimize the voltage distortion, traction loads are usually connected to an external grid of 100 kV or higher, however, this also makes them electrically very close to utility generators thereby raising concerns for excessive negative sequence injection into utility generators.

The most applicable and effective solution is the repetitive choosing the feeding phases of the traction substations so that the whole network would be

balanced if all the traction substations have the same load at the same time. This procedure is applied for the different transformer arrangements in the traction substations which have been described below. (Farhad, 2005)

6.2.1.3.(1) Single Phase Transformers

In this arrangement of the traction substations, a single phase transformer is used to feed the traction system which is fed through two phases. One of the two output phases is connected to the catenary feeding the trains along the track and the other is connected to the running rails as the negative return current path. The structure of such an electrification system is shown in Fig. 6.4.

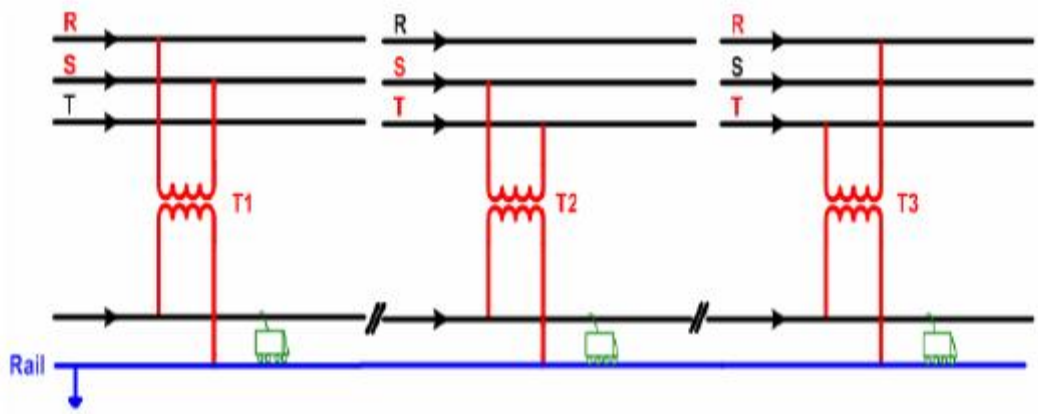


Figure 6.4 Traction electrification system with single phase transformer arrangement (Farhad, 2005)

Studying the different loading schedules for the traction system for this arrangements prove that if the three in after traction substations have almost the same loading, the voltage unbalance can reduce greatly and it might be even zero, but in the worst case, the maximum voltage unbalance of the AC network reaches 12.8%.(Farhad, 2005)

6.2.1.3.(2) Two Single Phase Transformers

The principle of this arrangement is dividing the single phase load between all the three phases resulting in decreasing the voltage unbalance of the AC network. Therefore, two single phase transformers are used as seen in Fig. 6.5 which each

feeds half of the whole power demand. Studying and calculating the voltage unbalance factors for this transformer arrangement proves a maximum of 6.5% unbalance which is almost half of utilizing a single transformer like the previous and zero, in the case of equal loading of all the transformers. (Farhad, 2005)

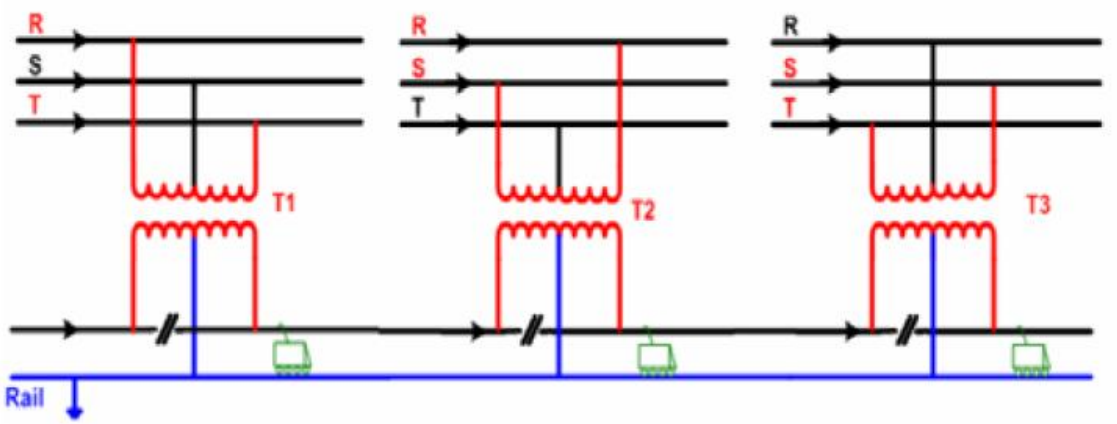


Figure 6.5 Traction electrification system with with single-phase transformer arrangement (Farhad, 2005)

6.2.1.3.(3) Star-Delta transformer

In such a structure, a three-phase transformer is utilized in the traction substations with the primary winding as Star and the secondary as Delta. The feeding phases of the primary winding are changed respectively so that the whole power network seems balanced. The schematic structure of such an arrangement is shown in Fig. 6.6. The maximum voltage unbalance factor of this configuration is about 8.6% but can be reduced to zero in the case of equal loading of all of the transformers. (Farhad, 2005)

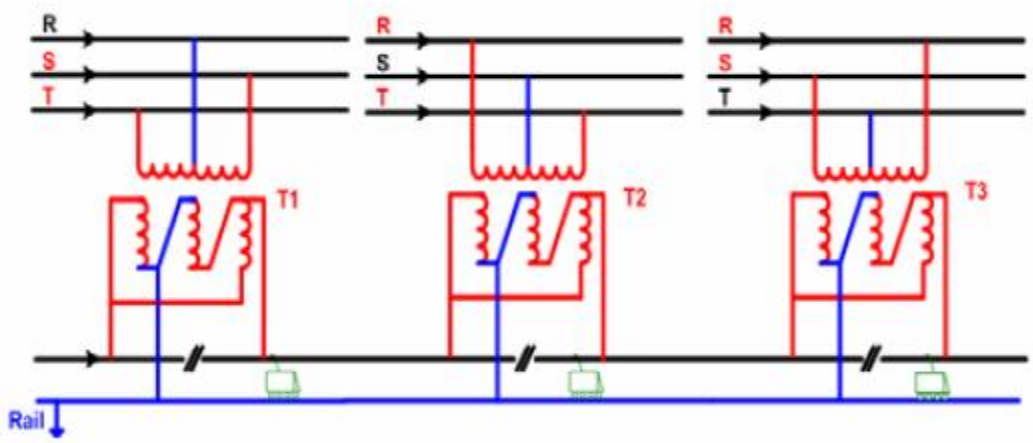


Figure 6.6. Traction electrification system with three-phase Star-Delta transformer arrangement (Farhad, 2005)

6.2.1.3.(4) Star-Star Transformer

In this configuration, a three-phase transformer is utilized in the traction substation with a Star-Star winding but the winding of the secondary side is irregular, i.e. the winding on one of the phases on the secondary has twice as many turns as the windings of other phases on that side. This causes a reduction in the voltage unbalance as the highest voltage unbalance factor is equal to 11%. The structure of this configuration is shown in Fig. 6.7. (Farhad, 2005)

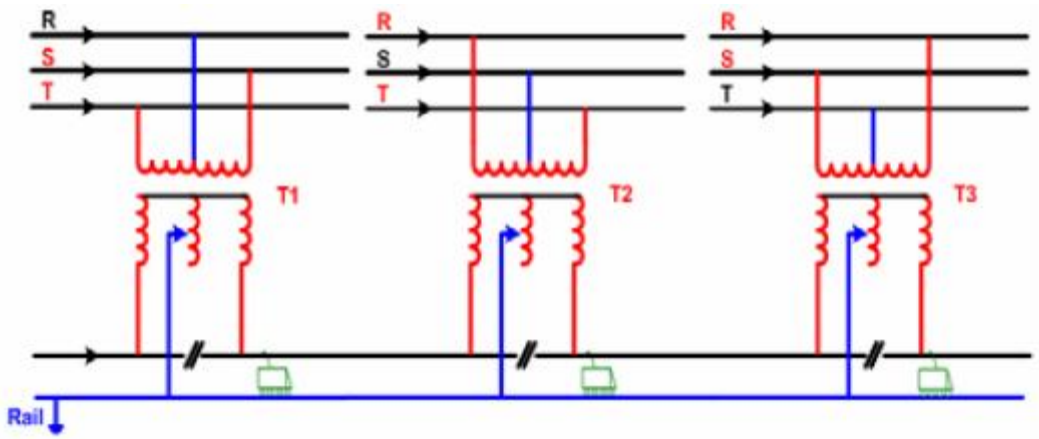


Figure 6.7. Traction electrification system with three-phase Star-Star transformer arrangement (Farhad, 2005)

6.2.1.3.(5) Scott Transformer

Utilizing Scott transformers is one of the most popular ways of reducing the unbalance problems in traction substations which can transfer the load side balanced

two-phase system to the balanced three-phase AC network. The schematic structure of such an arrangement is shown in Fig. 6.8. The maximum voltage unbalance factor of this configuration is about 10.24% but can be reduced to zero in the case of equal loading of all of the transformers. (Farhad, 2005)

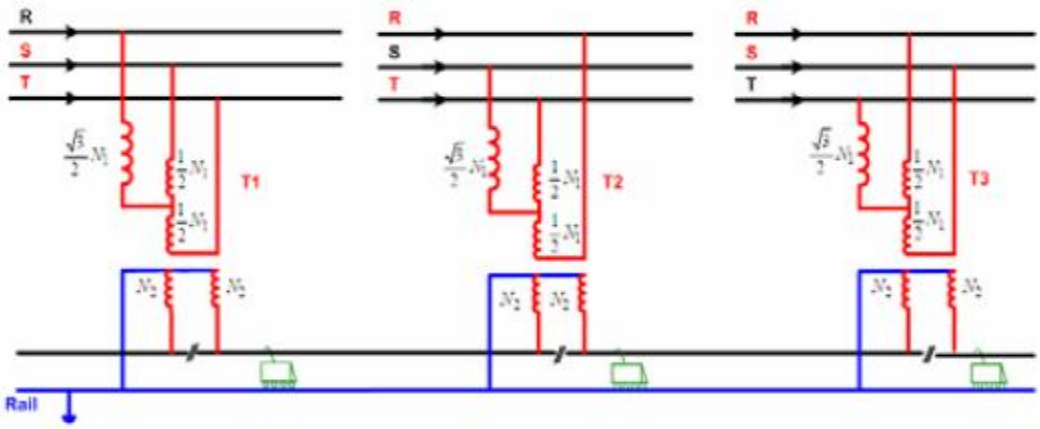


Figure 6.8. Traction electrification system with Scott transformer arrangement (Farhad, 2005)

6.2.1.3.(6) Leblanc Transformer

Another transformer configuration for reducing the unbalance problems is utilizing Leblanc transformers in traction substations which can transfer the load side balanced two-phase system to the balanced three-phase AC network. But due to the designing characteristics of Leblanc transformers in comparison with the Scott, Leblanc transformer configuration can be said to be the most utilized system in the world. The schematic structure of such an arrangement is shown in Fig. 6.9. The maximum voltage unbalance factor of this configuration is about 6.69% but can be reduced to zero in the case of equal loading of all of the transformers. (Farhad, 2005)

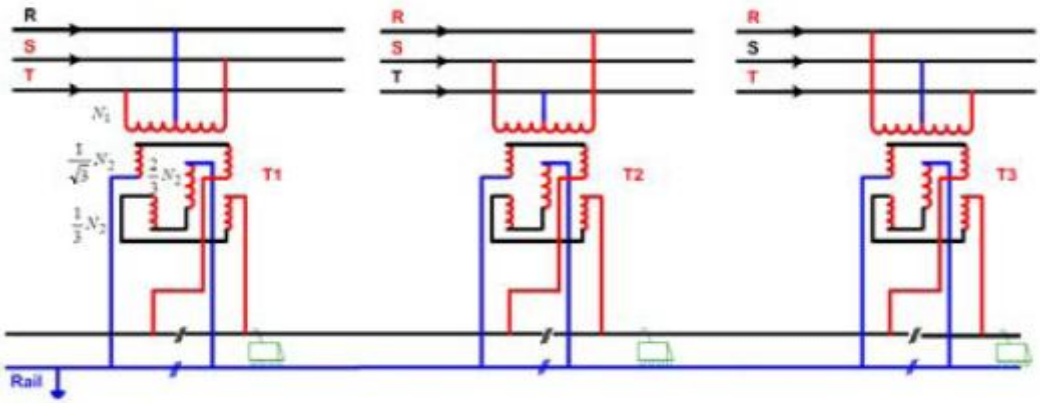


Figure 6.9. Traction electrification system with Leblanc transformer arrangement (Farhad, 2005)

6.2.1.4.Choosing Solution of Unbalancing Problem

As a result of this research traditional phase-rotation technique with symmetrical transformer is proved to be the only practicable solution at present for balancing the load among three phases, which splits the overhead feeder into many segments, each of 20-25km long, and a phase insulator about 30m long is used between two segments that belong to difference phase. The balancing effect can get at the equivalent common coupling point of this two system , when every phase has the same load.

But unfortunately it is not enough balance it enough level for public utility system. Because of traction load's distribution and randomness, it is almost impossible to get satisfied balancing effect.

Furthermore, when a train passes the insulator, a serial of operation must be taken and the power supply is interrupted. The existing of phase insulator becomes the main drawback of this method, which limits the trains to exert its rating power and speed, especial in the case of heavy or high-speed transportation.

To achieve better balancing effect, asymmetrical transformers such as the Scott, Leblanc, impedance matching balance transformer, etc, are widely used in railway. When the loads on the two arms that supplied by these transformer are the same (amplitude and phase), the transformer's input current will be balancing.

One leg of this case study balancing of unbalanced power that is why Scott Transformer will be used in proposed method which is one of the asymmetrical transformers .

6.2.2.Voltage Fluctuation

From instantaneous power demand values voltage dips (in %) can be easily calculated and plotted as a function of the number of occurrences. EEE Std. 141 indicates for the quantities the border line of flicker irritation. It may be noted that for the new locomotives with choppers or inverters the starting current changes smoothly. In d.c. electrified systems a step change of the current may then occur only for a switching-off of the load current. In normal conditions this event happens when the current is lesser than the maximum current of the locomotive so that the rapid voltage change is not critical. In a.c. electrified systems this disturbance may be more significant due to the passage of trains under line sections fed from different single-phase transformers, which must be insulated because of the phase shifting between the single-phase supply voltages.

The step change of the current may occur when the traction power demanded by a train is at the maximum (the worst case is a train with two locomotives). It can be observed that the disturbance is basically dependent on the short circuit level as for the voltage unbalance.

The design criteria adopted for the power supply system to comply with the limits required for the unbalance are usually able to maintain voltage fluctuations below the permitted levels as a natural consequence. (A. Capasso ,1998)

When considering the phenomena that affect power quality the effect of particular waveform features on system loads is important. The features may not be the same as those that disturb public electricity supply systems. Traction systems are subject to significant load changes giving rise to frequent voltage fluctuation of up to and beyond *5* per cent. While a frequent 5 per cent voltage fluctuation would be unacceptable to public electricity supplies, traction vehicles are immunised to deal with voltage change and they do not experience significant disturbance.

On the other hand the voltage level is well controlled in public electricity supplies. However, to maximise utilisation, voltages within typical 25kV traction systems may be allowed to vary from 29kV to 17.5kV. Without a wide voltage operating range many traction systems would not be economically viable. However the consequence of allowing the voltage to remain at a low level is lower vehicle performance and excessive system power loss. Therefore low system voltage is a more important power quality issue to traction supplies than voltage fluctuation. [Morrison 2001]

Table 6.2. System Voltage Variation Limits (White, 2006)

Definition of Operating System Voltages	25kV	15kV
$Umin_2$ lowest non permenant voltage duration 10min	17.5kV	11.kV
$Umin_1$ lowest non permenant voltage duration indefinitely	19 kV	12. kV
Un nominal voltage designed system value	25 kV	15.kV
Umax1 highest permanent voltage duration indefinetly voltage designed system value	27.5kV	17.25.kV
Umax2 highest non permanent voltage duration indefinetly voltage designed system value	29kV	18.kV

6.2.3.Load Factor:

The railway electrification load factor is dependent on the train frequency and usage. The typical load factor for a substation is about 15-25 percent depending on the, train frequency. Compared to the other utility loads, this is a poor load factor and the energy sales are much lower compared to the peak load demand. This type of load thus results in excessively high investment costs for the utility. (Bhargava,1996)

6.2.4.Voltage Flicker

The traction power demand on utility system rapidly changes as trains accelerate and decelerate, as they encounter track gradients, and as they enter and leave catenary feeding sections. The quick variation of the traction current results in sudden variation of voltage at the substation connection point and, to a lesser degree, on other utility busbars.

When selecting a utility feed point for supply of traction power substations, the available fault level at the tapping point needs to be determined. As the traction power substations are generally connected to a high voltage utility system, the available fault level will generally be sufficiently high to avoid undesirable effects due to the voltage flicker.

The abrupt regulation of the utility voltage may cause objectionable light flicker, disrupt industrial and commercial processes, and adversely affect operation of electronic apparatus, such as computers, instrumentation, and communications equipment. Also, the currents flowing in traction power supply equipment cause pulsating forces which can be of significant magnitude, and therefore, can be potentially harmful to substation equipment.

The light flicker is the most common and noticeable effect of fluctuating loads. Lighting equipment is particularly sensitive to supply voltage variation and people are sensitive, in varying degree, to sudden illumination changes. For example, a voltage change of just 0.25 to 0.5% will cause a noticeable change in the light output of incandescent lamps.

The severity of the problem depends on the utility system fault level (or equivalent system impedance) at the substation connection point, the magnitude of the load fluctuation from instant to instant, and frequency of the fluctuations (number of voltage dips in a time interval). (Kneschke, 2003)

6.2.5.Harmonic Distortion

Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz). An illustration of fifth harmonic distortion is shown in Fig.

6.12. When the frequencies of these voltages and currents are not an integer of the fundamental they are termed inter-harmonics.

Both harmonic and inter-harmonic distortion is generally caused by equipment with non-linear voltage/current characteristics.

In general, distorting equipment produces harmonic currents that, in turn, cause harmonic voltage drops across the impedances of the network. Harmonic currents of the same frequency from different sources add vectorially.

The main detrimental effects of harmonics are :

- maloperation of control devices, main signalling systems, and protective relays
- extra losses in capacitors, transformers, and rotating machines
- additional noise from motors and other apparatus
- telephone interference
- The presence of power factor correction capacitors and cable capacitance can cause shunt and series resonances in the network producing voltage amplification even at a remote point from the distorting load.(Dorf, 2000)

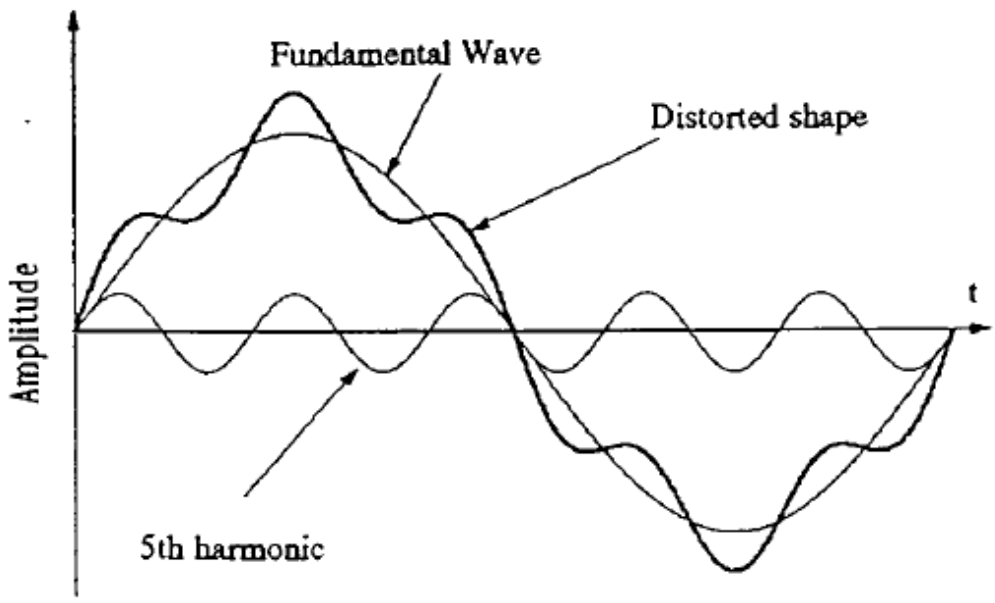


Figure 6.10. Example of a distorted sine wave

Most nonlinear loads as well as loads controlled by the power electronics system are harmonic source. Fluorescent lighting and AC/DC converters in power electronic system are typical example in point. All electricity companies are concerned about harmonic pollution, especially from large nonlinear loads such as railway system connected to their power system network.

Nowadays, there have been considerable developments in industrial processes which rely on controlled rectification for their operation. Railway systems are one of the important users of the technology and consequently they are a large source of harmonic. (Lai Tsz Ming Terence 1999)

As we mentioned before there are two system of electrical supply to railway: AC and DC system. Each system has its own harmonic characteristics, which depended on the network components used in the system. In DC systems, chopper and inverter equipment produces harmonic currents and switching transients. In AC systems, the use of converter equipments modifies the nature of the traction current spectrum , generally increasing magnitude of odd harmonics at some values of train speed when compared what is obtained with tap changer equipment. (Lai Tsz Ming Terence 1999)

Electric trains having thyristors or pulsewidth modulation (PWM)-controlled converters inject harmonic currents into the feeding overhead lines. Harmonic currents in the electric train are one of the biggest concerns, and the load current model to represent electric trains is proposed. The current harmonics injected from an ac electric train propagate through power-feeding circuits. Being a distributed RLC circuit, the feeding circuit can experience parallel resonance at a specific frequency. The harmonic current is amplified by the resonance, and the amplified harmonic current usually induces various problems, including interference in adjacent communication lines and the railway signalling system, overheating, and vibration at the power capacitors, and erroneous operation at the protective devices. Therefore, the harmonic current flow must be assessed exactly in the designing and planning stage of the electric traction system. Since the harmonic current flows through the catenary system, it needs to be accurately modelled to analyze and assess the harmonic effect on the power-feeding system. (Lee, 2006)

Although the harmonic problem tend to reduce as a consequence of technological development of the inverter fed locomotives , it is important to note that the life time of the locomotives is about 30-40 years ,and then the old generation locomotives will be still in use in the future for some time. Therefore the study of suppressing the harmonic currents in existing type of locomotive types is still very important. (Li, 2002)

Harmonic voltage distortion in traction systems may rise to levels which are 2 or 3 times higher than those normally accepted in public utility systems. There are few recorded problems associated with harmonic voltage distortion in traction systems, one exception being the presence of harmonic overvoltage. Harmonic overvoltage is a response by parallel resonant paths in the traction supply network to sudden step changes in the locomotive current waveform. Systems in which the phenomenon occurs have voltage waveforms containing a sine wave and a superimposed decaying oscillatory component (Fig 6.13).

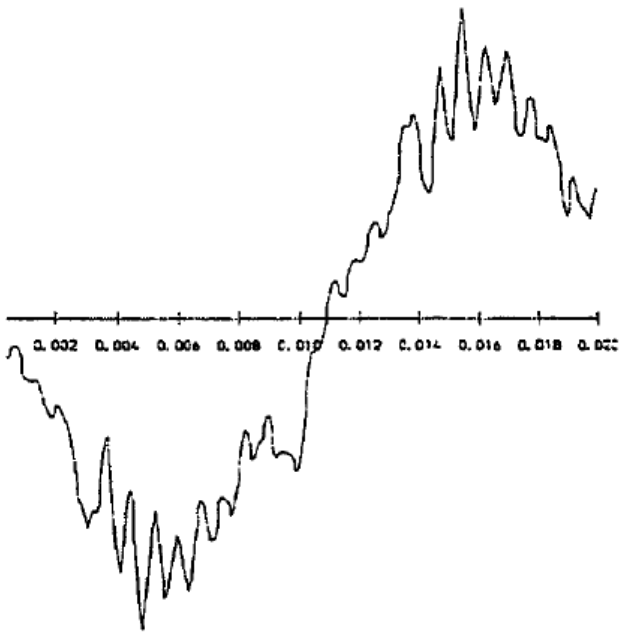


Figure 6.13. Voltage waveform for 25 kV traction feeder(Capasso, 1998)

Although the overvoltage is more likely to be generated by phase angle controlled locomotives, once the phenomenon is present the excessive crest voltage is transferred to all other locomotives operating on the same traction feeder. A

second waveform feature caused by harmonic distortion is loss of average voltage. Some types of locomotive have rating dependent on average voltage; a raised form factor leads to poor performance irrespective of the levels of RMS voltage. This problem is noticeable on systems having total harmonic voltage distortion in excess of about 10 per cent. Thyristor and diode bridge vehicles are most likely to give rise to loss of average voltage but the effect may pass on to all other loads on the same feeder. The more modern loads having PWM input converters are less likely to cause poor power quality but they may be affected by the problems caused by other types of load. (Morrison, 2001)

Harmonic produced by traction substations is injected into utility and sum at Point Common Coupling (PCC). Almost each standard deals with summation of multi-harmonic sources. Two kinds of summation law are defined by IEC 61000-3-6 to calculate summation of any kind of harmonic injected into utility. But the character of harmonic produced by electric locomotive is greatly different from other type harmonic because electric locomotive e is unsymmetrical load (single phase) and traction load varies quickly and greatly.

- First Summation Law : The first summation law is a simple linear law making use of diversity factors:

  $U_h = U_{ho} + \sum_j k_{hj} U_{hj}$ (6.1)

  where U_{ho} is the background harmonic voltage of the utility; U_{hj} is the harmonic voltage of individual load. The magnitude of the diversity factors k_{hj} depends on conditions that the kind of the appliance considered, the harmonic order h and the ratio between the rated power of the appliance considered and the short circuit power at PCC. The first summation law is simple to use but the second one is more general.

- The Second Summation Law: The second summation law is more general for both harmonic voltage and current. The law for resulting harmonic voltage of order *h* is:

  $U_h = \left(\sum_i (U_{hi})^{\alpha} \right)^{1/\alpha}$ (6.2)

  where: uh is the magnitude of the resulting harmonic voltage (order h); U_{hi} is the magnitude of the various individual emission level (order h*)* to be combined; α is

an exponent depending mainly upon two factors: the probability for the actual value not to exceed the calculated value and the degree to which individual harmonic voltages vary randomly in terms of magnitude and phase. (Xie, 2003)

7.PSCAD MODEL FOR APF SYSTEM

Among all traction network electrification systems, the system which is most commonly used all around the world is the 25 kV industrial frequency system. This high voltage system makes it possible to supply power via simple permanent way installations to trains with high power consumption by limiting the amount of current send from the OHL to the pantograph.

It usually gets the power from the three-phase grid, and supplies to the inductive, single phase locomotives. Transformer is the only device that acts as the adapter between the three-phase source and the single-phase load in this system at present. Considering the load's random distributing in time and location, no matter what kind of transformer is adopted, the traction system causes load unbalance problem to the three-phase power distribution system.

To solve the unbalance problem, phase rotation technique is used to get a total balance effect at the equivalent point of common coupling of utility system and traction system. This measure can work, but the effect is far from satisfaction, and because the overhead line is split to many sections that belong to difference phase, a new problem arises when the train passes the region between two sections. This derived problem has not been fully solved, which affects the performance of safety, speed and traction ability.

Another problem of the present system is the reactive and harmonic current generated by the locomotives. Although it can be solved by adopting high performance vehicle, this problem cannot he neglected considering the large amount of rectifier locomotives that are running. (Guohong, 2003)

A significant proportion of the locomotives still employing ac-dc phase controlled thyristor converters to feed dc motor drives. These railway systems are found in Australia, Italy, India, and Zimbabwe for example, and are expected to power older thyristor-based locomotives, operating in coexistence with the newer generation of gate turn-off thyristors (GTO) or insulated-gate bipolar transistor (IGBT) locomotives for many years to come since the average locomotive life is about 30 years .

To overcome the disadvantages mentioned above, many solutions have been proposed, some of them has been put into practice. Scott transformer and impedance matching balance transformer are used to decrease the load unbalance. In recent years, more attentions have been paid to using active power filters (APF) to improve the railway's performance and power quality, and the results are proved to be prominent and potential.

All power quality problems had already been explained in previous chapter . The major problems to be fixed by the proposed topology is listed below.

1- Load unbalancing in utility transmission line .
2- Voltage unbalancing in traction distribution line .
3- Harmonic current in traction distribution line .
4- Reactive current in traction distribution line .
5- Voltage flicker due to moving load from one section to another .

The proposed model consists of following parts to solve all problem mentioned in above .

1) Power Supply
   a) Transmission line
   b) Scott Transformer
   c) Catenary line
2) Loads
3) Active power filter
   a) Power circuit
      i) Voltage source inverter
      ii) Interface inductor
      iii) DC Link
   b) Control circuit
      i) Reference current generation (EPLL)
      ii) Current control

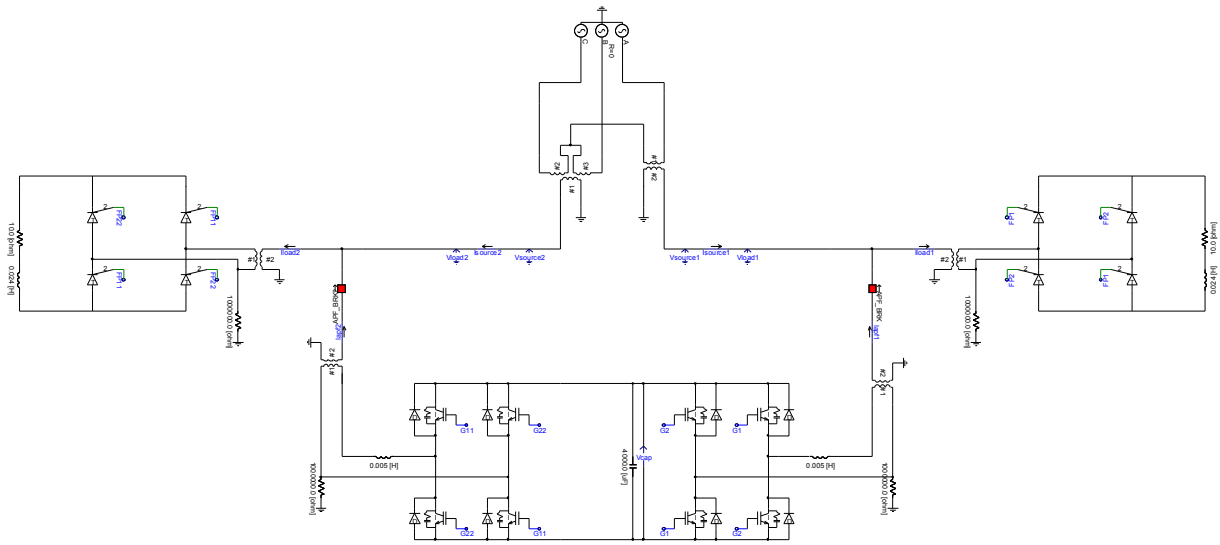


Figure 7.1. Overview of the modeled system

7.1.Power Supply

7.1.1.Transmission Line

The electrified railway systems have several different options and products in the market. Due to size and power demand of projects the feeding arrangements are also changing. For example the power demand of tram system that is located in city center is much lower than high speed train which is travelling between the cities. By the way the transmission line voltage levels have several application levels and basically the voltage level can be different from one country to another like 110kV, 132 kV, 154 kV, 220 kV, 275 kV, 380 kV, 400kV.

Railway electrification schemes draw a single-phase supply from the national electricity HV supply system. It is inevitable therefore that train loads of between 2 12 MW, will create unbalanced current within the HV 3 phase supply system, harmonic distortion and voltage fluctuation to the supply system. (White, 2006)

Higher design basis loads require that the short circuit duty of the system be enough so that the voltage flicker, unbalance and harmonics standards are satisfied. These are dependent on the system strength at the substation. The only solution is to push for a higher voltage system. A 230 kV or higher voltage substation would be

required to serve single phase loads with more than 60 MVA power. Most of the substations built in France to supply power to TGV high speed trains which feed power to substations with 40-60 MVA capacity are built with primary voltages of 275 kV or 400 kV. (Bhargava, 1996) The feeding voltage level is 154kV for high speed train in Turkey.

Single phase transformers are connected to different phase pairs of the grid supply at successive feeder stations along the railway route, so as to provide the grid system with a load that is distributed between the three phases.

The level of the traction load and the availability of the grid will decide the point of connection. At the railway feeder stations two incoming circuits are normally made available, both of the feeds being capable of individually carrying the total traction load under normal traffic conditions, this will provide a power supply with a high degree of security. It is not sensible to provide an incoming feeder arrangement, which had a level of security that was less than the 25kV overhead traction system it is feeding. To increase the security of the supply the railway 25kV busbar are fed from independent parts of the H.V. network or by two H.V. busbars being fed independently by the H.V. system. If there is a failure on one of the supplies the fault does not interrupt the supply to the second railway feed [see Figure 7.1]. The two railway feeders could be independent or may be banked with 33 kV or 11 kV transformers feeding local industry or distribution networks.

If there is a total loss of supply at a feeder station, supply to the overhead railway network is transferred so that the adjacent feeder station supplies power up to the non-functioning feeder station. This new feeding arrangement will give rise to loss of train performance due to the increased voltage drop between the operational feeder stations and individual locomotives. Any loss in time to the traction unit, due to the outage of a feeder station should be recoverable in the next normally fed feeding section.(White, 2006)

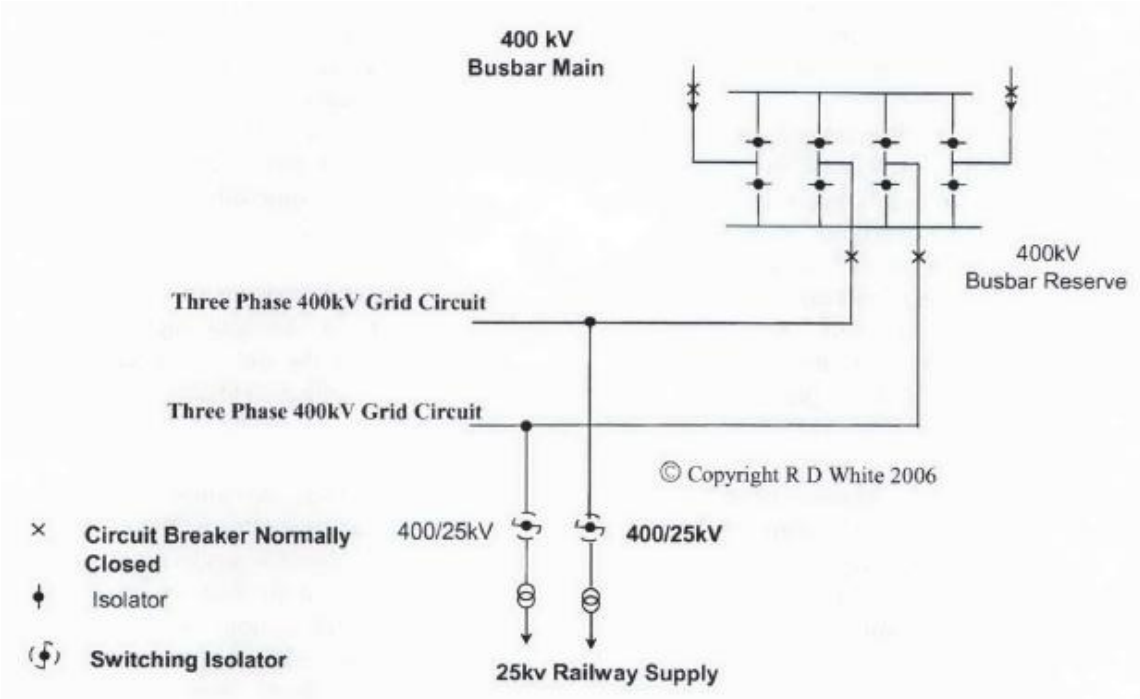


Figure 7.2. Typical Supply Feeding Arrangement for a 25kV Electrified Railway (White, 2006)

7.1.2.Scott Transformer

The scott transformer is introduced in the previous chapter and scott transformer is an important part of proposed model.

The increasing attention of power-quality (PQ) issues in railway electrification systems today is leading to studies on the influence of traction loads on three-phase utility systems. Recent studies concerning the specially connected transformers have been emphasized on several topics, such as modelling for particular studies, evaluating voltage unbalance, discussing the effect of harmonics, and revising the differential protection methods. (Huang, 2006)

What exactly is the Scott Transformer? It is a means by which a three phase input voltage is transformed into a two phase output voltage. The two output voltages are 90^0 out of phase. The input current on each of the three phase input lines is balanced. Also, if the output is rectified, the ripple voltage is close to the ripple from a conventional three phase transformer.

The Scott-T connection shown in Figure 7.2 is probably the most widely used technique in transformer design for converting a three-phase input voltage to a two-phase output voltage. It was invented by C. F. Scott and is known as the Scott-T connection, Scott for the inventor and T because the schematic looks like the letter "T". It consists of two transformers, each with a different number of primary turns and each wound differently.

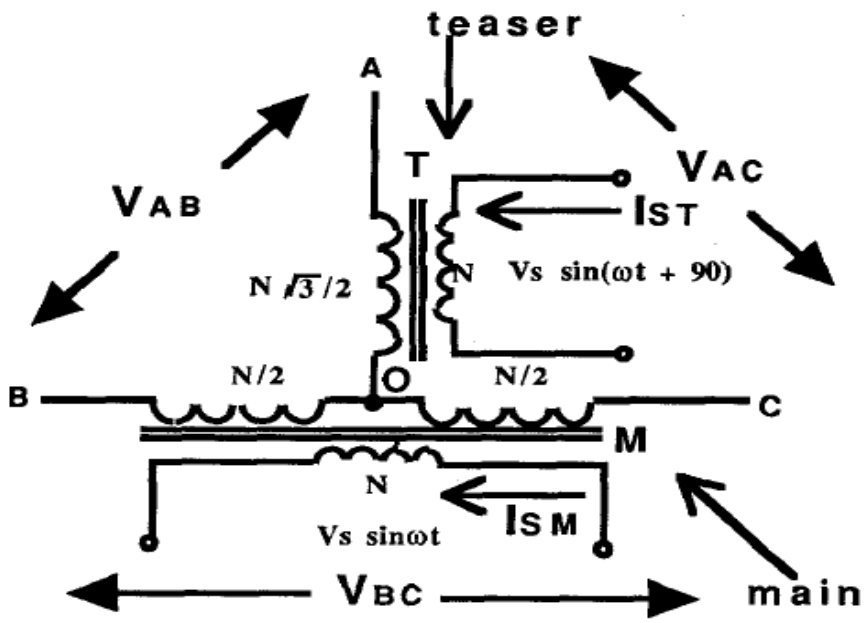


Figure 7.3. Scott T Transformer Connection (Kakalec, 1994)

Transformer M is known as the "main" transformer. It has a single winding on its two-phase side and a center-tapped winding B-0-C on its three-phase side. The teaser, transformer T, has a single winding on each side. The two transformers have different ratios of transformation and different windings, (this will be proven as part of this article) yet have balanced input currents on each phase when equal voltages are applied by the three phase line A-B-C. Proof of the voltage relationship in Figure 7.2 and of balanced currents will now be derived. (Kakalec, 1994)

Scott transformer is a widely used transformer that converts the three-phase supply into two single-phase power supplies. It has been used in many electric railway systems to reduce the unbalance problem, for instance in Tokaido-Shinkansen electric railway . If two loads are equal, Scott transformer presents them

as one balanced three phase load to the three-phase supply system. This solves the imbalance problem. Nevertheless, these two single-phase loads are rarely equal in reality. The transformer still draws unbalanced power from the system. However, the degree of unbalance is reduced in comparison with the case in which loads are directly connected the system. References investigated the degree of load unbalance seen from the three phase system when two single-phase loads have different sizes. The special connection in Scott transformer causes two unbalanced single-phase loads to be presented less unbalanced to the power system. . (Hooman Erfanian Mazin, and Wilsun Xu, 2008) .

7.1.2.1.Voltage Relationships

The direction of power flow is from the three-phase to the two-phase system. However, it may be simpler to explain the operation of the transformers based on the assumption that the two voltages, V_S sinwt and V_S sin(wt + 90), shown in Figure 7.2., are applied to the secondary windings and that the leakage inductance of each transformer is low. The voltages across the three windings on the three primary side are as indicated by the voltages V_{AO}, V_{BO}, and Voc in Figure 7.2. According to the Figure, V_{AO} is in phase with V_S sin(ωt + 90) and V_{BO}, Voc are in phase with Vs sinωt. In Figure 7.2, note that the line-to-line voltages on the three-phase side are:

$$V_{AB} = V_{AO} + V_{OB} \tag{7.1}$$

$$V_{BC} = V_{BO} + V_{OC} \tag{7.2}$$

$$V_{AC} = V_{AO} + V_{OC} \tag{7.3}$$

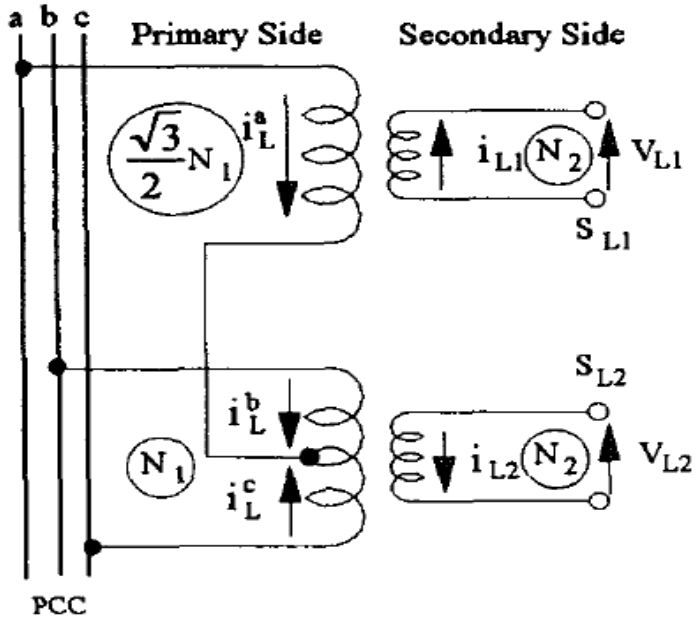


Figure 7.4. Scott T Transformer Connection (Chen ,1994)

These are vector voltages and if they are to form a balanced three-phase system, the phase must be displaced by 120^0 and the magnitude of each voltage must be the same. Referring to Figure 7.3, the voltages form a right triangle and the following relationships hold:

$$V_{AB} = V_{BC} = V_{AC} \tag{7.4}$$

$$V_{BO} = V_{OC} = 1/2V_{BC} \tag{7.5}$$

V_{AO} is perpendicular to V_{BO} and V_{CO}

Then with these relationships, if winding V_{BC} is assumed to be V volts, then V_{BO} is V/2 volts. If V_{AB} is V volts, then

$$V = \sqrt{(V/2)^2 + X^2} \tag{7.6}$$

where X is the magnitude of the voltage V_{AO}. From the above equation, the voltage X**,** known as the "teaser" voltage, has a magnitude of $(3/2)^{1/2}$ or 0.866 of any of the three-phase line-to-line voltages. Therefore, if the "main" and "teaser" transformers have the same number of turns in their two phase windings, there must be 0.866 as many turns in the winding A0 of the "teaser" as there are in the complete winding BC of the "main" transformer. This completes the proof that the relations shown in Figure 7.2. are valid. (Kakalec, 1994)

7.1.2.2.Current Relationships

The proof that the magnitude of each of the phase current is equal will now be presented. Referring to Figure 7.2., the secondary voltages are assumed to be equal and 90^0 out of phase. It is also assumed that the secondary currents are resistive and that:

$$[Ist]= [Ism] = Is \tag{7.7}$$

Since the teaser turns are $(3/2)^{1/2}$ N, then the current la is $(3/2)^{-1/2}$ Is. Figure 7.2. can be reduced to Figure 7.4 . Here the currents ib and ic are, given that currents divide equally:

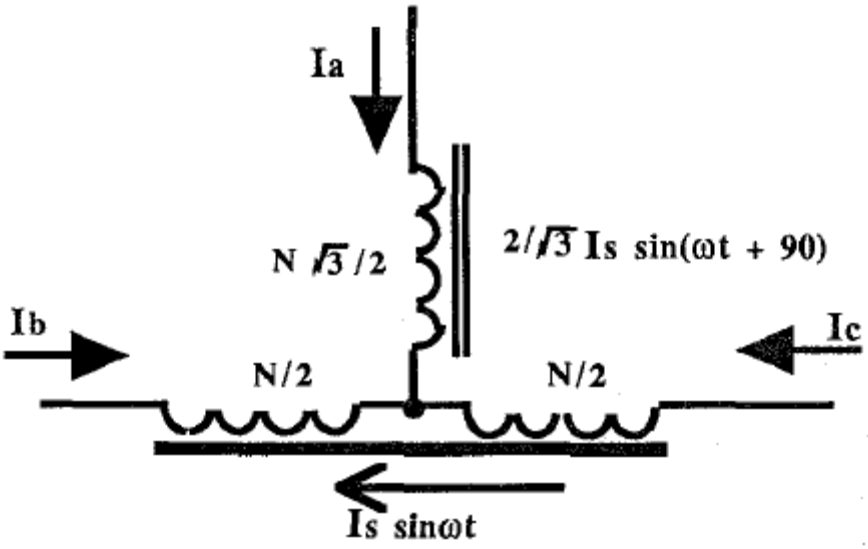


Figure 7.5. Current in the Scott Transformer (Kakalec, 1994)

$$Ib = Issin\omega t - \frac{1}{2}\frac{2}{\sqrt{3}} Issin(\omega t+90) \tag{7.8}$$

$$Ic = - Issin\omega t - \frac{1}{2}\frac{2}{\sqrt{3}} Issin(\omega t+90) \tag{7.9}$$

Calculating the magnitude of the three currents,

$$Ia = \frac{2}{\sqrt{3}} Is \tag{7.10}$$

$$Ib = \sqrt{(1)^2 + (\frac{-1}{\sqrt{3}})^2}\ I = \frac{2}{\sqrt{3}} I \tag{7.11}$$

$$I = \sqrt{(-1)^2 + (\frac{-1}{\sqrt{3}})^2} \quad I = \frac{2}{\sqrt{3}} I \tag{7.12}$$

Thus it is shown that the magnitude of all three phase currents are equal. (Kakalec, 1994)

7.1.3.Overhead Line System (Catenary System)

Overhead line system is a some kind power distribution system for electric trains . (Overhealine system has been described in chapter 4.) Electric trains takes power from conductor named contact wire using a device named pantograpf .

The catenary system have different types of geometry due to system design , speed of train , environmental conditions , voltage level , substation distance , voltage drop, impedance etc…

Harmonic distortion to the network voltages is caused by machine saturation effects and non-linear elements such as thyristor power converters. Electricity Supply authorities specify limits for total distortion which are generally in the range 0.5 - 3%. The harmonics produced by power converters can cause resonance of the power supply network due to the series/parallel characteristic of the overhead line, and the supply transformer, this in turn can produce over voltages. The impedance of the supply system is required to be controlled with the use of damper [RC circuits] to ensure that the system impedance is such that potentially dangerous over voltages do not occur.

An overhead line system behaves as a transmission line and has certain values of capacitance, inductance and resistance per unit length that are determined by physical characteristics such as the diameter of the copper conductor and its height above the ground. As a result the overhead has characteristic impedance which by transmission line theory can be shown to alternate between capacitive and inductive values in the form of a hyperbolic curve. The supply from the grid to the feeder station is essentially inductive and resonant conditions exist between the supply and the overhead, i.e. the system has a set of characteristic resonant frequencies. (White, 2009)

Parameters for catenary system conductor will be taken from references research essay. (Pee-Chin Tan , Poh Chiang Loh , Donald Grahame Holmes 2005) The traction system considered in this investigation consists of a 10-km single-phase contact feeder section with a longitudinal impedance of (0.169 + i0.432) Ω/km at 50 Hz and a shunt capacitance of 0.011 μF/km, fed from a substation step-down.

7.2.Loads (Trains)

Power drawn from the load (train) depends upon the train's speed and operation mode which are in turn determined by the traction equipment characteristics, train weight, aerodynamics, track geometry and train control strategies etc. The power demand may thus vary significantly within a very short period of time during an inter-station run.

The fact that the train is moving only further perplexes the load flow calculation and it signifies the difference between a conventional power system and a supply system in railways. The number of trains in a feeding section is also vital to the calculation as they may be running at different speeds, drawing (or feeding) different amount of power and thus posing different effects on the supply system. Nominal separation among trains is yet another important consideration and it should follow the timetables or dispatching schedules of the train services. (Ho, 2004)

As a summary of explanation determining load that takes power from catenary has lot of difficulties and several different conditions have to be taken care, these conditions can be listed as in below .

- Number of load can change due to traffic.
- Size of load can change due to different vehicles and different traction motors.
- Changing speed of vehicles in time interval due to driver behaviour and time scheduling.
- Load differences on different sections of catenary system.

Many single-phase 25-kV electrified ac railway systems have been operated to supply power to a range of locomotives with a significant proportion of the locomotives still employing ac-dc phase-controlled thyristor converters to feed dc motor drives. These railway systems are found in several countries , and are expected to power older thyristor-based locomotives, operating in coexistence with the newer generation of gate turn-off thyristors (GTO) or insulated-gate bipolar transistor (IGBT) locomotives for many years to come since the average locomotive life is about 30 years.

It is well reported now that thyristor-based locomotives draw current with a low displacement power factor and rich harmonic content. In particular, the lagging load current causes a significant amount of reactive voltage drop along the feeder line, while the flow of harmonic load current through the feeder impedance results in a distorted pantograph voltage waveform that has a reduced (rectified) average value. The former effect [low rootmean- square (rms) voltage] can significantly limit the distances between substations and also the number of locomotives that the system can support. As a standard, IEC specification 349 has stipulated that the minimum pantograph voltage must be above 19 kV continuously and 17.5 kV for short periods. The latter effect (low average voltage) is also important because for phase-controlled locomotives, the power output is proportional to the average voltage (rather than the rms voltage) (Tan, 2005)

Basically the load block that we will use is a controlled thyristor rectifier feeding a DC motor. The DC motor is modeled with a resistance , inductance and a back emf and the motor size will be 2,5 MW. It is possible to control the firing angle of the controlled three-phase rectifier. Finally simulation will be done in several load conditions like different number of loads, different firing angles to investigate the performance of proposed system as much as possible.

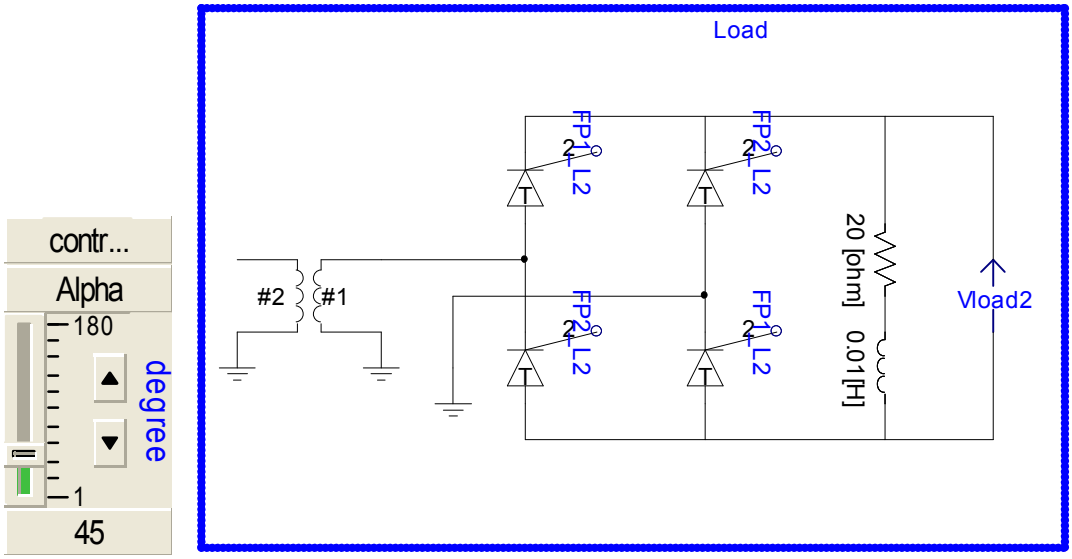


Figure 7.6. The load and and firing angle of the thyristor

7.3. Active Power Filter

Modern semiconductor switching devices are currently employed in a wide variety of domestic and industrial loads. These loads are often referred to as “power electronic loads”. They often reliable and economical solutions to control electric power, from a few watts to many megawatts. The nonlinear characteristic of semiconductor devices as well as operational function of most power electronics circuits cause distorted currents and voltage waveform on the supply system . It contrast with the conventional linear loads , the power electronic load are categorized as nonlinear loads. An example of a nonlinear load is a six pulse bridge rectifier with smoothing reactor . These loads are commonly referred to as “ power system polluters “ or “ distorting sources” in relevant literature . The presence of power electronics related distorting elements in virtually all major industrial loads viewed by the power distribution authorities as the major cause of an alarming amount of harmonic distortion in electronic power systems. The problems caused by these types of loads is a part of Electric Power Quality studies .

The development of the energy improving technologies, widely used for industrial loads , has already been expanded to domestic electric appliances. This has resulted in a further significant increase in the background distortion level of harmonic frequencies within electric power system reducing the adverse effects of

cumulative distortion, caused by aggregated small industrial and domestic loads, requires complicated and innovative power filtering techniques . The problems associated with harmonically polluted power systems are well known . Among often-cited problems caused by harmonic distortion in supply system ,the poor use of the Ac source and distortion wiring volt-ampere capacity as well as distortion of the line voltage waveform caused by harmonic current in particularly in ” weak ” system buses are considered highly important .Nuisance tripping of computer-controlled industrial processes and medical equipment , excessive heating in transformers and equipment failure due to resonant over voltages are other sever distortion problem . It is interesting to note that the power semiconductor-based loads which are the major contributors to power system pollution tend to be sensitive to pollution caused by other nonlinear loads.

Synchronous condenser can be very effective for system var flow/ voltage control. However because of their relatively slow response time , they are unable to compensate fully for undesirable effects of rapidly changing loads. An alternative approach to the use of controllable reactive power devices utilizes the “static var compensator (SVC)” systems , which have faster response and a good potential for lower initial and operating costs. The contribution to suppression of harmonics and transition harmonic correction is non-existent for the SVC`s .

Passive filters are being used widely for harmonic elimination. However they may create system resonances , need to be significantly over-rated to account for possible harmonic absorption from power system , must be coordinated with reactive power requirements of the loads and need a separated filter for each harmonic frequency to be cancelled .

The problems associated with performing switching operation on a large scale capacitors and inductors within the static var compensators , simultaneously with using frequency filters to absorb harmonic distortion generated by nonlinear load and the SVC itself , motivated the investigation of utilizing fast switching technology to generate the required “ corrective “ or “ compensating “ waveform . This waveform has to be injected into carefully selected point in a power system to correct the voltage or current waveform on distorted bus-bar. The approach is based

on the principle of injecting harmonic current into the Ac system , of the same amplitude and the reverse phase to that of the load current harmonics. The concept of injecting the compensating waveform into a power system bus are commonly referred to as "active power filtering " (K.Cagatay Bayindir 2000). The switching compensator itself has been known by different names such as active power filter , active power line conditioner and static var and distortion compensator .

Some interesting features normally associated with active power filtering approach can be outlined as follows

- While passive filter have to be design with a KVA rating based on the worst case total distortion at each frequency , the active power filters can be designed for the lower KVA rating than the worst case total distortion .
- They do not introduce system resonance like passive filter .
- They are capable of reducing the effect of distorted current/voltage waveforms as well as compensating fundamental displacement component of current drawn by nonlinear loads .
- Because of high controllability and quick response of semiconductor devices , they have faster response time than conventional SVC`s
- They primarily utilize power semiconductor device rather than conventional reactive components (storage elements). This results in reduced overall size of a compensator and expected lower capital cost in future due to continuously downward trend in the price of the solid state switches . They are usually called system with " minimum storage elements " or " no storage elements" .
- Active power filters are better for compensating low order harmonics such 3rd , 5th and 7th , while passive filter better for compensating higher order harmonics such as the 11th, 13th and higher . The reasons of this may be listed as follows .
    - Active filtering of high order harmonic components need hih switching frequencies and high di/dt capability for the active power filter . However this not the case for a passive filter .

- Size of the passive filter becomes larger for compensating lower order harmonics .
- Harmonic current division between source and finally tuned passive filter depends on the ration R_{int}/nX_s , where R_{int} is the internal impedance of the passive filter and nX_s is the supply impedance at nth harmonic frequency . This ration should be as low as possible for perfect filtering . Since the ratio is inversely proportional to harmonics number "n" , performance of passive filter becomes better at higher harmonic orders. (K.Cagatay Bayindir 2000)

7.3.1.1.Classification of active filters

Fig.7.5 shows the components of a typical active-power-filter system and their interconnections. The information regarding the harmonic current, generated by a nonlinear load, for example, is supplied to the reference-current/voltage estimator together with information about other system variables. The reference signal from the current estimator, as well as other signals, drives the overall system controller. This in turn provides the control for the PWM switching pattern generator. The output of the PWM pattern generator controls the power circuit via a suitable interface. The power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations, depending on the connection transformer used.

On the basis of the above, the published work in this field can be classified using the following criteria.

- power rating and speed of response required in compensated systems;
- power-circuit configuration and connections;
- system parameters to be compensated (e.g. current harmonics, power factor, unbalanced three-phase system etc.);
- control techniques employed; and
- technique used for estimating the reference current/voltage.

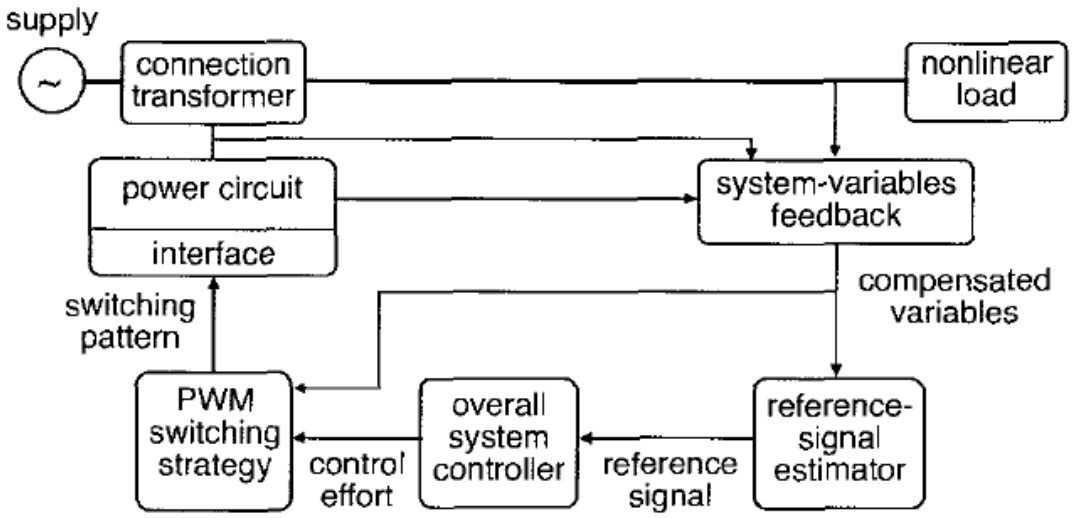


Figure 7.7. Generalized block diagram for active power filters (Habrouk, 2000)

According to above criteria active power filter can be classified and several different types of can be used due to application needs . One of the active power filters, the shunt active filter has been researched and developed, and it has gradually been recognized as a feasible solution to the problems created by nonlinear loads. It is used to eliminate the unwanted harmonics and compensate fundamental reactive power consumed by nonlinear loads with injecting the compensation currents into the AC lines .The performance of APF is based on three control technology: design of power inverter; types of current controllers used; methods used to obtain the reference current. Many control techniques have been used to obtain the reference currents. These techniques such as instantaneous reactive power theory , notch filters , flux based controller, power balance theory , and sliding mode controller have been used to improve performance of the active filters.

However, most of these control techniques include a number of transformations and are difficult to implement.

7.3.1.2.Active Power Filter Configuration

The active filter configuration investigated in this study based on voltage source inverter that interfaces to the system through an interface reactor. In this configuration , the filter is connected in parallel with the load being compensated.

Therefore the configuration is often referred to as single phase shunt active filter. The approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and reverse phase to that of the load current harmonics. (Bayindir, 2000)

Active filter model consists of the following main parts.

- Voltage source inverter
- Interface reactor
- Reference control signal generator (EPLL)
- Current control firing pulse generator (Hysteresis Control)

7.3.1.3.Voltage Source Inverter

The voltage source inverter used in the active filter makes the harmonic control possible. This inverter uses a DC capacitor as the supply and can switch at a high frequency to generate a signal which will cancel the harmonics from nonlinear load. The DC capacitor is initially charged before system operation and during operation, in order to maintain a constant DC voltage in storage elements , only a small fundamental current is drawn to compensate the active filter losses. The active filter does not need to provide any real power to cancel harmonic current from load .The harmonic current to be cancelled show up as reactive power.

The current waveform for cancelling harmonics is achieved with the voltage source inverter and an interface reactor .The interface reactor converts the voltage signal created by the inverter to a current signal . The desired waveform is obtained by accurately controlling the switches in the inverter. Control of current wave shape is limited by switching frequency of the inverter and by the available driving voltage across the interface reactor.

The driving voltage across the interface reactor determines the maximum di/dt that can be achieved by the filter. This is important because relatively high values of di/dt may be needed to cancel higher order harmonic components .The rate of chance of an inductive current is related to available change in voltage across the reactor by (7.13)

$$\Delta v(t) = L\frac{di}{dt} \tag{7.13}$$

where ,

$\Delta v(t)$ - voltage across the inductor

L – Inductance of inductor

i(t)- current flowing through to inductor .

With a constant interface reactor L , the driving voltage for the active filter is the potential difference between the DC voltage stored on the DC capacitors and the instantaneous value of the AC system voltage on the other side of the inductor .

This means that the filtering effectiveness is also dependent on the relative position of the current waveform harmonics with respect to the voltage waveform. The voltage source inverter is the heart of the active filter. (Bayindir, 2000)

7.3.1.4.Interface Reactor

The interface provide the isolation and filtering between output of the voltage source inverter and the power system where the active filter is connected .

The inductance allows the output of the active filter to look like a current source to the power system . The inductance makes it possible to charge the DC capacitor to a voltage greater than the AC line to line peak voltage. The inductance also functions like a commutative impedance. It limits the magnitude of a current spike during commutative and prevent switching device from seeing and excessive rated of current charge. Besides these, it is not possible to connect a sinusoidal voltage supply to the non-sinusoidal output of the voltage inverter without a reactor.

Sizing of the inductor value must take into account control of the inverter switching frequencies and characteristics of the nonlinear load to be compensated. (Bayindir, 2000)

7.3.1.5.Reference Current Generation

Active compensation of harmonics, reactive power and unbalance is required for improving power quality, control and protection. An integral part of an active

compensation device is the detection unit which generates the reference signals. Various methods, e.g. Discrete Fourier Transform (DFT), Phase-Locked Loop (PLL), notch filtering and theory of instantaneous reactive power have been presented in the literature for this purpose.

As a reference signal generator EPLL will be used in this study because of advantages and good performance. The single-phase signal processing system for extraction of harmonic and reactive current components for use active power filters (APFs) will be explained later. The system is based on an enhanced phase-locked loop (EPLL) system and its features with respect to other methods are as follows.

- It simultaneously extracts harmonic and reactive current components independently.
- Its structure is adaptive with respect to frequency.
- Its structure is robust with respect to the setting of the internal parameters.
- Its performance is immune to noise and external distortions.
- Accuracy and speed of its response are controllable.
- Its structural simplicity provides major advantage for its
- Implementation within embedded controllers.(Karimi-Ghartemani, 2004)

The main idea of conventional PLL is the ability to generate a sinusoidal signal whose phase is coherently following the main component of the input signal. The basic structure of the conventional PLL is shown Fig. 7.6. It has three main blocks; PD, LPF and VCO. PD detector is a signal multiplier. The output of PD passes through the LPF and the noises and high frequency component of multiplying operation is attenuated. The LPF generates ideally dc error signal for VCO. The VCO used in PLL is a conventional VCO which is used in many applications. VCO generates a coherent phase approximately 90° between input signal and output signal. A small modification is necessary to achieve a synchronized output signal with in input signal in same phase. (Ghartemani, 2001)

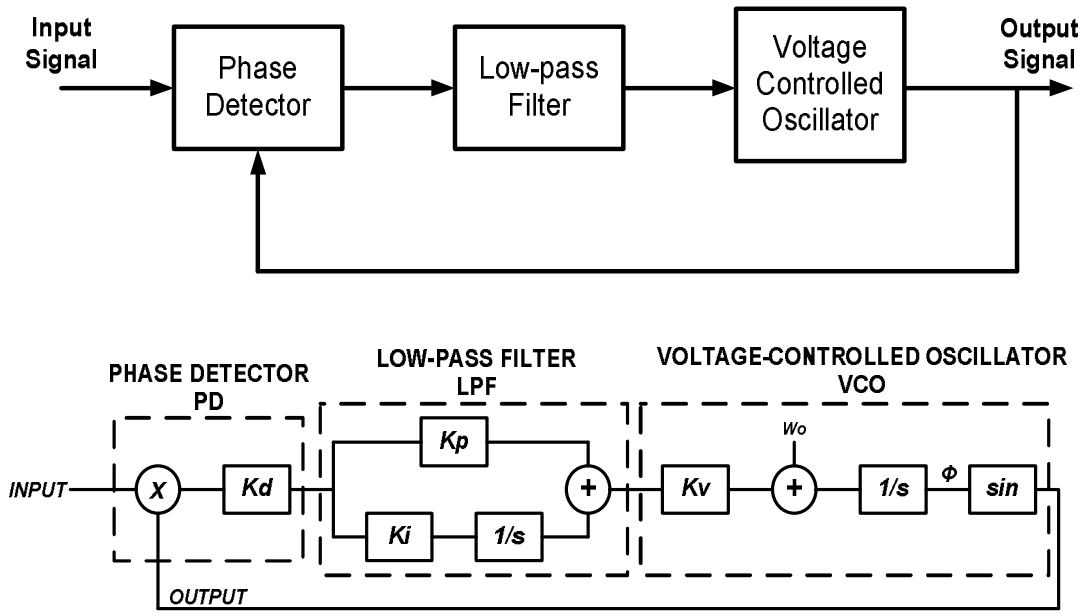


Figure 7.8. The Phase locked loop structure (Ghartemani, 2001)

EPLL is developed by M. Karimi-Ghartemani in 2001. The EPLL is formed from three main block as PLL; PD, LPF and VCO. The structure and functions of LPF and VCO in EPLL is same as LPF and VCO of PLL. The innovation is performed in PD of EPLL. The new PD adds new features like amplitude estimation, in phase output signal and more robust and stable loop than conventional PLL. Moreover EPLL has higher convergence time than conventional PLL.

These new features are performed by changing the structure of PD. The amplitude estimation feature is achieved by adding a peak detector mechanism into PD. A very basic peak detector mechanism is used but this structure has many successful effects on the stability, robustness and convergence time of loop.

Since the EPLL offers more information than the conventional PLL, the range of applications of the EPLL is far wider than that of a conventional PLL .The EPLL extracts and directly provides the following pieces of information from the input:

- Fundamental sinusoidal component of the input; this signal is synchronous with the input and is smooth and noise free,
- Amplitude of the fundamental component of the input

- Phase angle of the fundamental component of the input; this phase can be adjusted to be its constant phase or total phase.

This information makes the EPLL suitable for many applications encountered in diverse areas of engineering. For example, in electrical power engineering the following list presents several potential applications of the EPLL.

1) Harmonic detection and extraction for measurement as well as active compensation.
2) Disturbance detection and extraction.
3) Generation of smooth noise free reference signal synchronous with a distorted and noisy input, useful for synchronous measurement and zero crossing detection.
4) Voltage flicker detection and estimation.
5) Peak detection and amplitude modulation.
6) Phase angle estimation and phase demodulation. (Ghartemani, 2002)

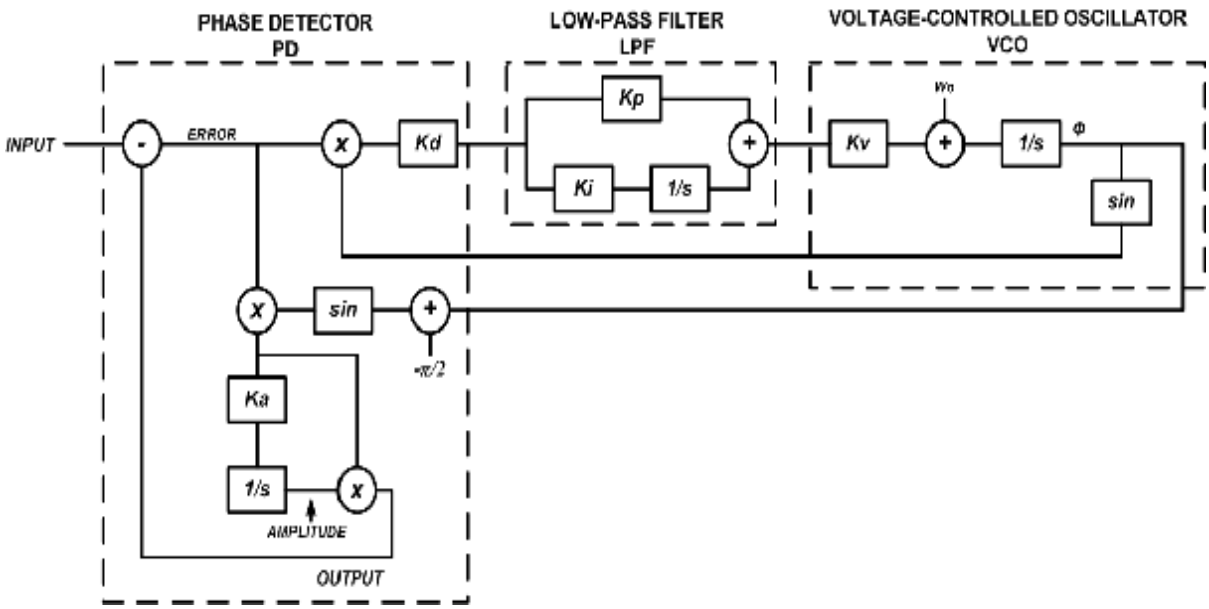


Figure 7.9. Enhanced phase loop lock structure (Ghartemani, 2002)

7.1.3.5. (1) Single-Phase Harmonic/Reactive-Current Extraction

This section explains the structure of a single-phase harmonic and reactive current extractor unit based on the EPLL. The proposed unit, although is intended for extracting harmonic and reactive current components, also extracts other pieces of information such as peak value, phase angle and frequency of the fundamental component, Total Harmonic Distortion (THD), and power factor. Assume

$$v(t) = v^f(t) + v^h(t) \tag{7.14}$$

is the distorted load voltage and

$$v^f(t) = V_1 \sin(Ǿv) \tag{7.15}$$

is its fundamental component extracted by employing an EPLL. Thus, the total harmonic content and the amplitude, phase angle and frequency of the fundamental component are also extracted and made available. Let

$$i(t) = i^f(t) + i^h(t) \tag{7.16}$$

denote the distorted load current where

$$i^f(t) = I_1 \sin(Ǿi) \tag{7.17}$$

represents its fundamental component which is extracted by another EPLL unit. Signal $i^h(t)$ represents the total distortions of the current signal. The amplitude and phase angle of the fundamental component of the current signal are also made available at the outputs of the unit.

The fundamental component $i^{f(}t)$ of the current signal can be written as

$$i^f(t) = I_1 \sin(Ǿi) = i_a^f(t) + i_r^h(t) \tag{7.18}$$

where $i_a^f(t)$ and $i_r^h(t)$ represent active and reactive components of and expressed as

$$i_a^f(t) = I_1 \cos(Ǿi - Ǿv) \sin(Ǿv) \tag{7.19}$$

$$i_r^h(t) = I_1 \sin(Ǿi - Ǿv) \cos(Ǿv) \tag{7.20}$$

It is noteworthy that I_1, Ǿv, Ǿi, sin(Ǿv) and cos(Ǿv) are all made available by the two EPLLs and the additional calculations needed are: a subtraction to produce Ǿi - Ǿv , a sine function and two multiplications.

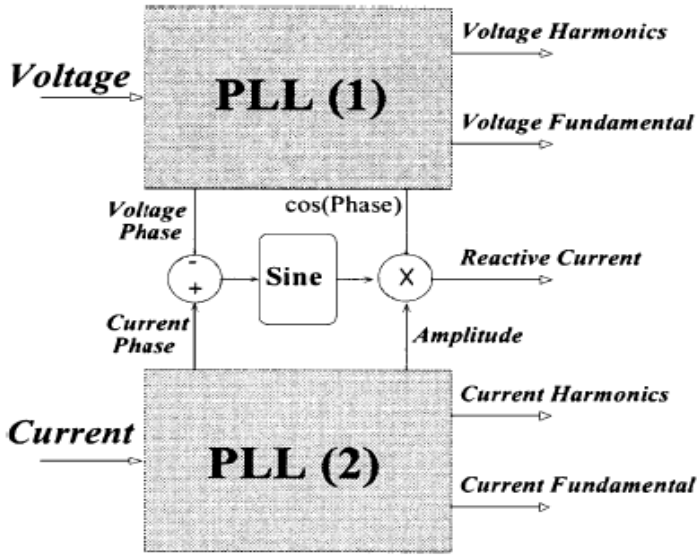


Figure 7.10. Block diagram of the proposed single-phase harmonic/reactive-current extraction unit employing two units of the EPLL. (Ghartemani, 2004)

Fig. 7.10. shows a block diagram of the single-phase harmonic/ reactive-current component extractor. Two identical EPLL units are used for voltage and current signals. The top portion of the unit is used for voltage and the bottom portion is used for current signal processing. The link between the two parts is to calculate the fundamental reactive current component. This structure also provides harmonic content of voltage, $v^h(t)$, peak values of both voltage and current fundamental components, Ai and Av, their phase angles Ǿv and Ǿi, and the phase angle between voltage and current signals. (Ghartemani, 2004)

7.1.3.5. (2) THD Calculation

The THD calculation of the input signal (being voltage or current) can be computed using the outputs of the corresponding EPLL. Let x(t) be the input signal to the EPLL and $x^f(t)$, $x^h(t)$, Ax, Ǿx and be the outputs of the EPLL corresponding to

the fundamental component, harmonic content, amplitude and phase angle. By definition, the THD of x(t) is

$$\text{THD x} = \frac{\sqrt{\left(\frac{1}{to}\int To\left[x^{h}(t)\right]^{2} dt\right.}}{Ax\sqrt{\frac{1}{2}}} \times 100\% \tag{7.21}$$

in which the numerator is the square root of the dc value of $[x^h(t)]^2$, which can be provided by a Low-Pass Filter (LPF), and $f_0 = (1/\ T_0)$ is the input center frequency. (Ghartemani, 2004)

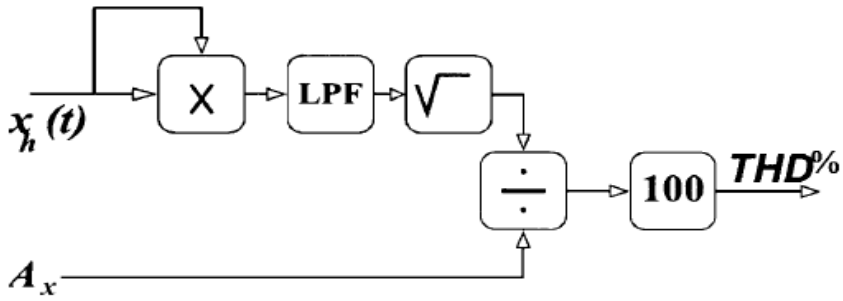


Figure 7.11. Block diagram of the THD calculating unit. (Ghartemani, 2004)

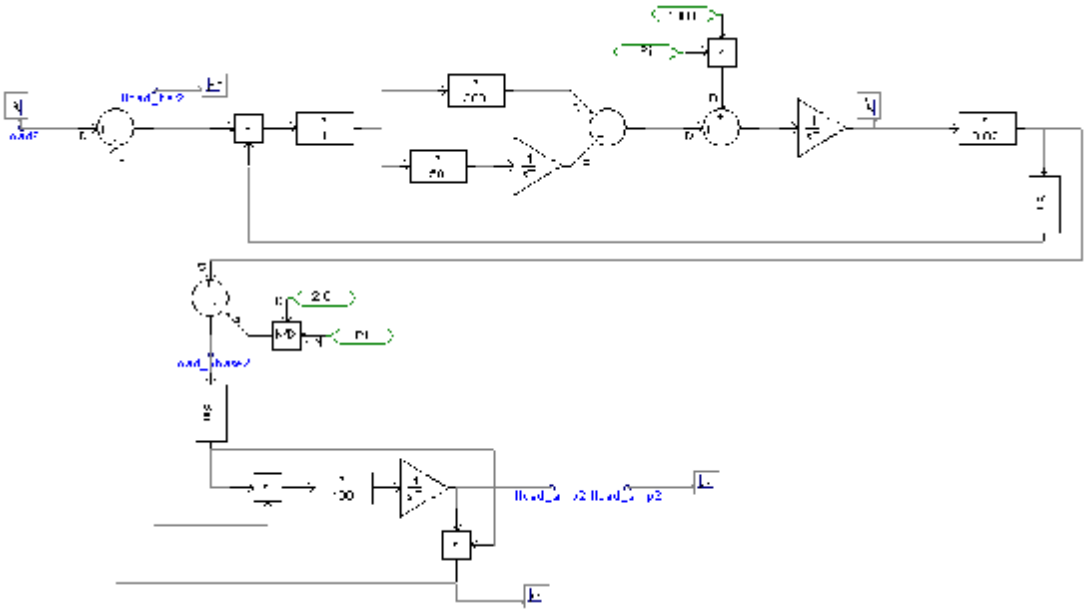


Figure 7.12.PSCAD model of EPLL .

7.1.3.5. (3) Working Principle

As mentioned above the structure and operation principles of LPF and VCO are the same as conventional PLL. While EPLL is unlocked the input signal, error signal is occurred in PD. With the help of this error signal, the peak detector part in PD begins to estimate the amplitude of input signal and LPF filter attenuate the higher frequency component in the product of VCO output and error signal and provide VCO control signal. The amplitude estimation is achieved by taking integral of product of in phase component of VCO output and error signal. Finally the output signal is created by the product of estimated amplitude and in phase component of VCO.

When the EPLL is locked the input signal; in other words amplitude, frequency and phase of the output signal and input signal are equal to each other; the generated error signal is equal to zero. If the error signal becomes zero, the product of error signal and output of VCO is equal to zero so control signal of VCO is equal to the constant w_o frequency in locked condition. This condition cannot be achieved in conventional PLL. In PLL there is always oscillation in control signal of VCO because the low pass filter cannot be suppressed the higher frequency component

completely. Because of these in conventional PLL, the variations in phase can be seen. This property of EPLL provides stable and robust structure to itself. When the error signal is equal to zero if the peak detector is examined, it is seen that the product of error signal and in phase component of VCO is equal to zero. Hence, the integral of zero is equal to zero; the output of integral is equal to amplitude of input signal.

7.1.3.5. (4) Effects of Parameters:

The gains and time constants of integrals can affect the lock time, shape of output signal and phase difference between input and output signals.

Increasing the value of Ka increases the speed. However, it creates oscillations in the response. There is a trade-off between speed and accuracy (or smoothness).

Decreasing Ka and KpKd yields an estimation of the peak which is insensitive/robust to the undesirable variations and noise in the input signal.

The EPLL is highly robust in the sense that any small changes in parameters K,Kd,Kp,Ki and the high frequency superimposed signal do not affect its performance. (Ghartemani, 2002)

7.3.1.6.Current Control

As in most PWM applications, the interval between two consecutive switching actions varies constantly within a power frequency cycle. It means that the switching frequency is not constant but varies in the time operating point and conditions. A rigid definition of the switching frequency is not applicable. Thus the concept of average frequency is commonly used .In principle increasing the inverter switching frequency helps to get better compensating current waveform. However, there is device limitation and increasing the switching frequency causes increased switching losses, audible noises and EMF related problems. The range of the frequencies used are based on a compromise between these two factors. Control of the switching frequency is realized by introducing a hysteresis characteristic into

PWM firing pulse generation logic. The PSCAD/EMTDC model of firing pulse generator is shown in figure. (Bayindir, 2000)

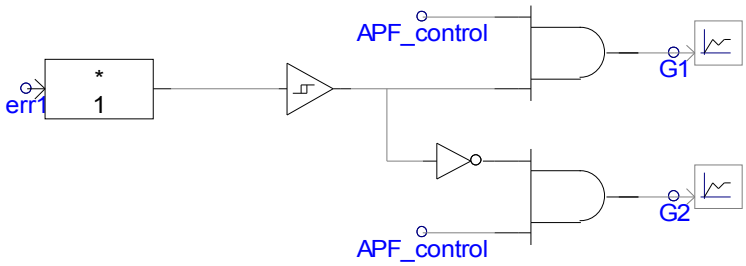


Figure 7.13 PSCAD model of firing pulse generator

8.CASE STUDIES

In this chapter the operation principles and performance of the power conditioner model will be investigated for several different conditions. The proposed model is simulated by PSCAD/EMTDC. PSCAD is a powerful electromagnetic time domain transient simulation environment and study tool Such a complex model like railway system can be developed and simulated very easily by using PSCAD/EMTDC and due to quick response time of program , the system performance can be investigated for several different condition in short time period.

The parameters that effect the simulation result are shown in table. (Tan)

In this simulation study 154kV utility power supply feeds the railway system. Scott transformer converts the 154kV three phase voltage into 25kV two phase and it injects power to the catenary system. Each phase of Scott transformer feeds different side of catenary system separated by section isolators. The catenary system impedance is assumed (0.169 + j0,432)Ω/km at 50 Hz . 4000 μF is used as a voltage source connected to the inverter VSC. The interface reactor is converting the voltage to current to compansate the effect of the load to source . To adjust the signal 25kV level the coupling transformer that convert 2.5kV to 25kV is located infront of the inductor.

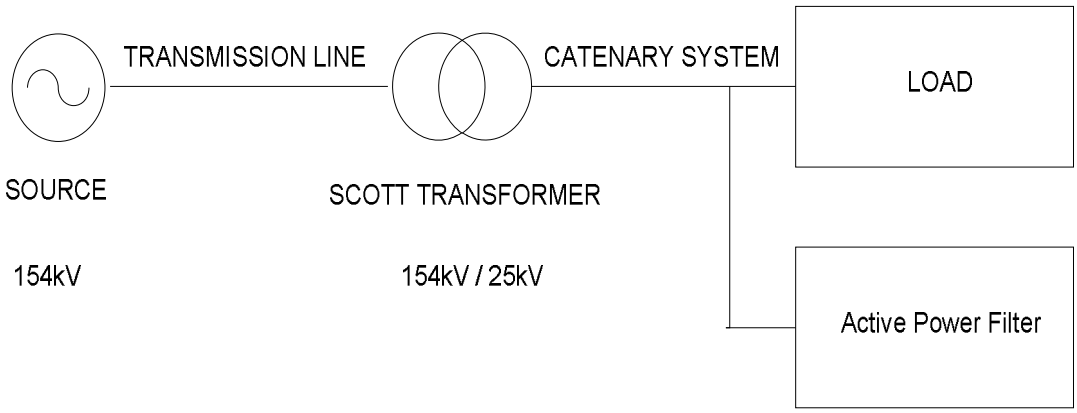


Figure 8.1 Single line diagram of the modeled system

8.1.Case 1 :

The system has two equal load on different catenary sides at the same distance. The distance from one train to substation is assummed 10 km , that means the distance between the train is 20 km . The firing angle of thyristors of loads are 90^0 . The result is shown under these circumstances

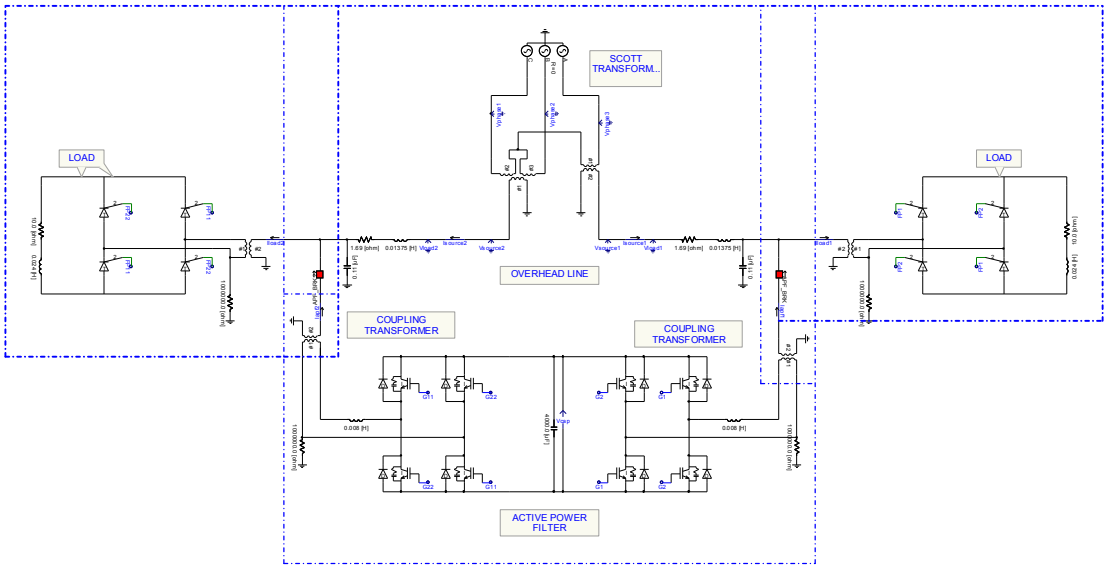


Figure 8.2.The overview of the system

8.1.1.Case 1-a

The graph of THD at 90^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation.

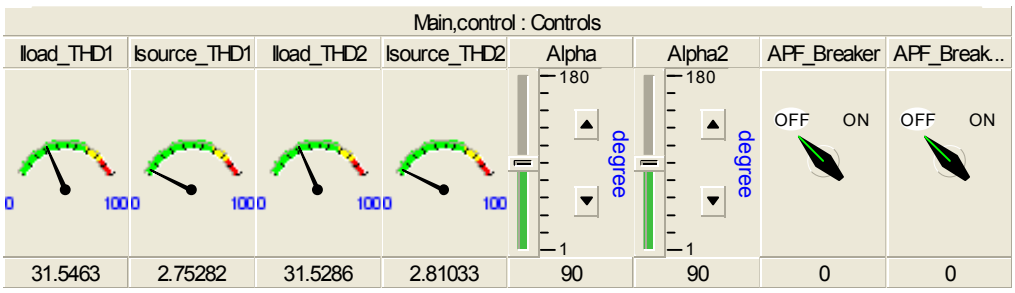


Figure 8.3.The THD levels on both sides of OHL

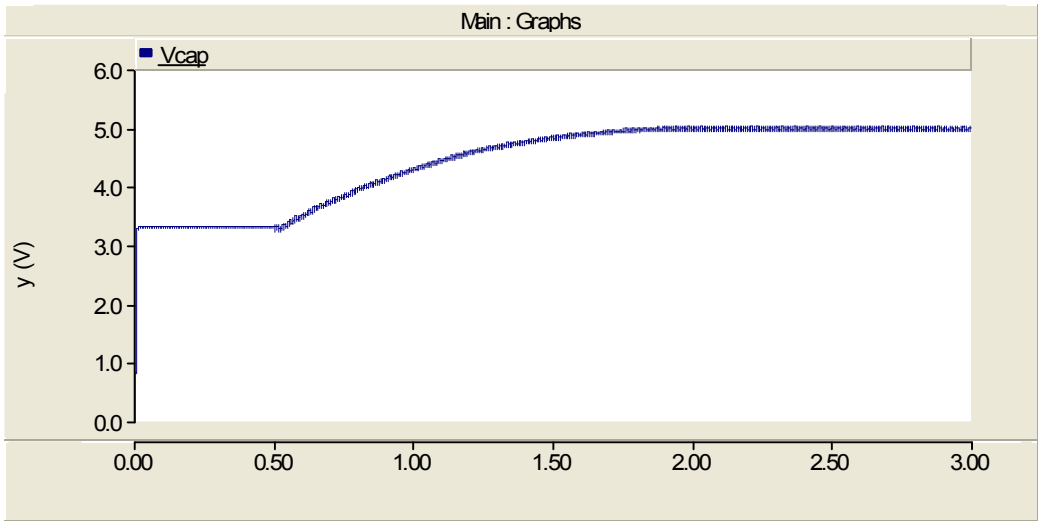


Figure 8.4.The DC link capacitor voltage characteristic

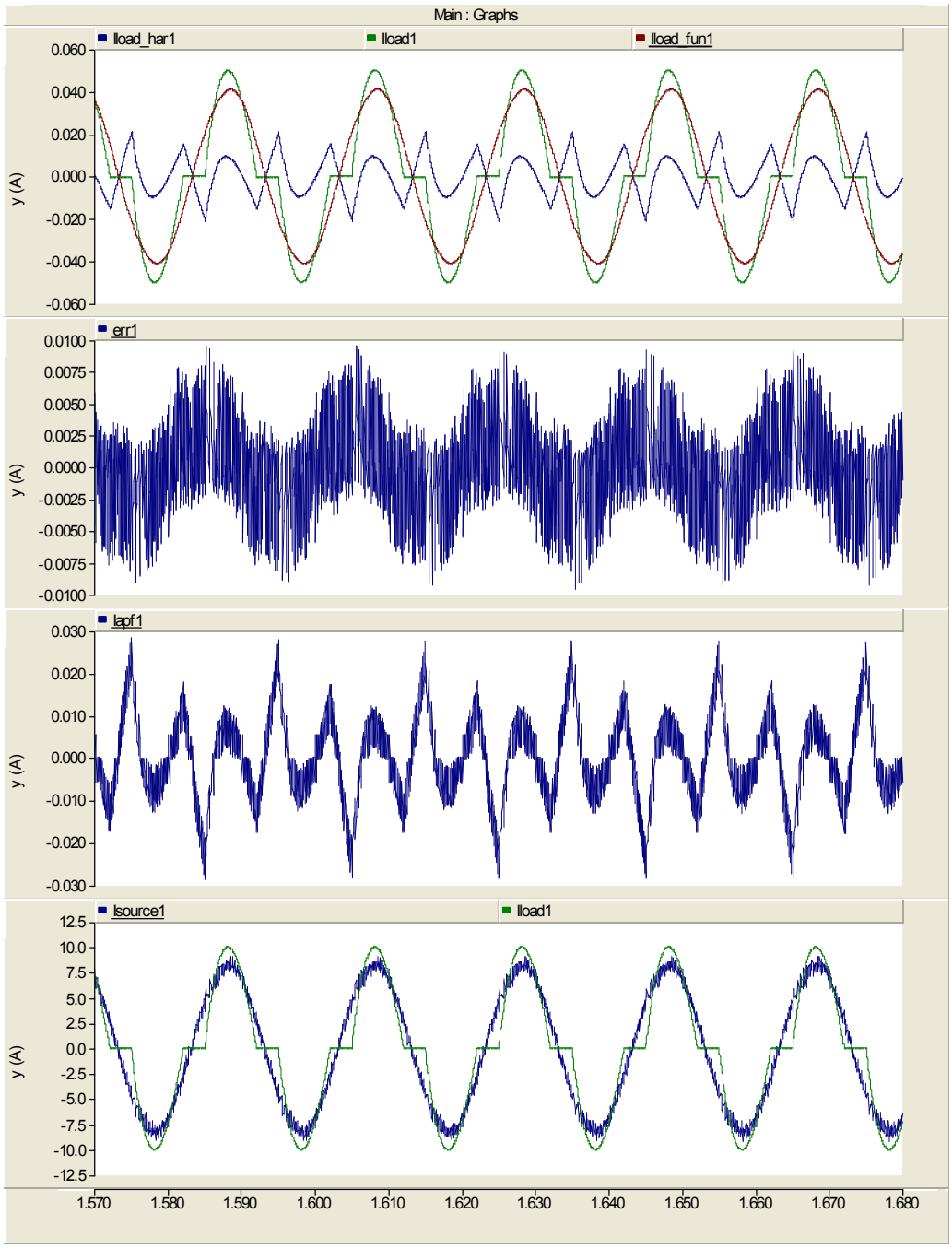


Figure 8.5.The simulation results of load 1 the current, the error signal that calculated by EPLL , harmonic signal and source signal

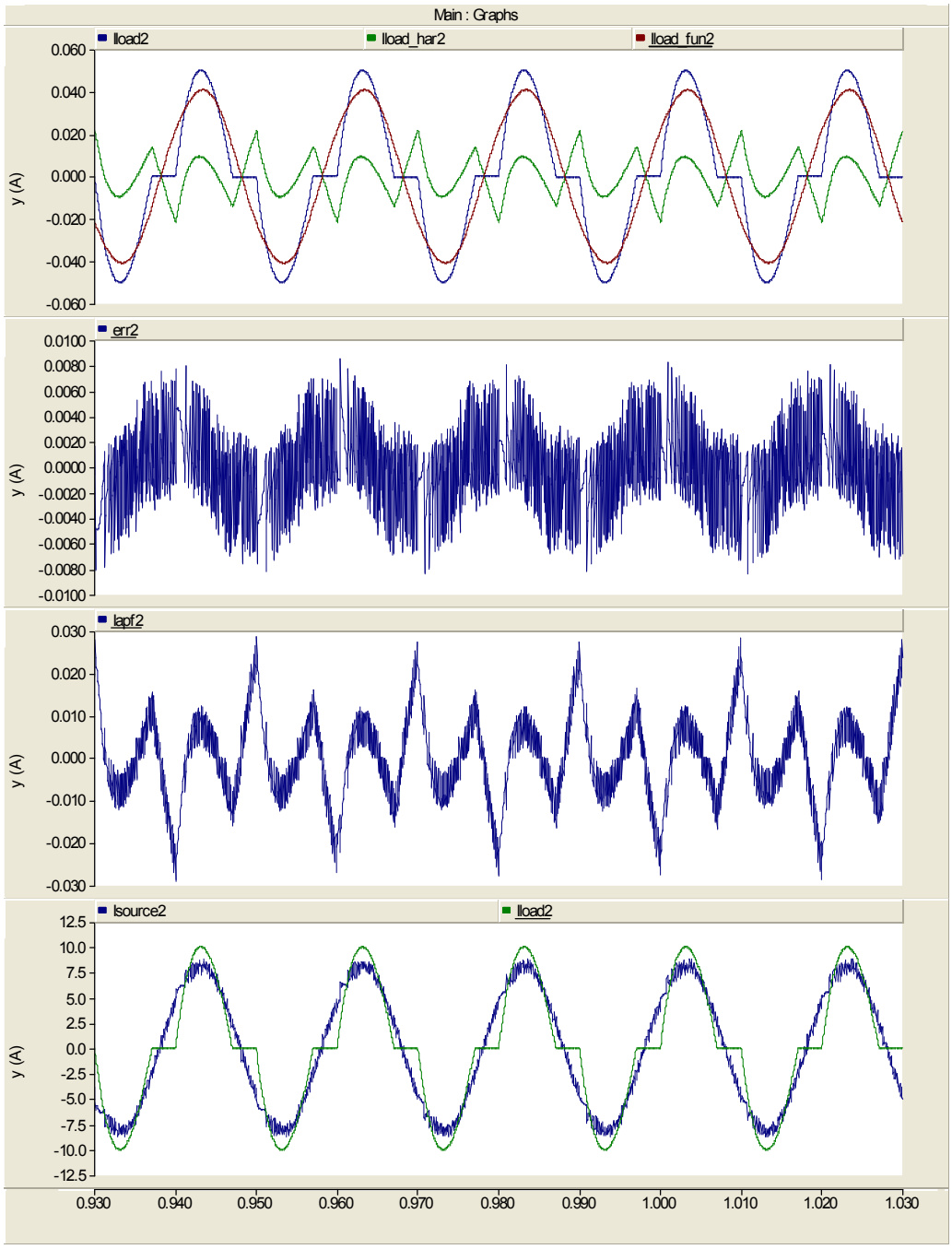


Figure 8.6.The simulation results of load 2 the current, the error signal that calculated by EPLL , harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

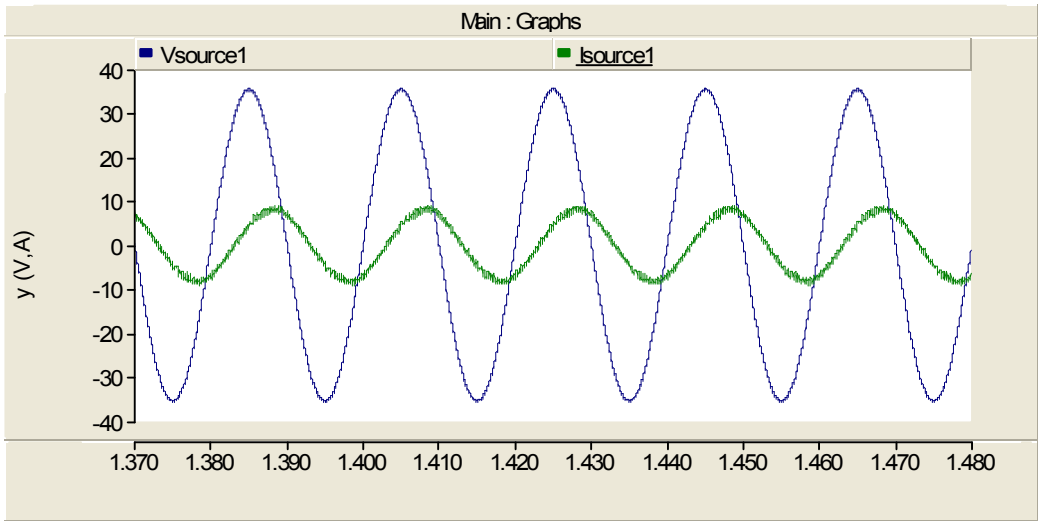


Figure 8.7.The phase difference between voltage and current (lagging) due to reactive power .

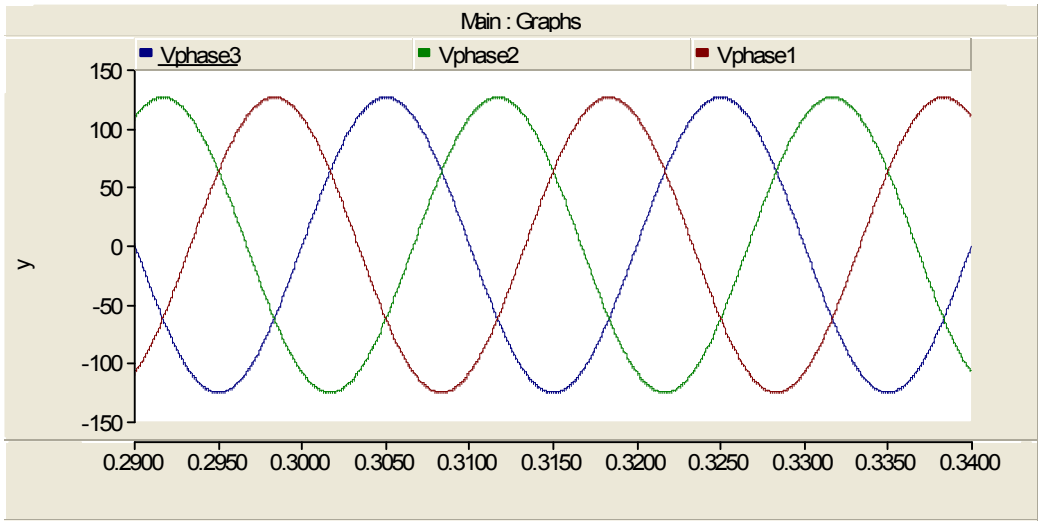


Figure 8.8. The voltage characteristic on utility network

8.1.2.Case 1 –b :

The graph of THD at 90^0 firing angle of vehicle converter. The line inductor is adjusted 0.008 H. Without reactive compensation.

The results show that while inductor size is increasing , the THD is getting lower so this is a better result . But the response time of APF is getting worse than before .

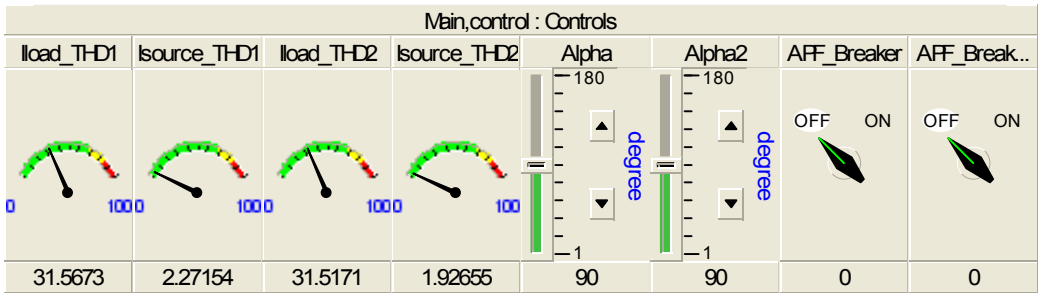


Figure 8.9.The THD levels on both sides of OHL

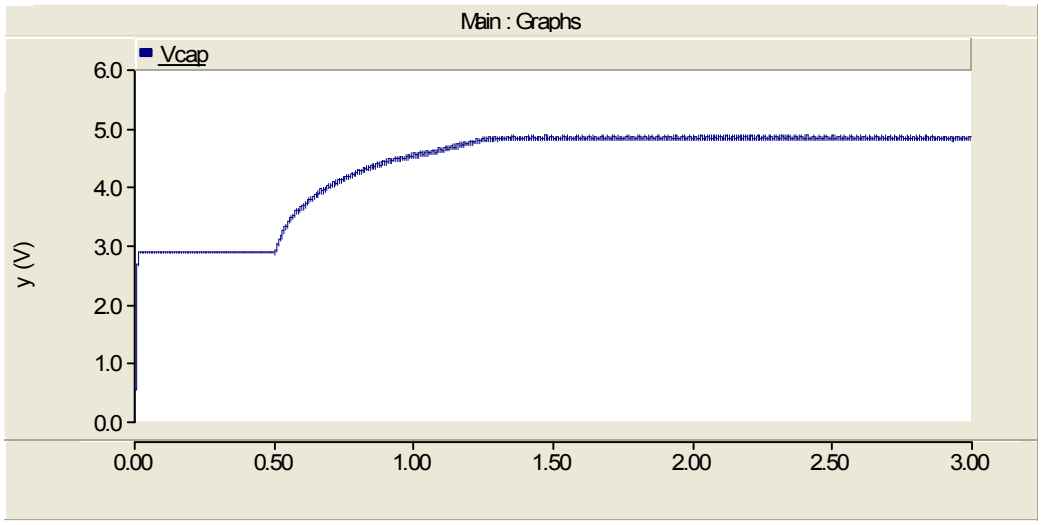


Figure 8.10.The DC link capacitor voltage characteristic

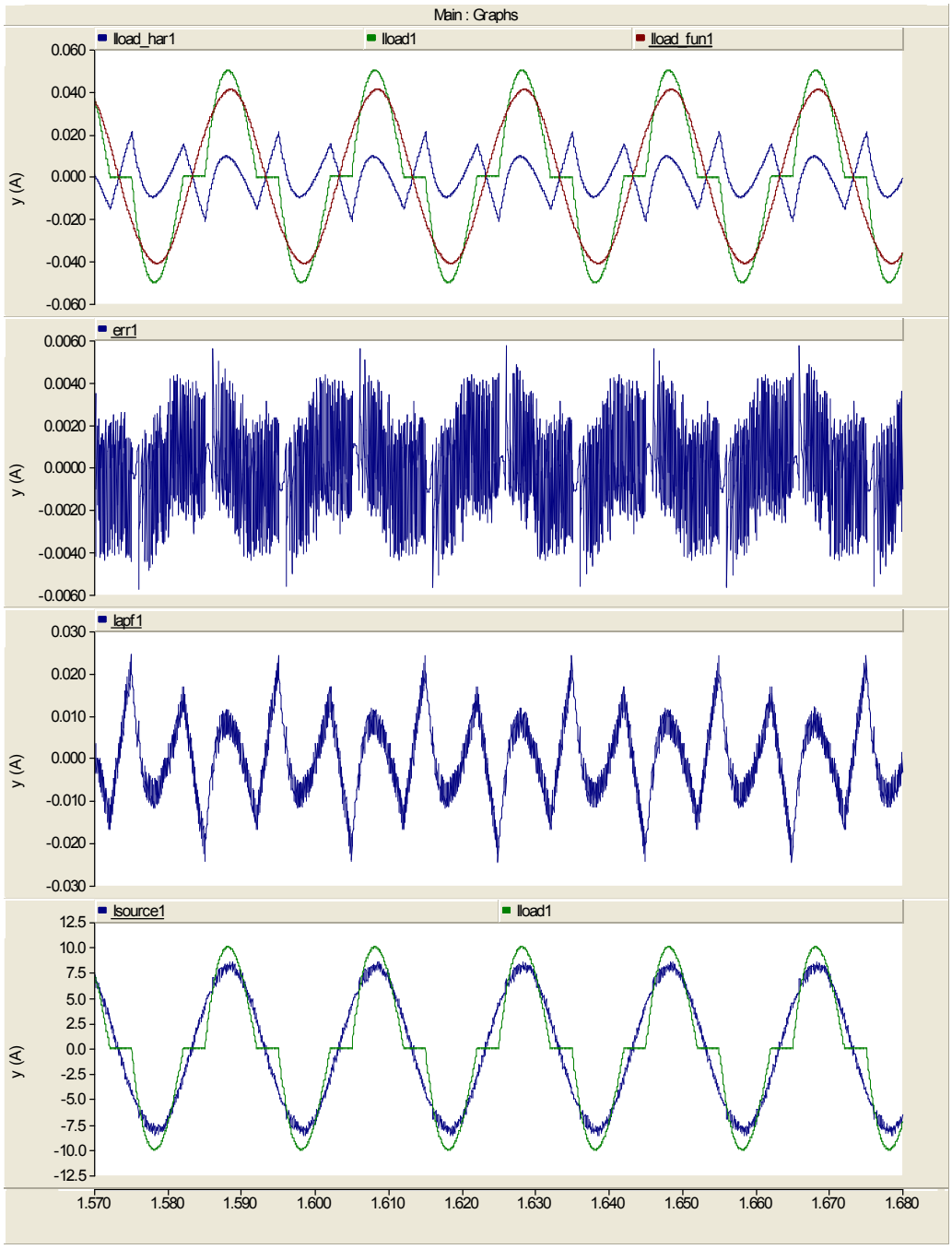


Figure 8.11.The simulation results of load 1 the current, the error signal that calculated by EPLL , harmonic signal and source signal

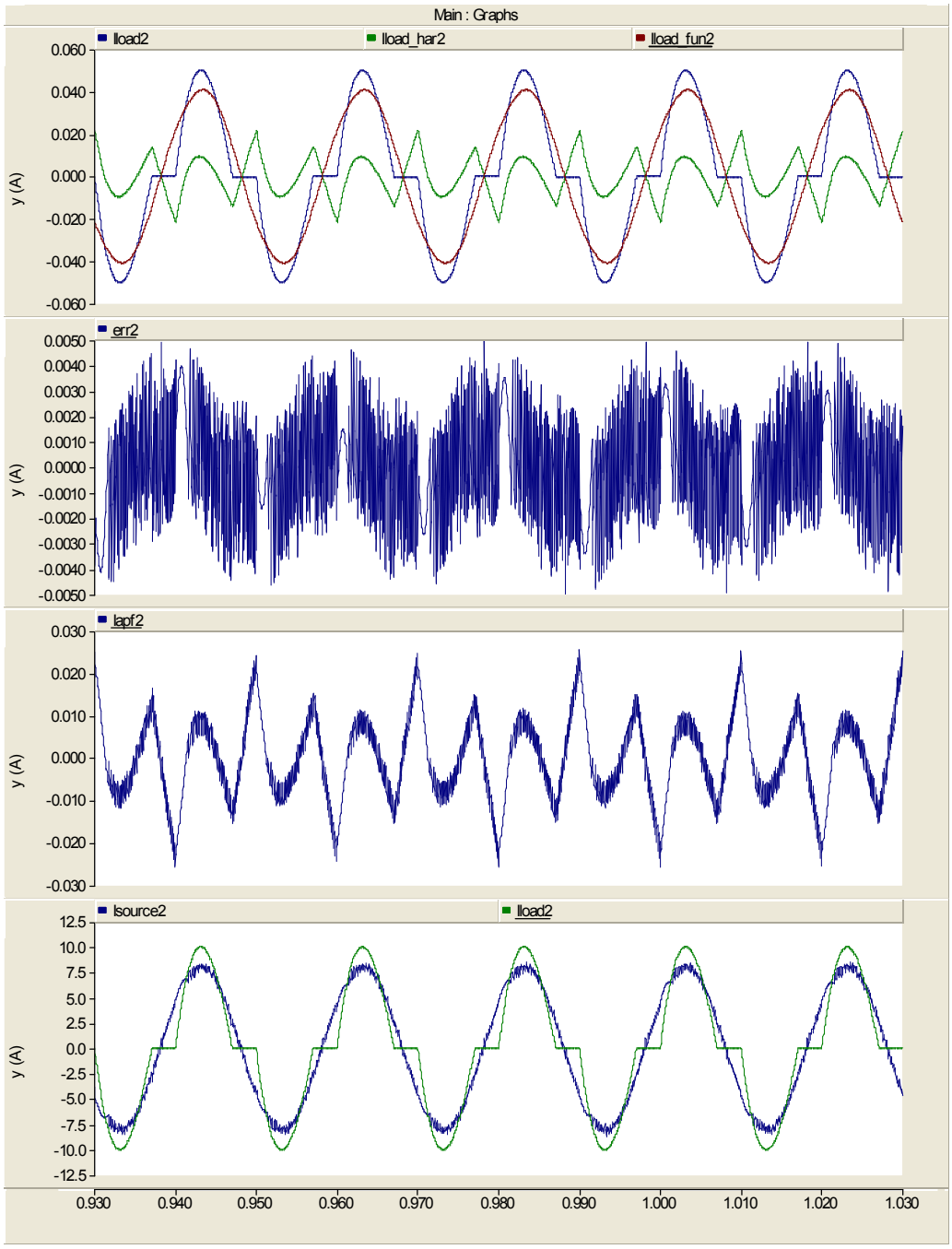


Figure 8.12.The simulation results of load 2 the current, the error signal that calculated by EPLL , harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

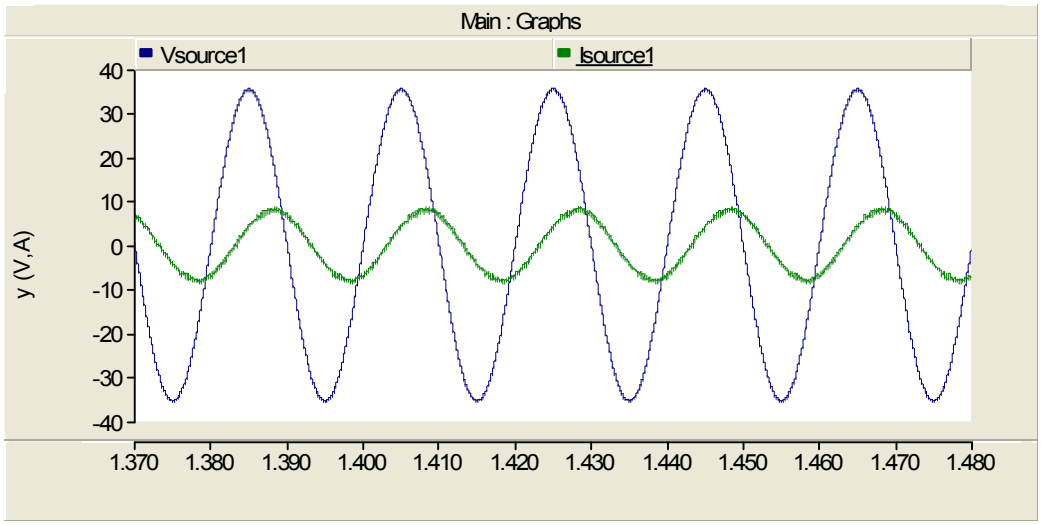


Figure 8.13.The phase difference between voltage and current (lagging) due to reactive power .

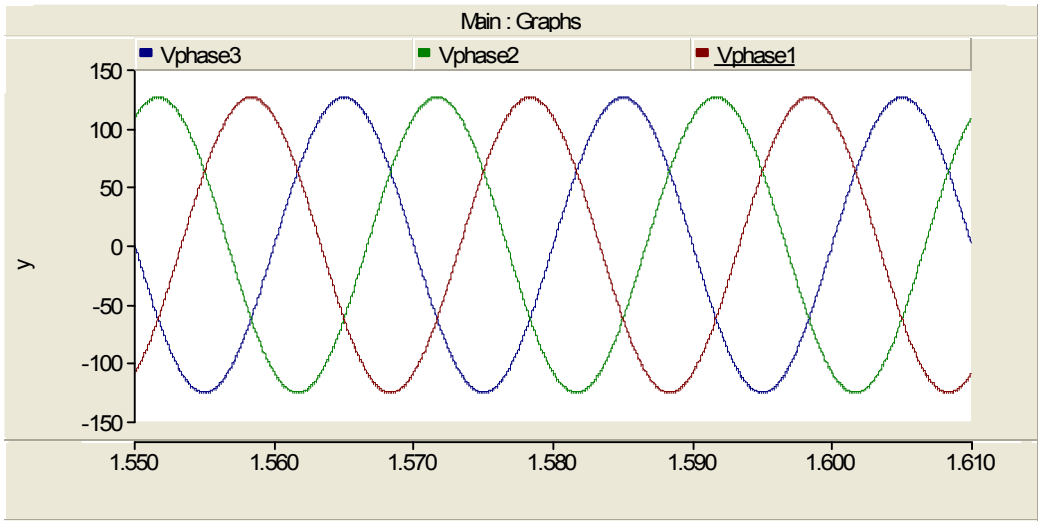


Figure 8.14. The voltage characteristic of utility network

8.1.3.Case 1 –c

The graph of THD at 90^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation.

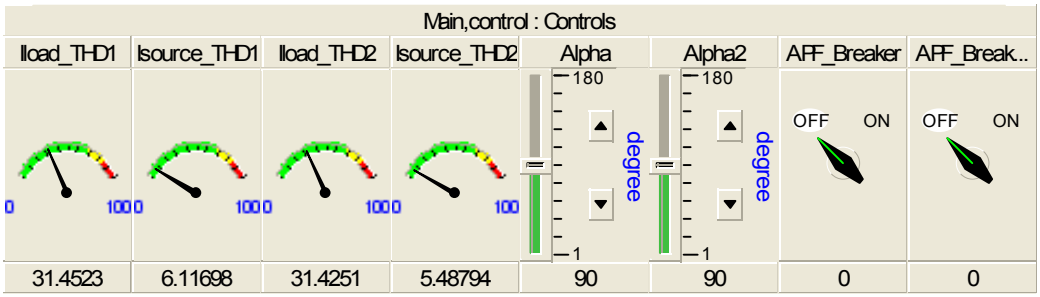


Figure 8.15.The THD levels on both sides of OHL

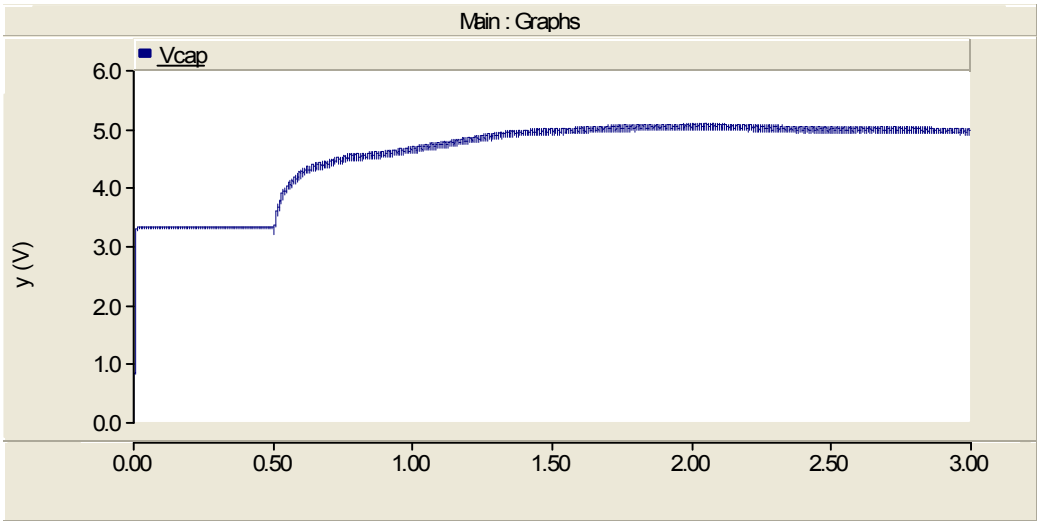


Figure 8.16.The DC link capacitor voltage characteristic

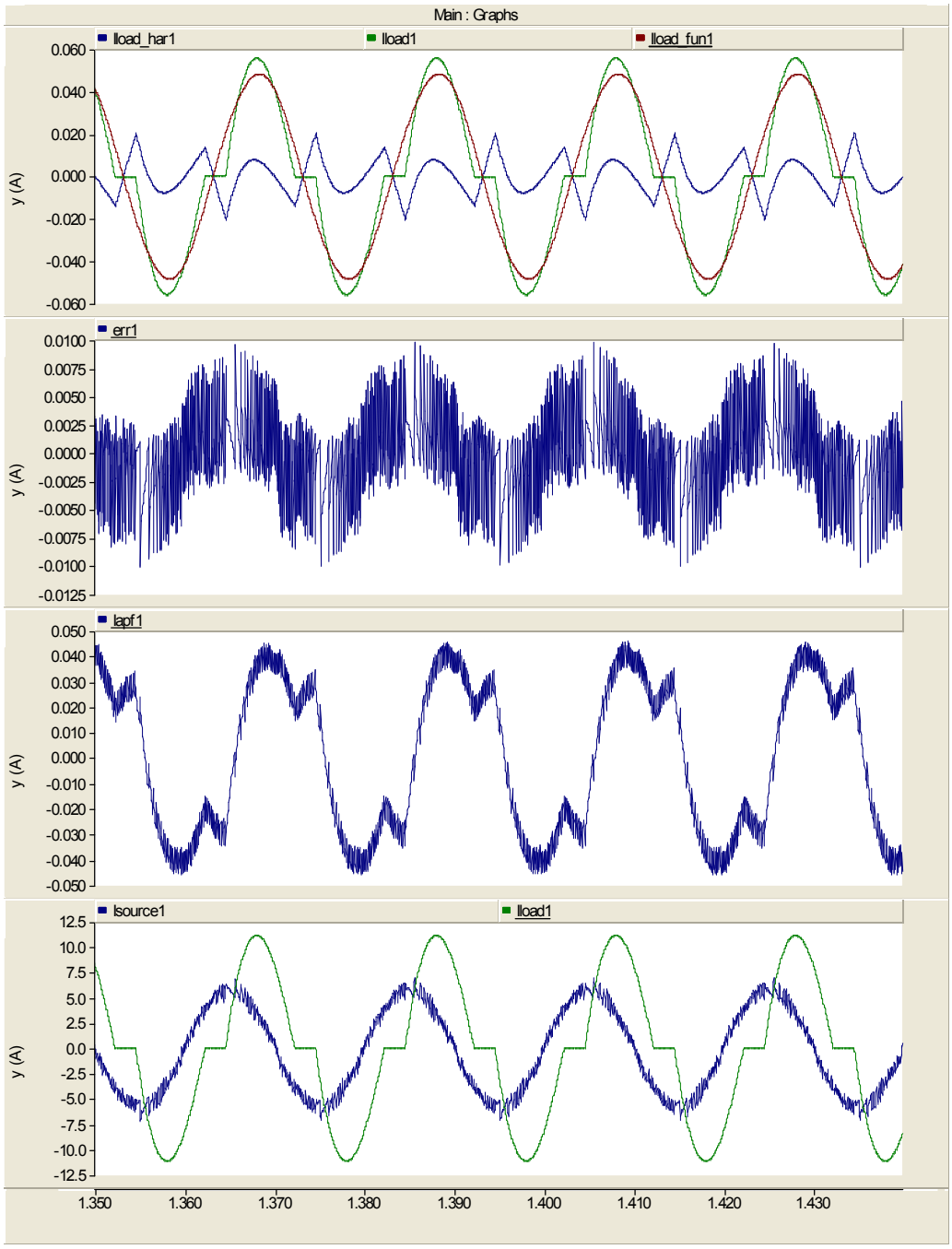


Figure 8.17.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

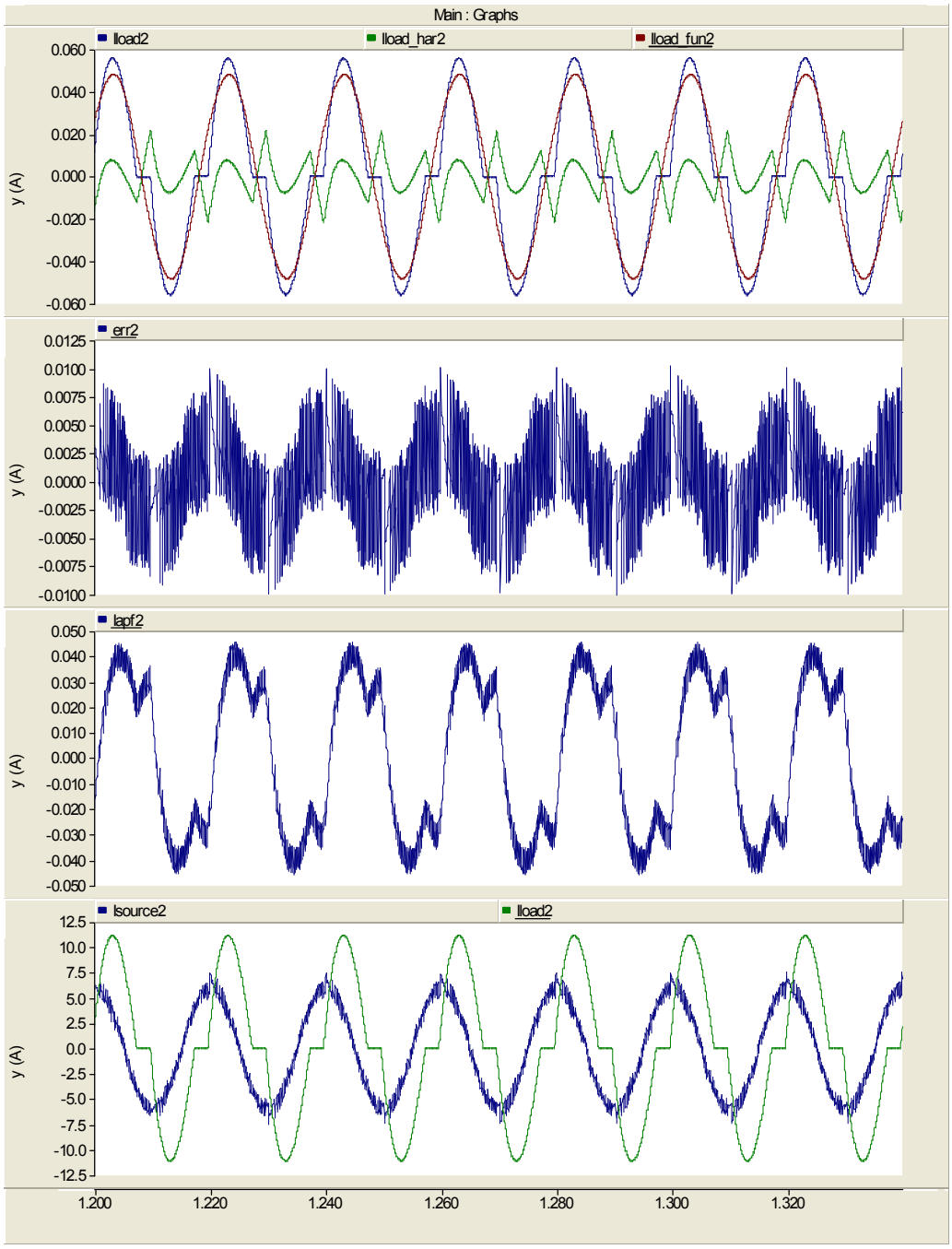


Figure 8.18.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

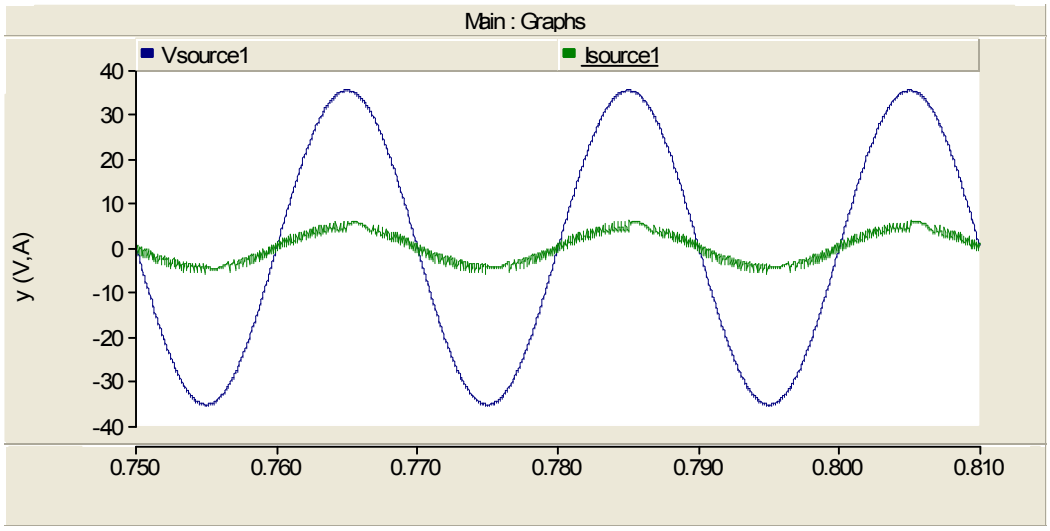


Figure 8.19.Compansated reactive power , voltage and current signal

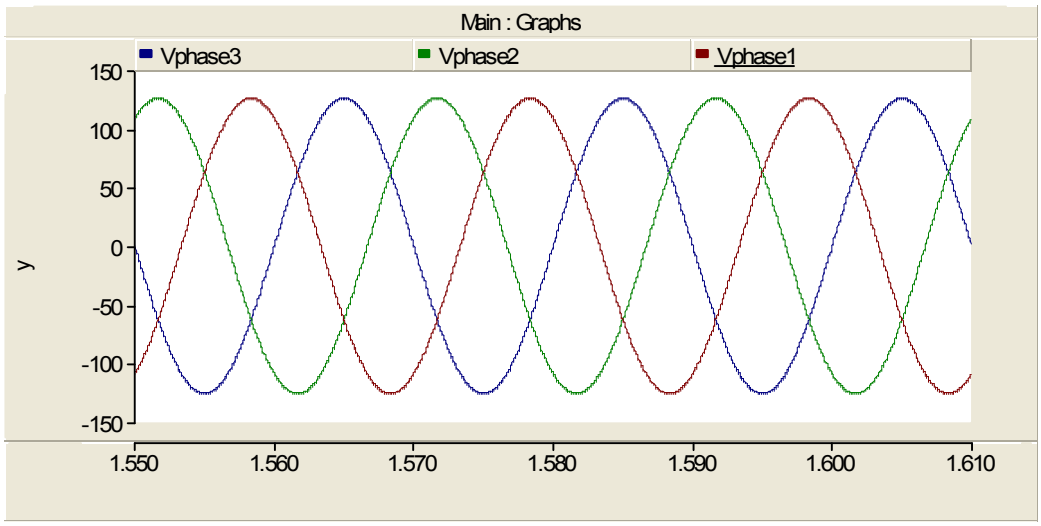


Figure 8.20.The voltage characteristic of utility network

8.2.Case 2

8.2.1.Case 2 –a

The graph of THD at 60^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation .

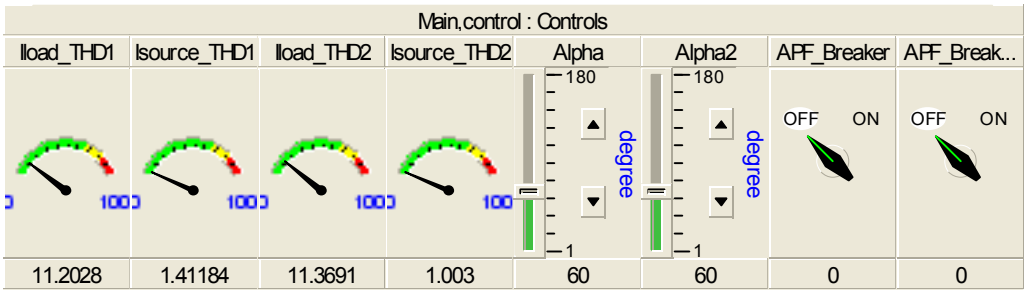


Figure 8.21.The THD levels on both sides of OHL

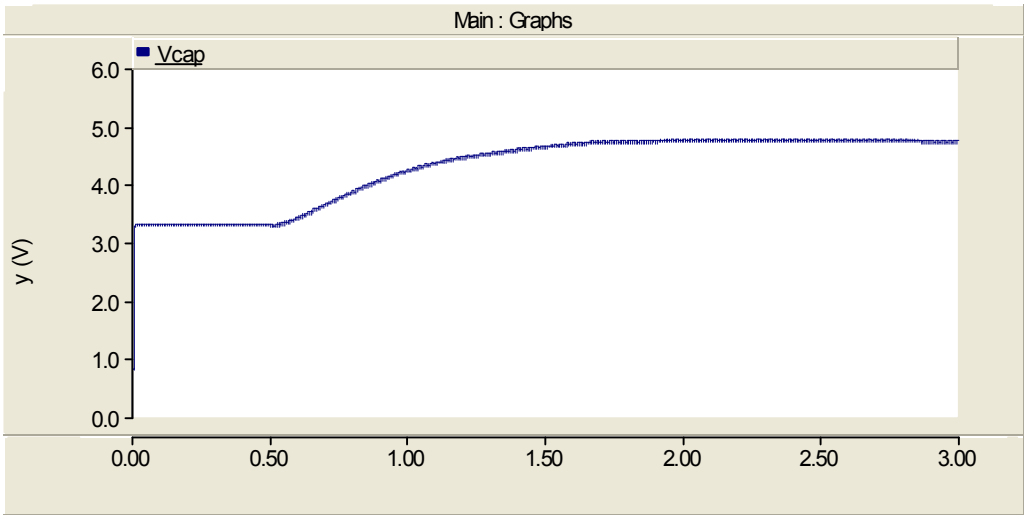


Figure 8.22.The DC link capacitor voltage characteristic

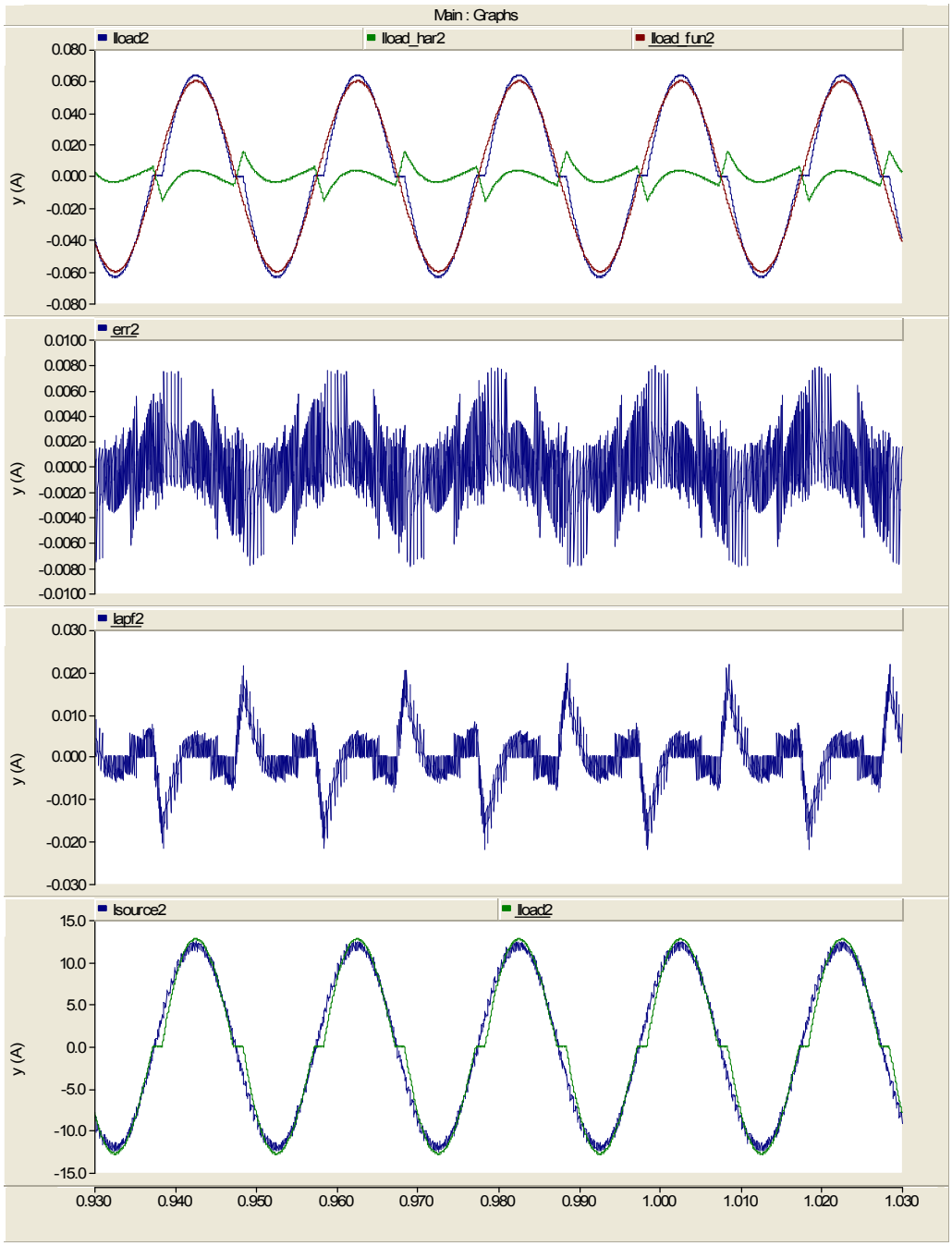


Figure 8.23.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

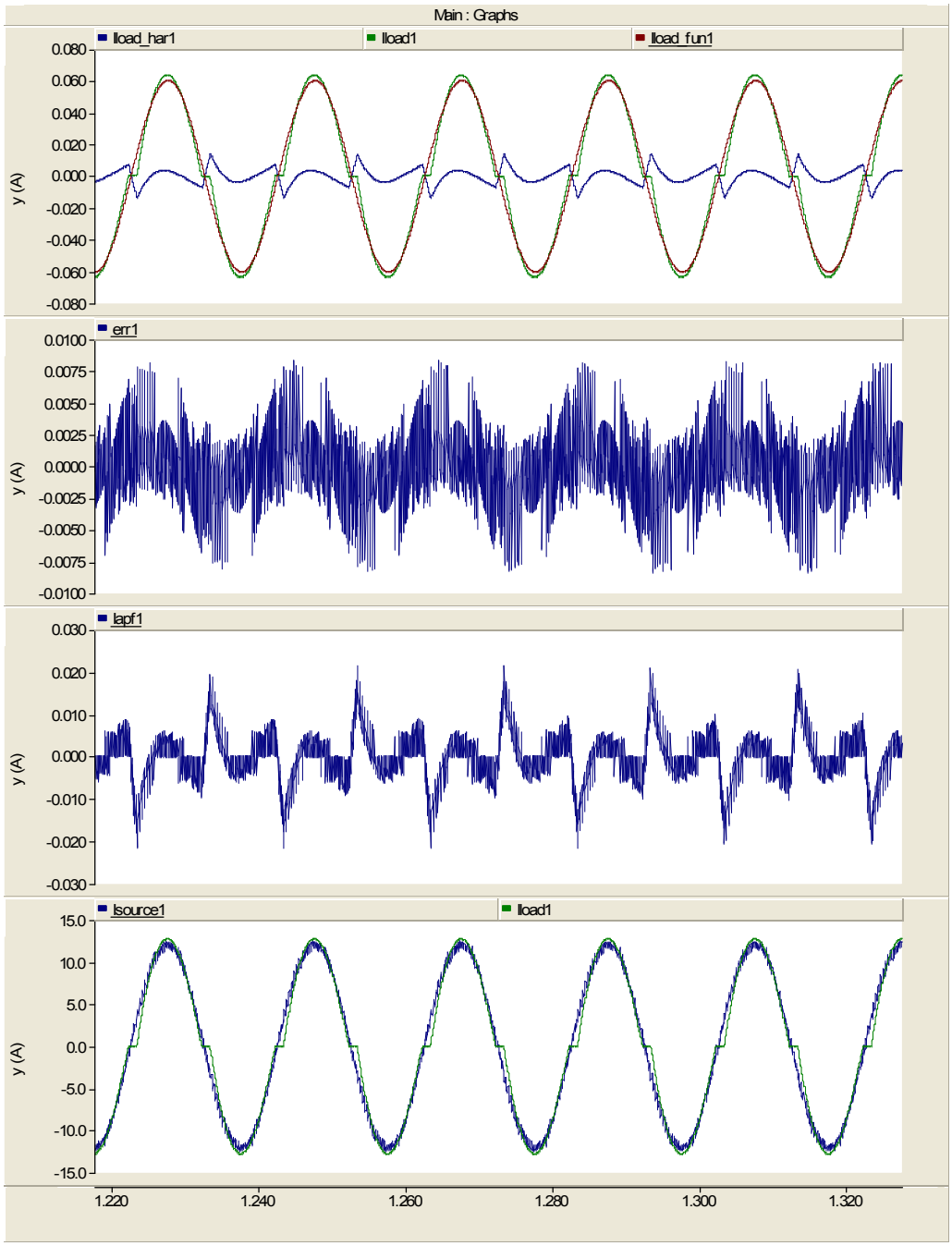


Figure 8.24.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

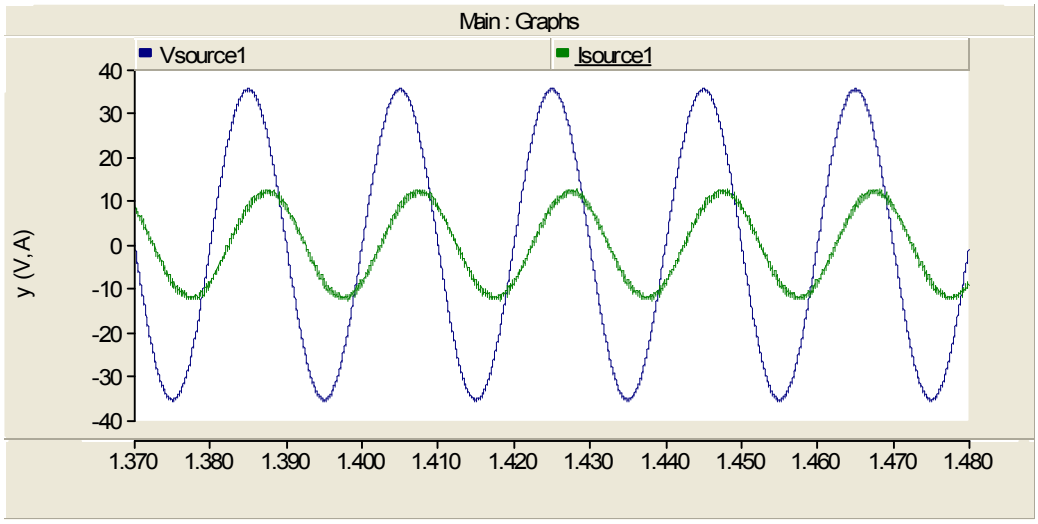


Figure 8.25.The phase difference between voltage and current (lagging) due to reactive power

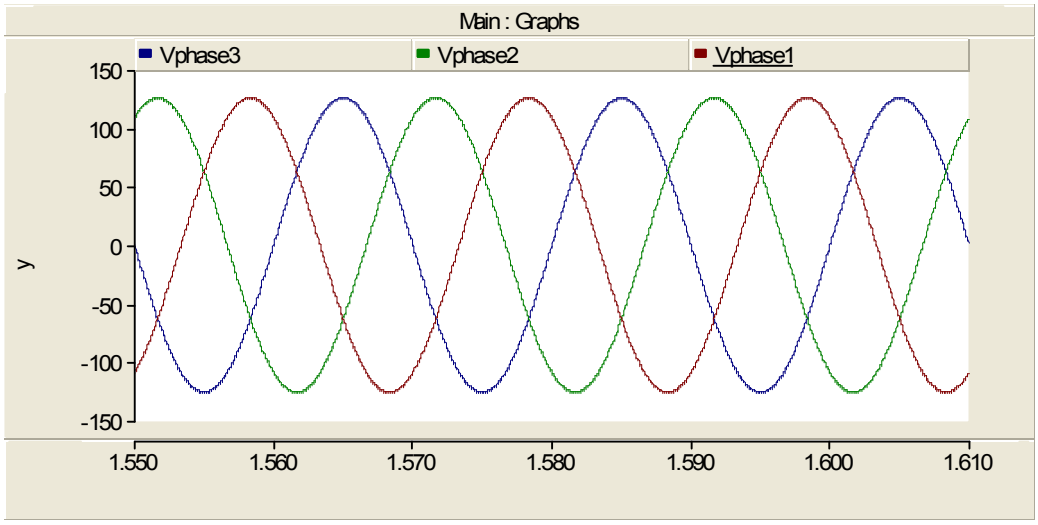


Figure 8.26.The voltage characteristic of utility network

8.2.2.Case 2 –b

The graph of THD at 60^0 firing angle of vehicle converter. The line inductor is adjusted 0.008 H. Without reactive compensation .

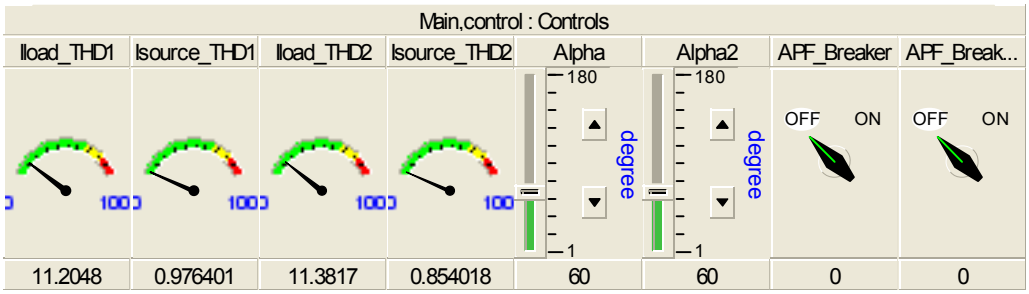


Figure 8.27.The THD levels on both sides of OHL

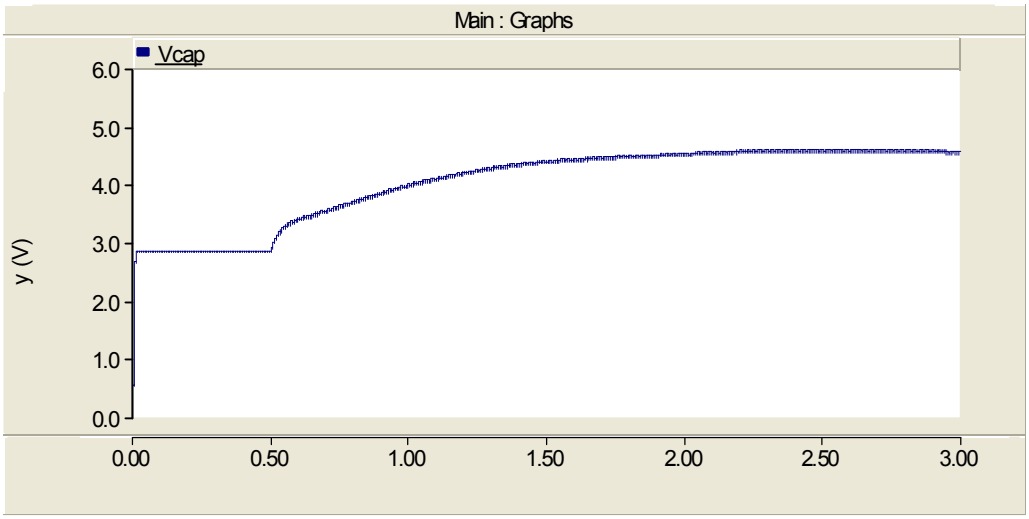


Figure 8.28. The DC link capacitor voltage characteristic

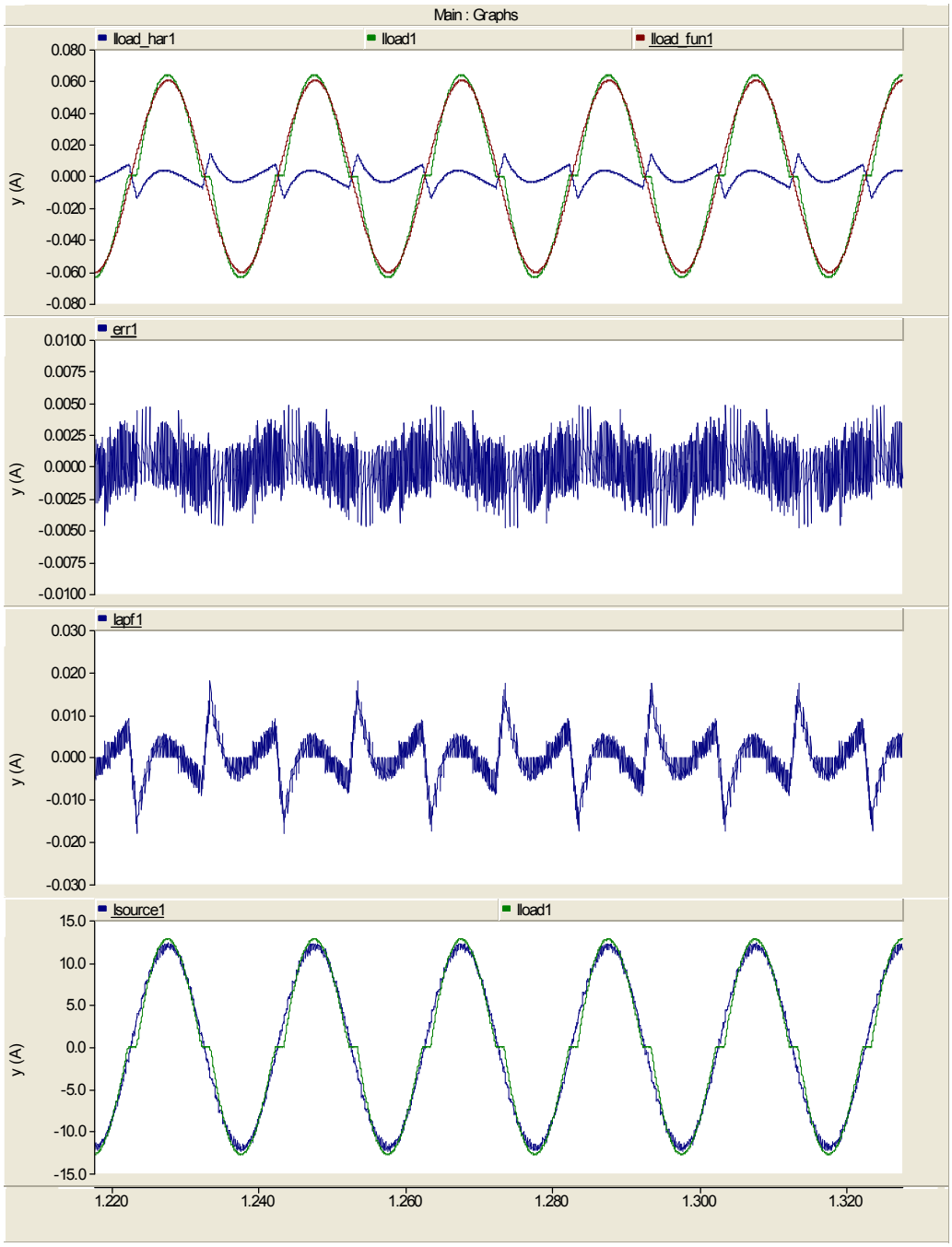


Figure 8.29.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

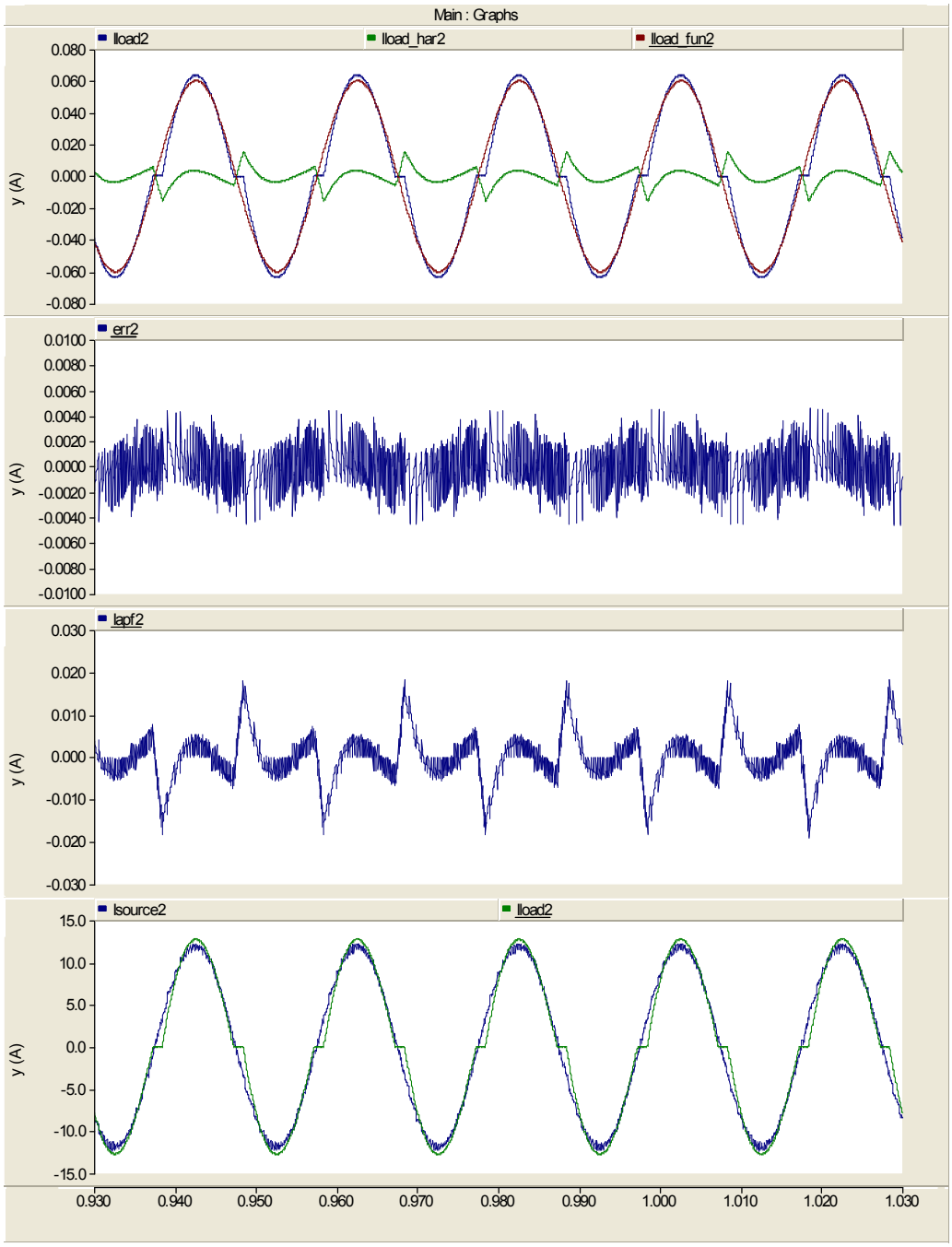


Figure 8.30.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

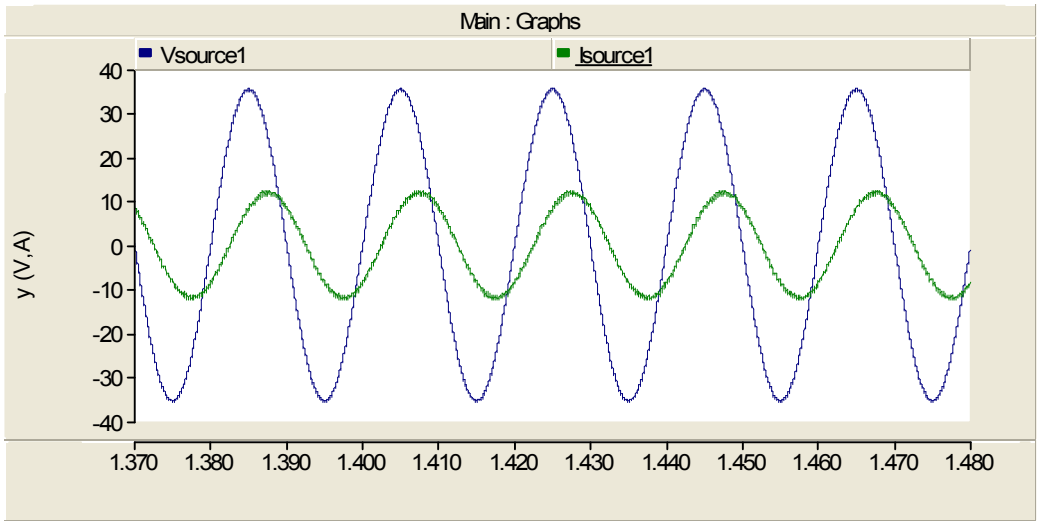


Figure 8.31.The phase difference between voltage and current (lagging) due to reactive power

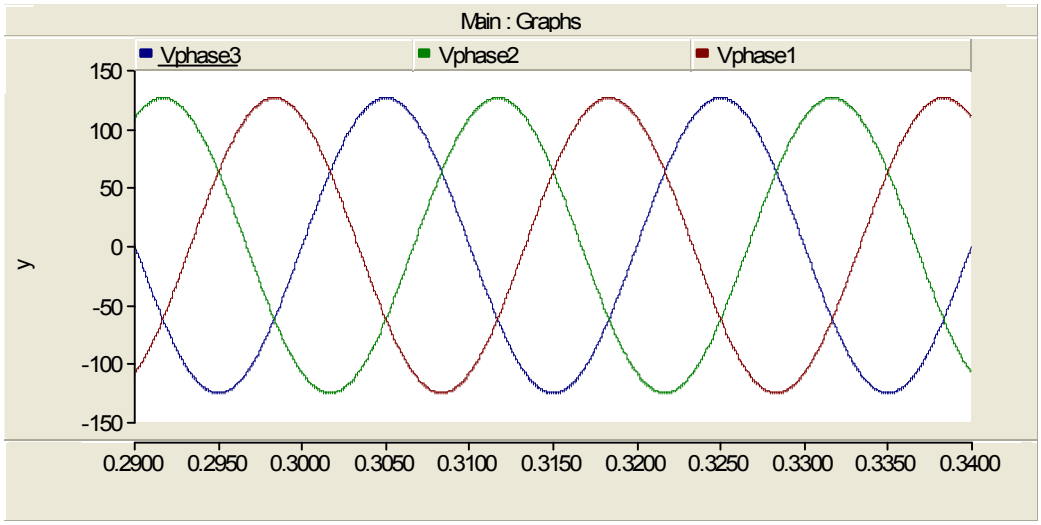


Figure 8.32.The voltage characteristic of utility network

8.2.3.Case 2 –c

The graph of THD at 60^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation .

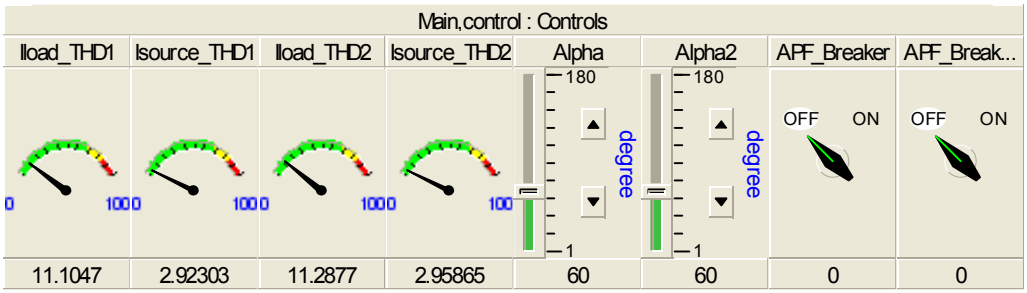


Figure 8.33.The THD levels on both sides of OHL

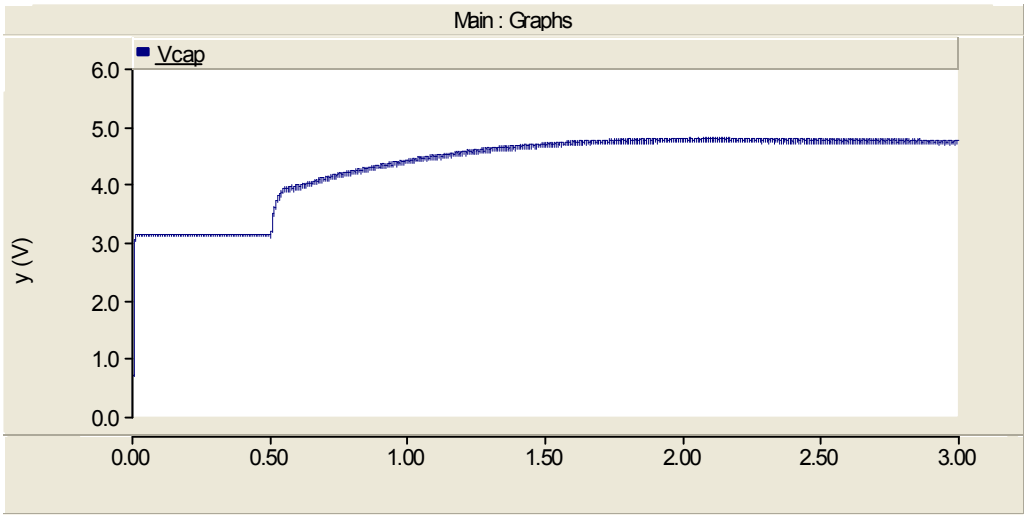


Figure 8.34.The DC link capacitor voltage characteristic

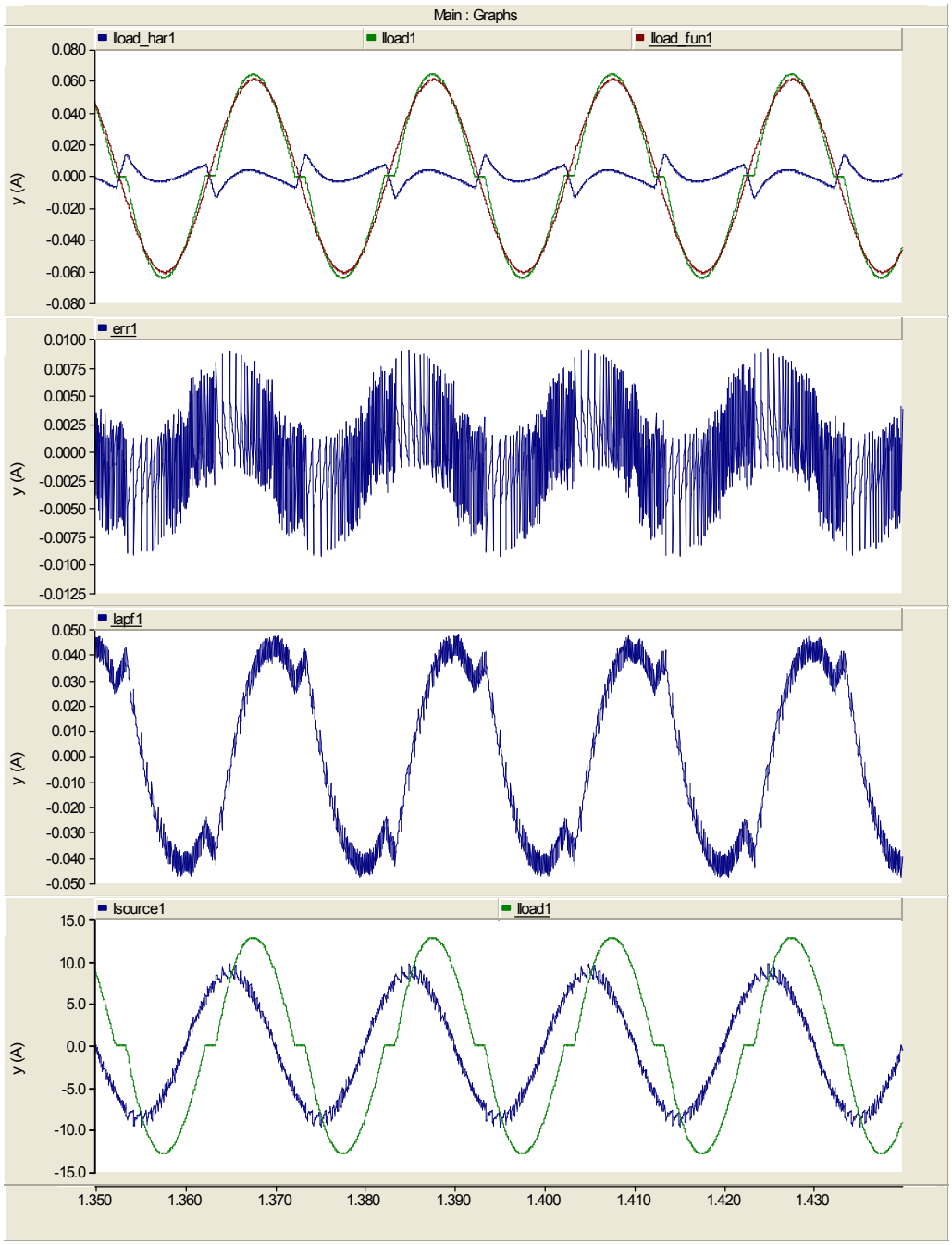


Figure 8.35.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

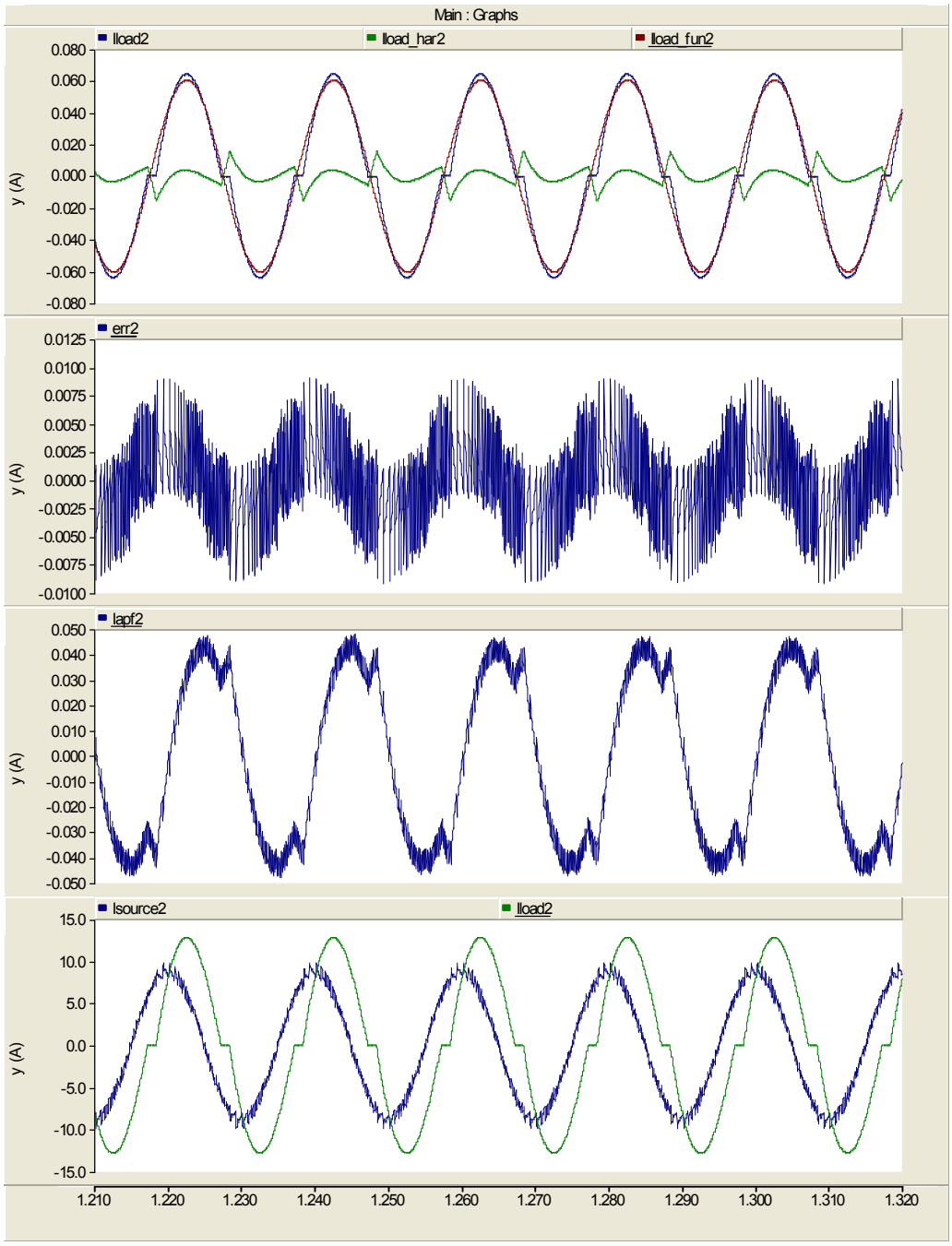


Figure 8.36.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

The scale of current signal in below graph was increased 200 times to make figure more clear to understand.

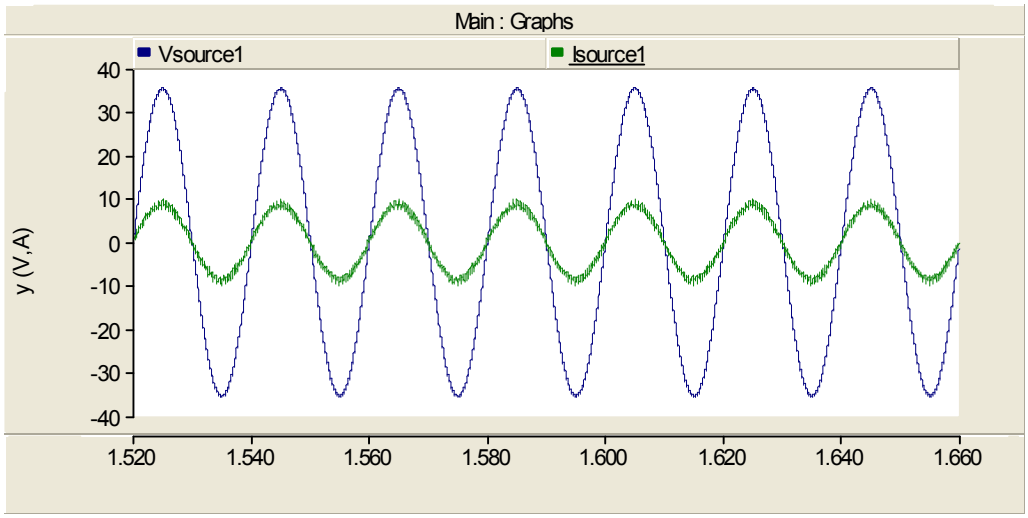


Figure 8.37.The phase difference between voltage and current (lagging) due to reactive power

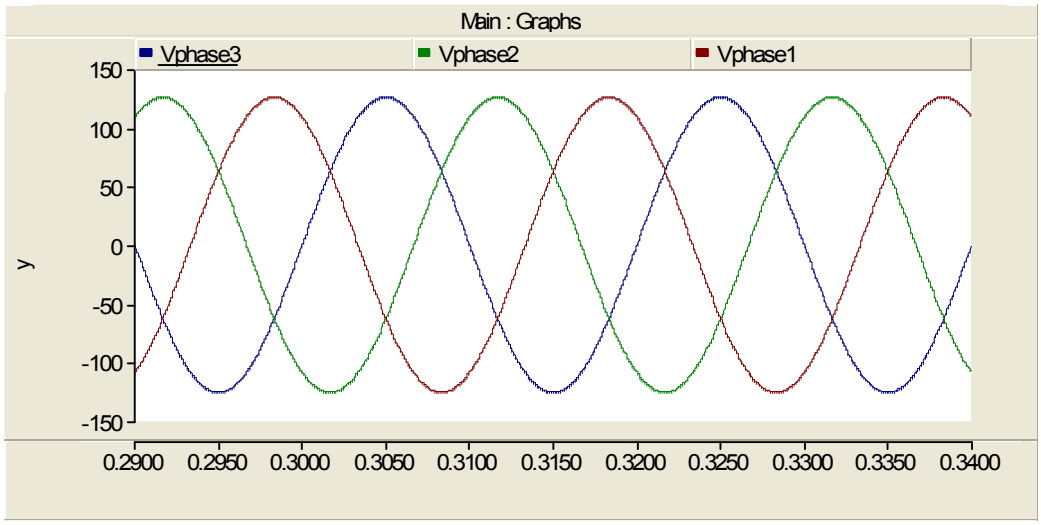


Figure 8.38.The voltage characteristic of utility network

8.3.Case 3

8.3.1.Case 3 –a

The graph of THD at 30^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation .

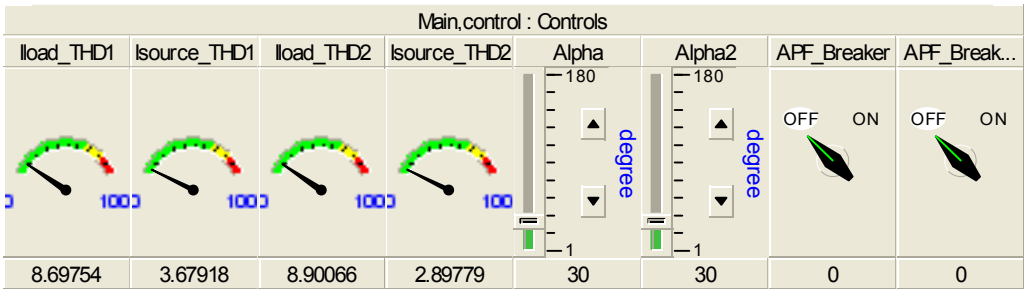


Figure 8.39.The THD levels on both sides of OHL

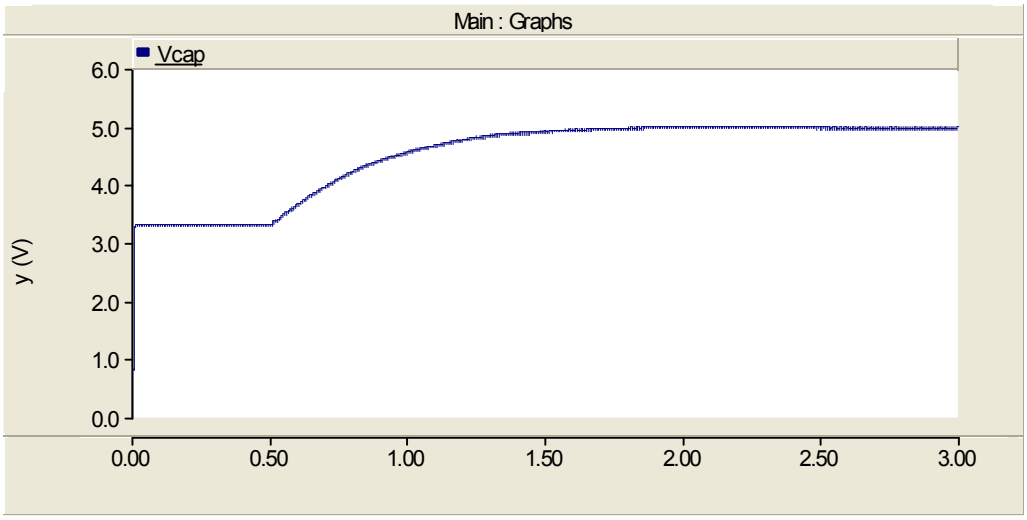


Figure 8.40.The DC link capacitor voltage characteristic

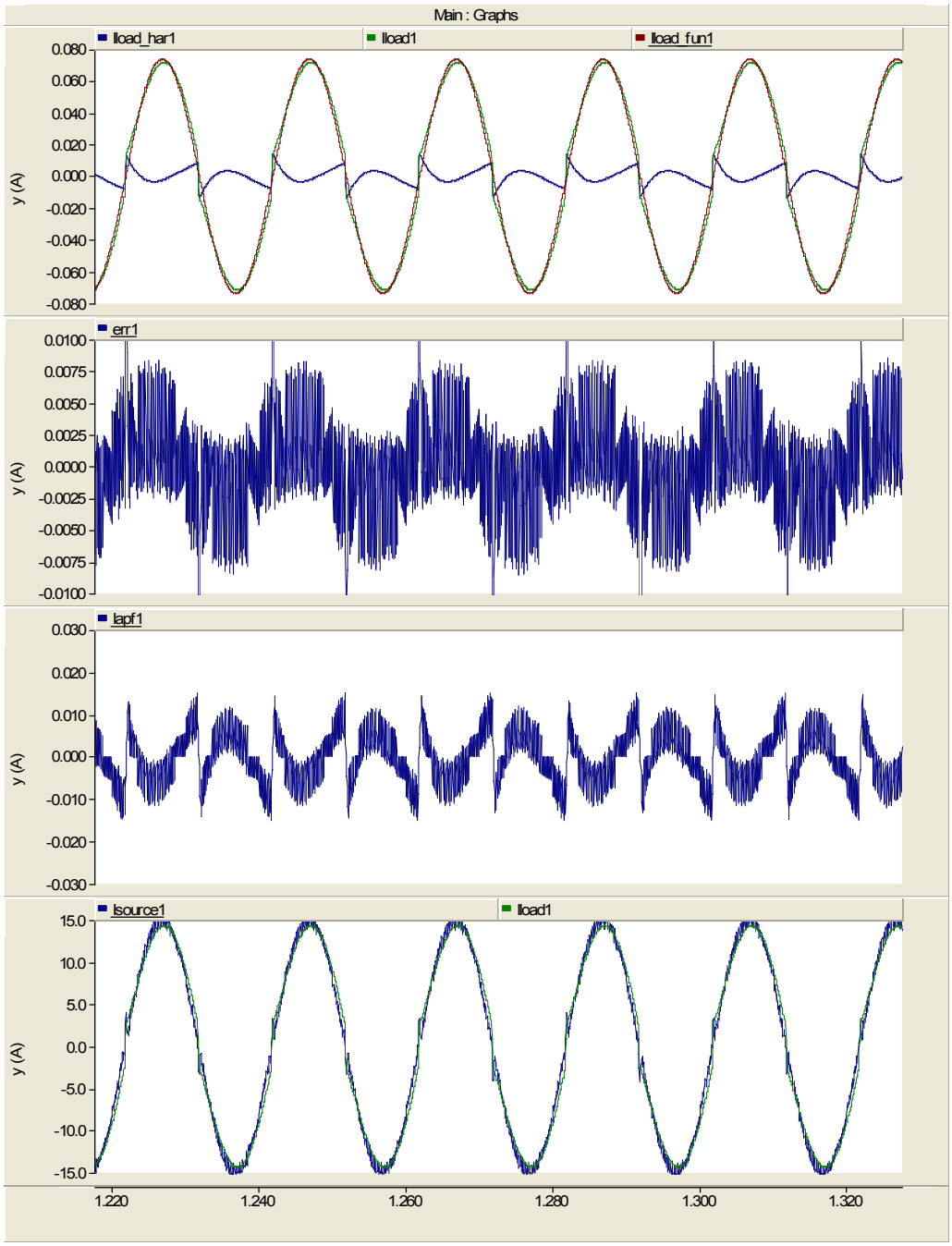


Figure 8.41.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

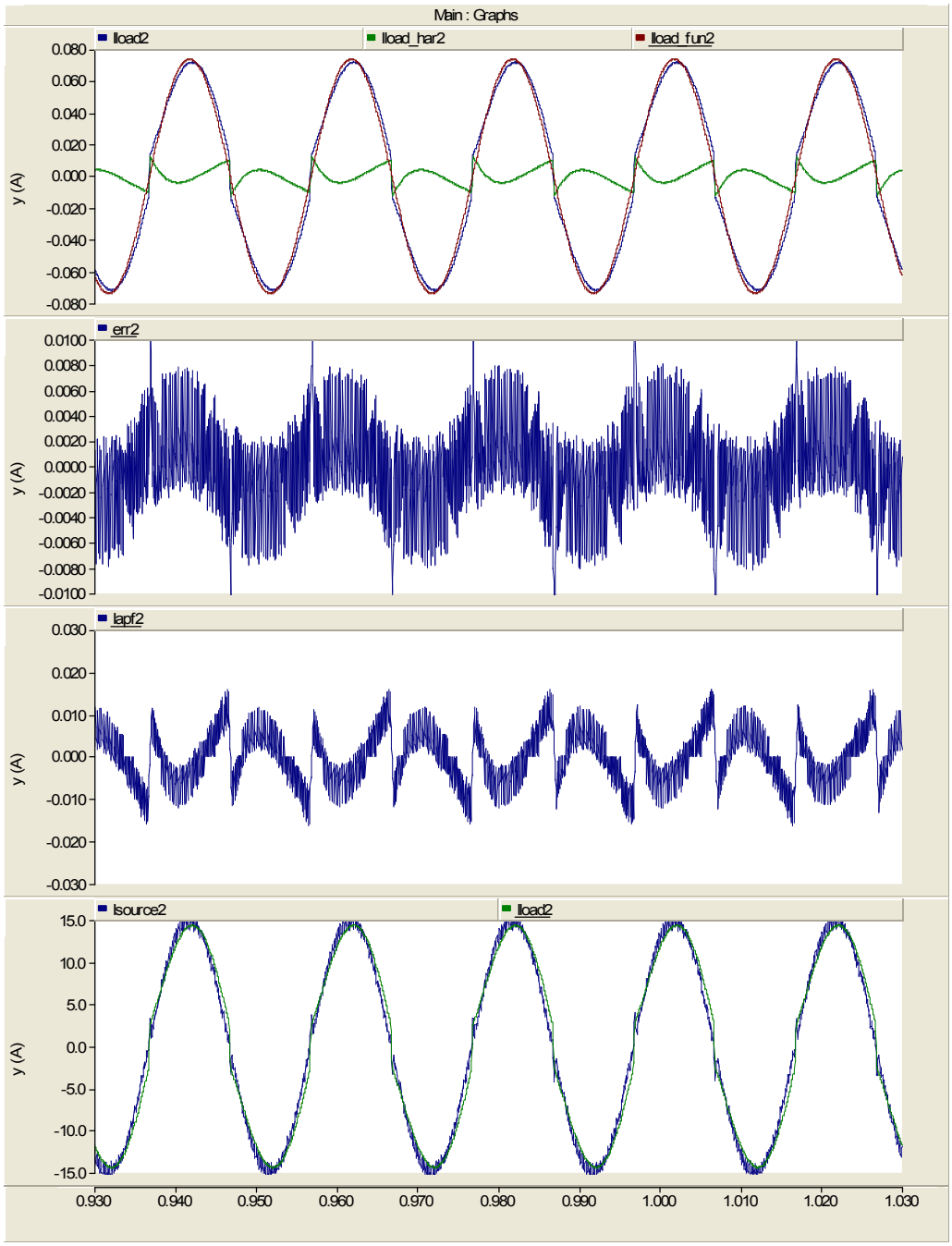


Figure 8.42.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

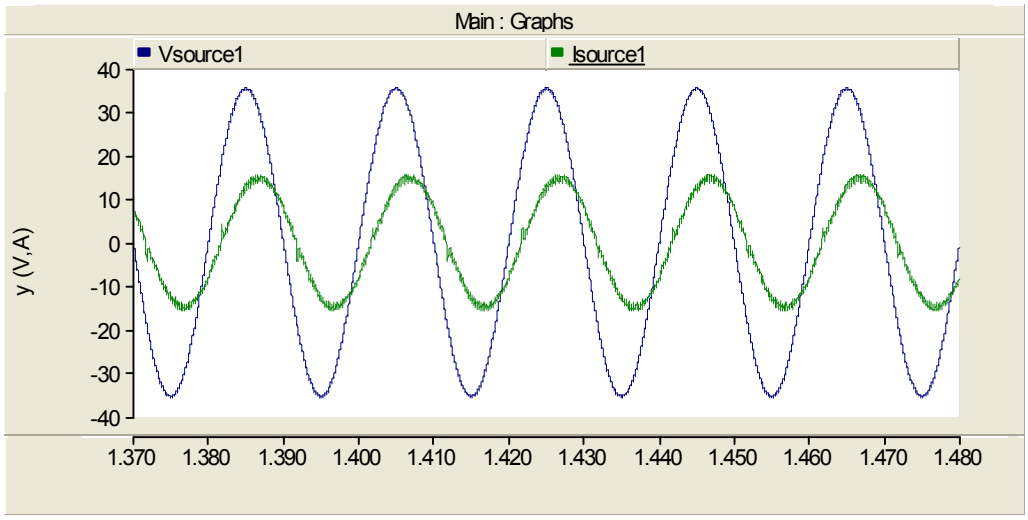


Figure 8.43.The phase difference between voltage and current (lagging) due to reactive power

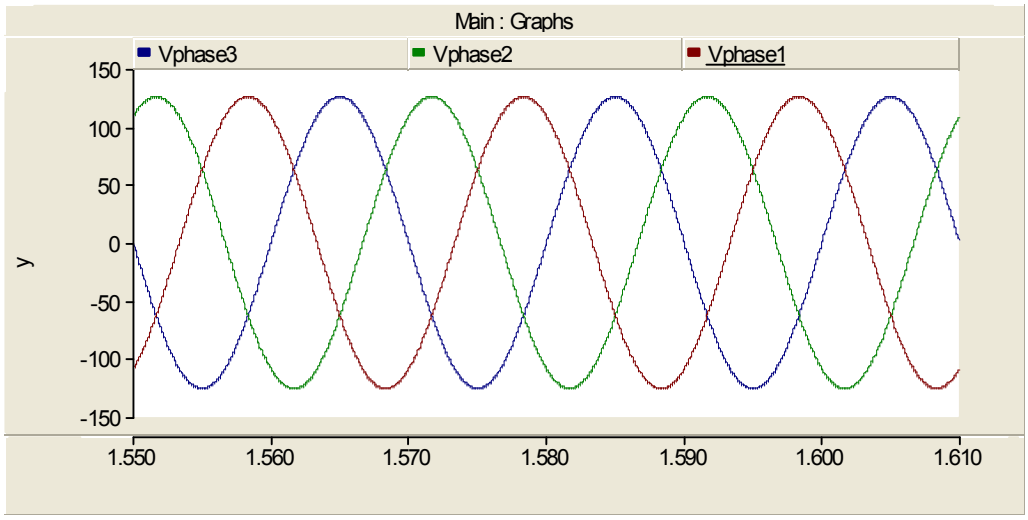


Figure 8.44.The voltage characteristic of utility network

8.3.2.Case 3 –b

The graph of THD at 30^0 firing angle of vehicle converter. The line inductor is adjusted 0.008 H. Without reactive compensation .

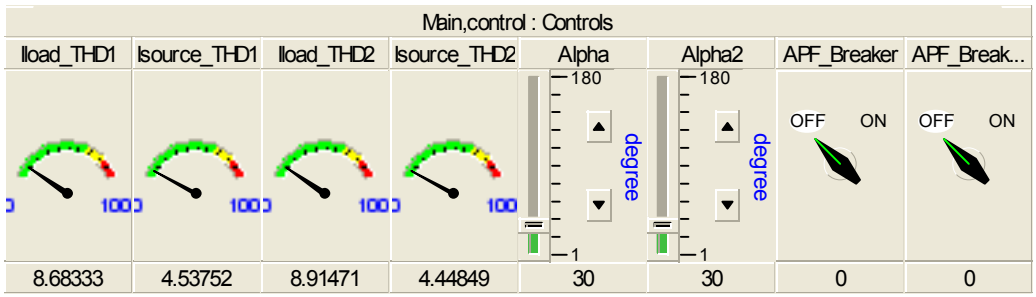


Figure 8.45.The THD levels on both sides of OHL

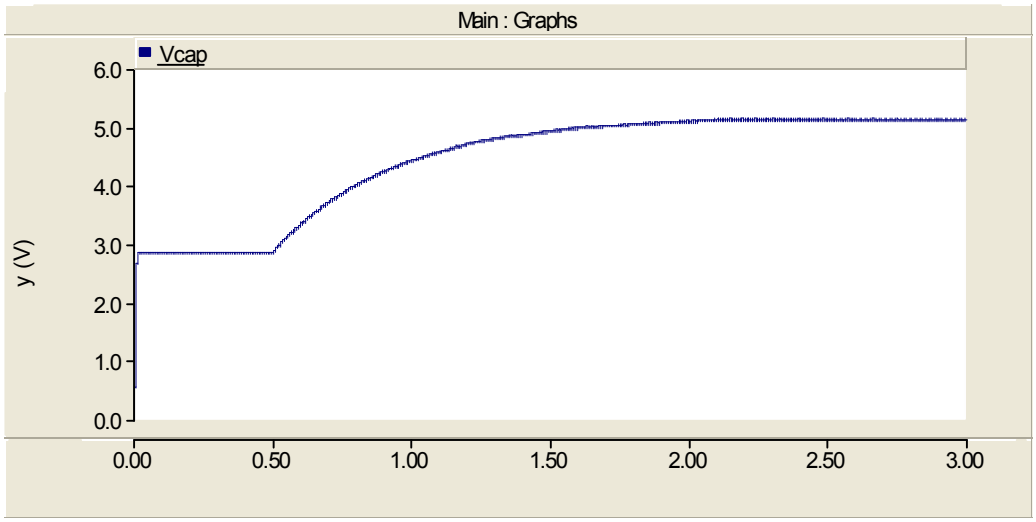


Figure 8.46.The DC link capacitor voltage characteristic

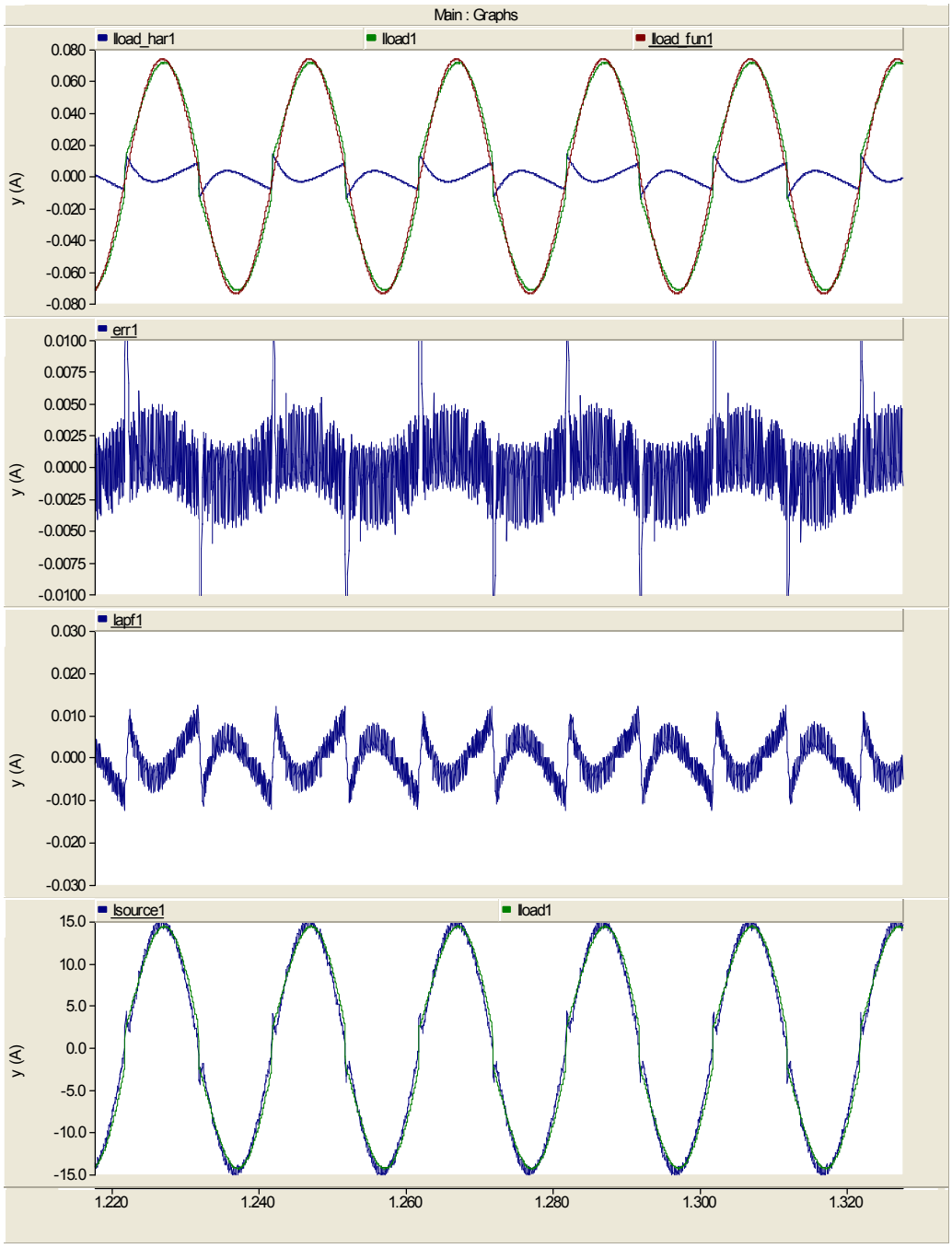


Figure 8.47.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

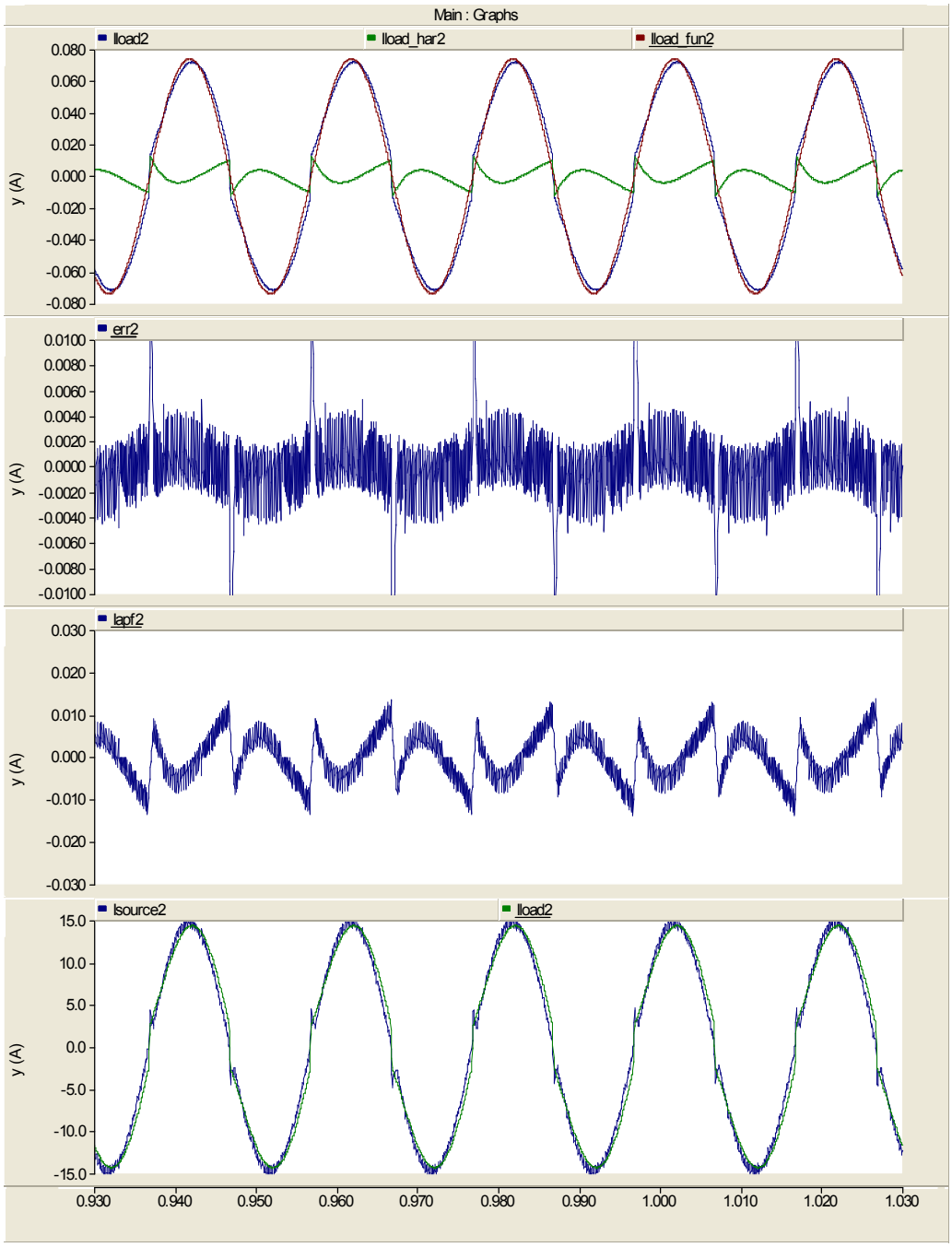


Figure 8.48.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

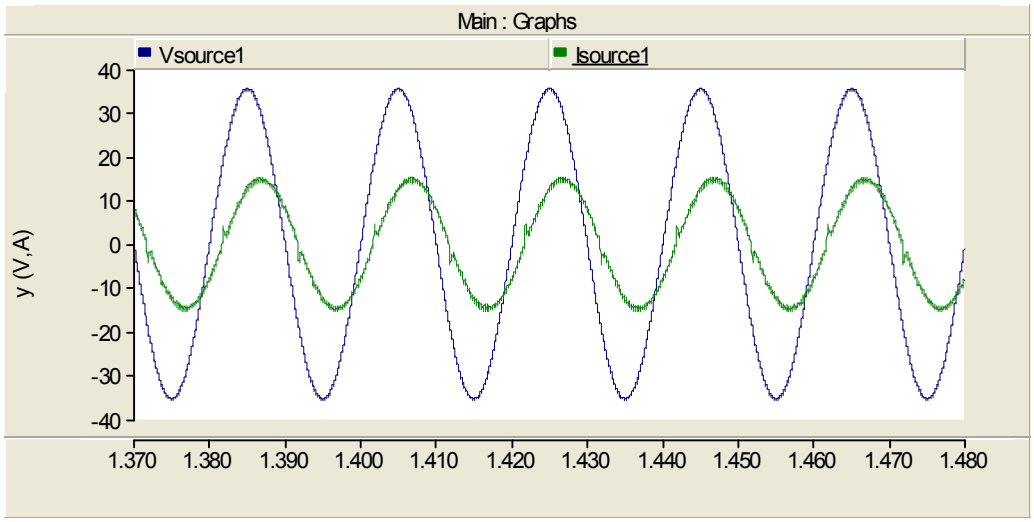


Figure 8.49.The phase difference between voltage and current (lagging) due to reactive power

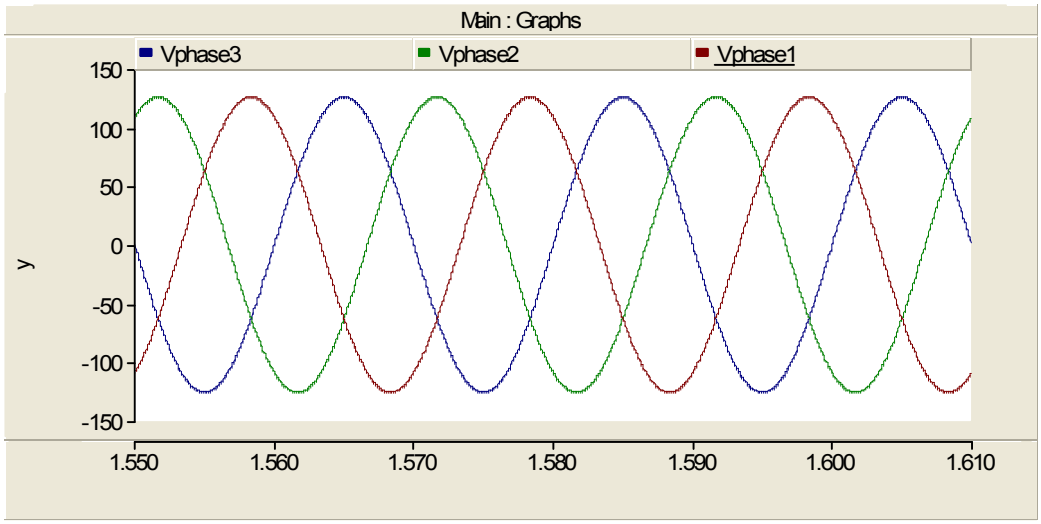


Figure 8.50.The voltage characteristic of utility network

8.3.3.Case 3 –c

The graph of THD at 30^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation .

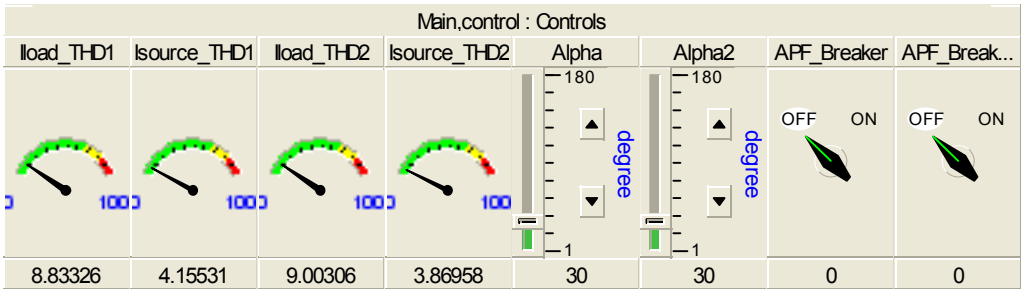


Figure 8.51.The THD levels on both sides of OHL

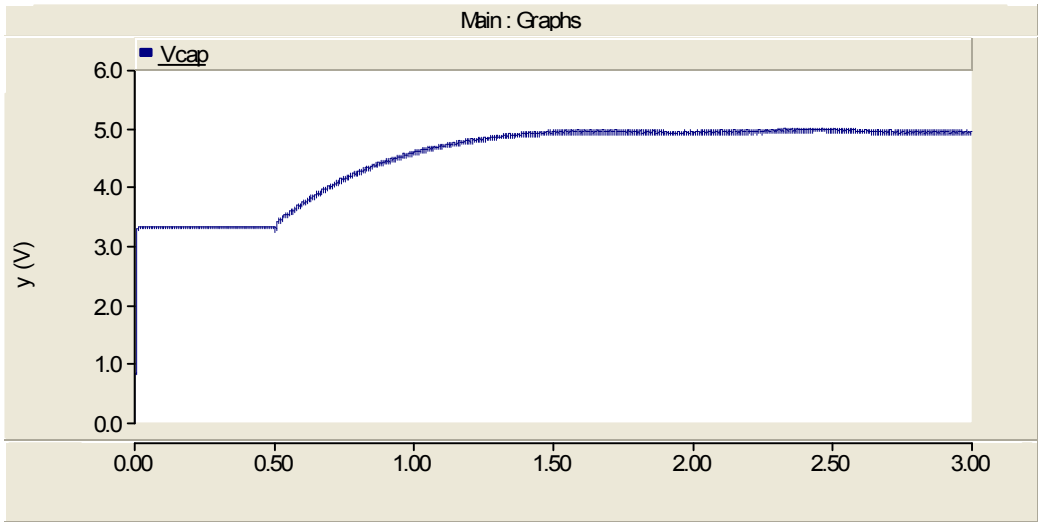


Figure 8.52.The DC link capacitor voltage characteristic

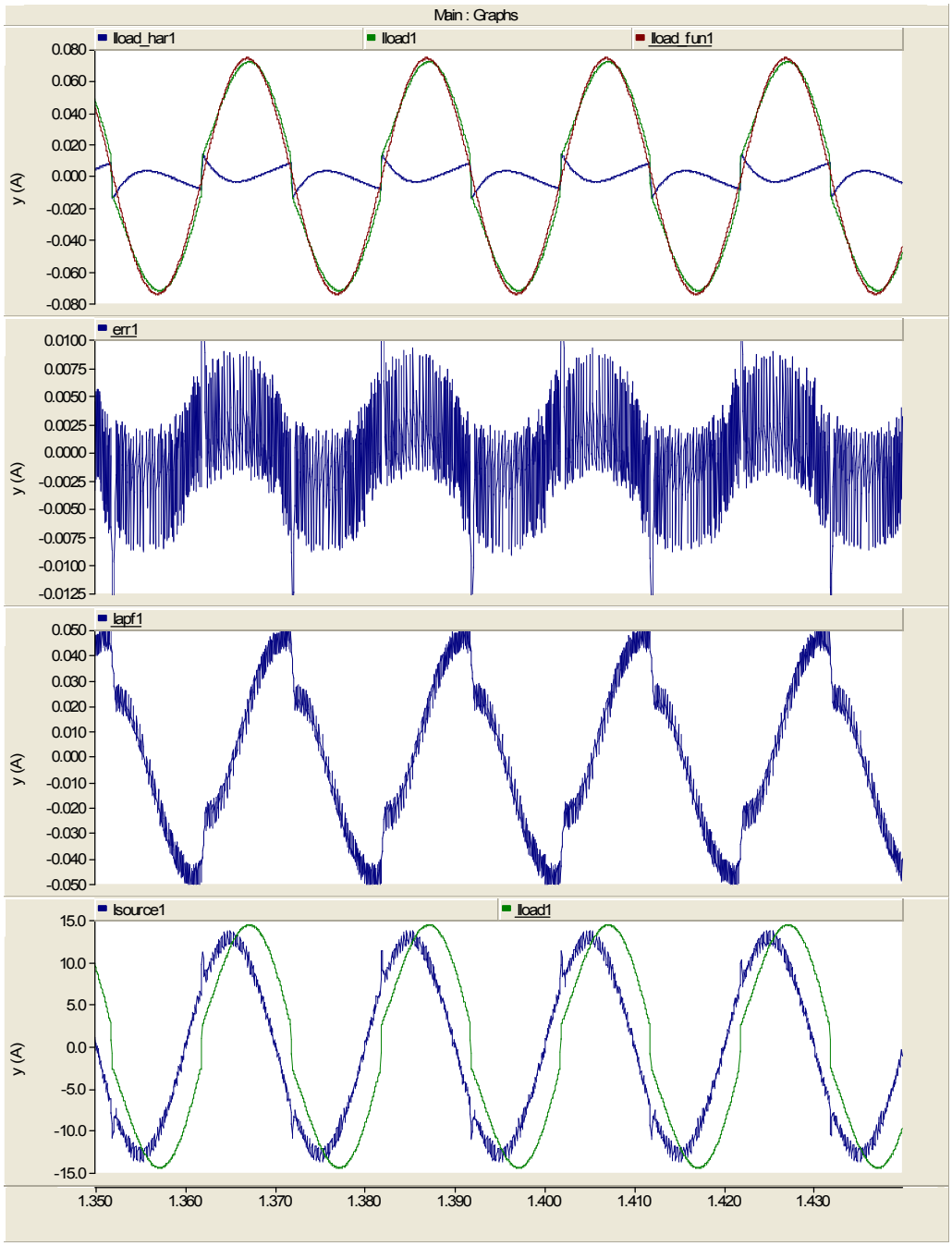


Figure 8.53.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

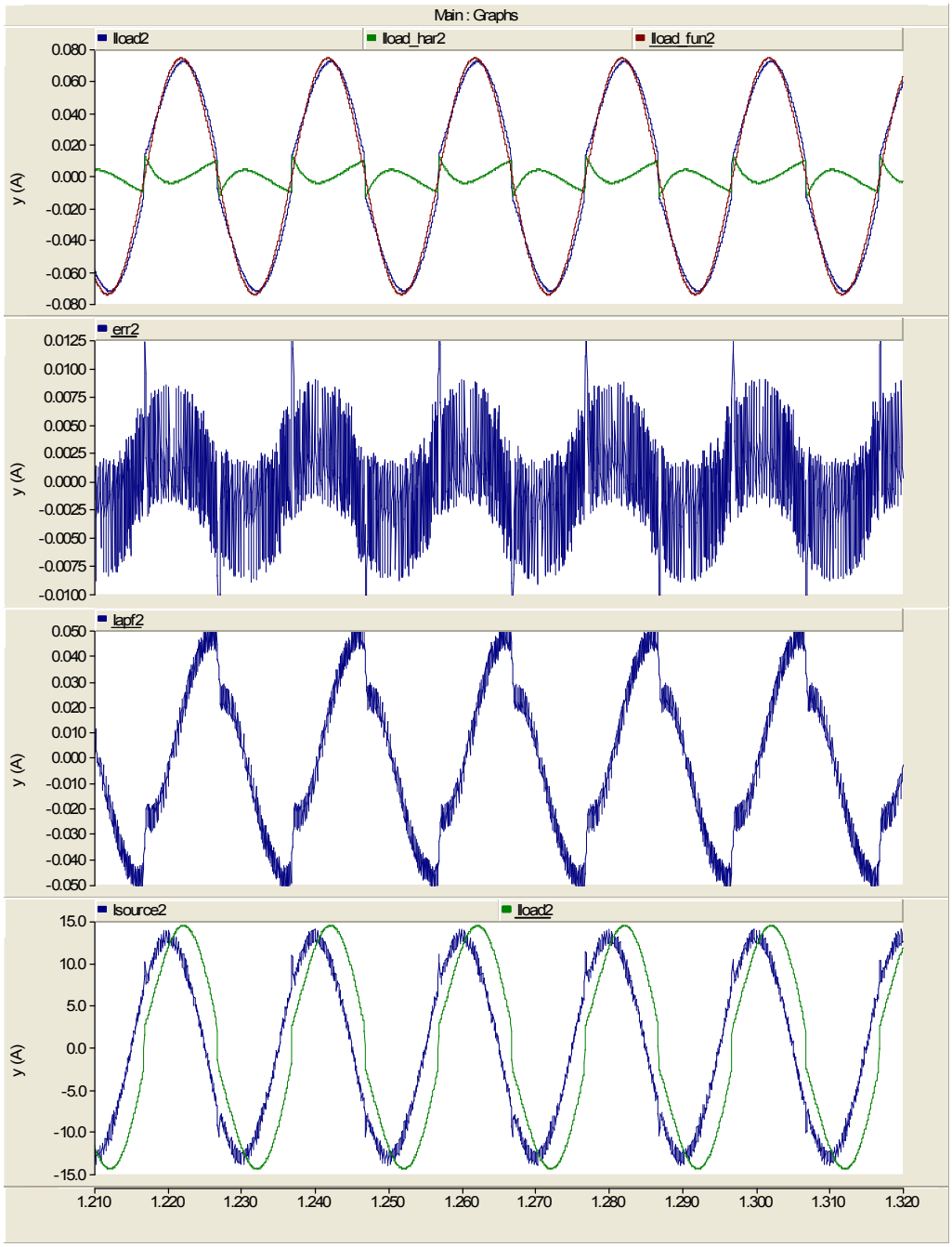


Figure 8.54.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

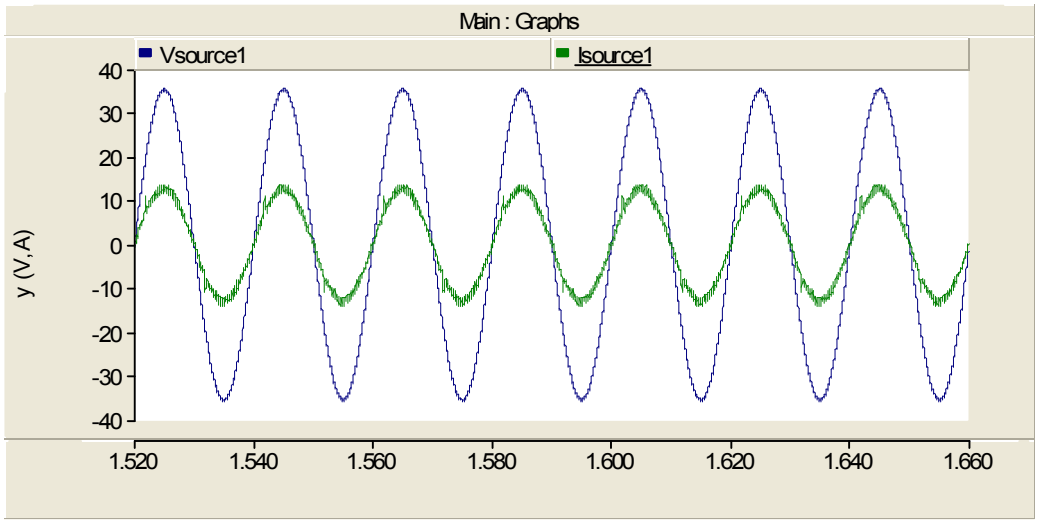


Figure 8.55.The phase difference between voltage and current (lagging) due to reactive power

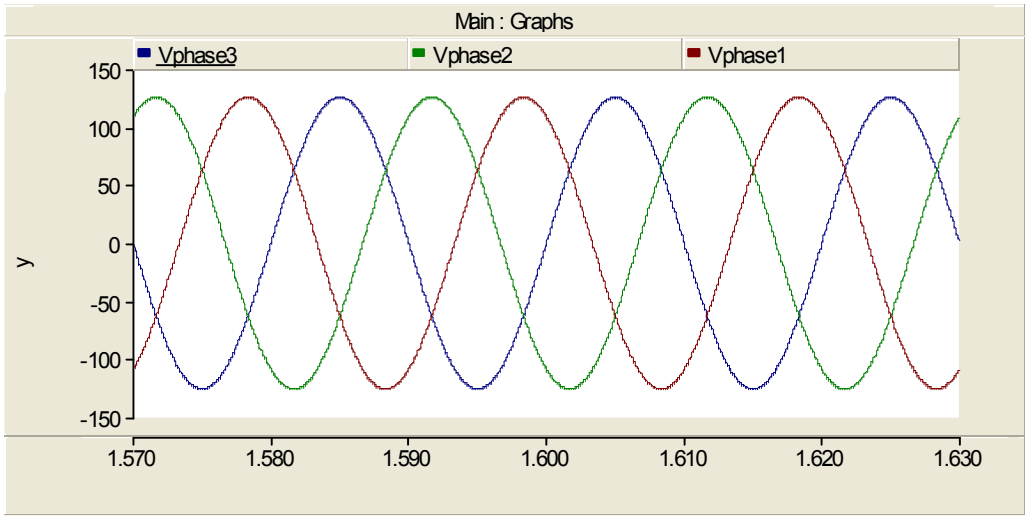


Figure 8.56.The voltage characteristic of utility network

8.4.Case 4

8.4.1.Case 4 –a

The graph of THD at 0^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation .

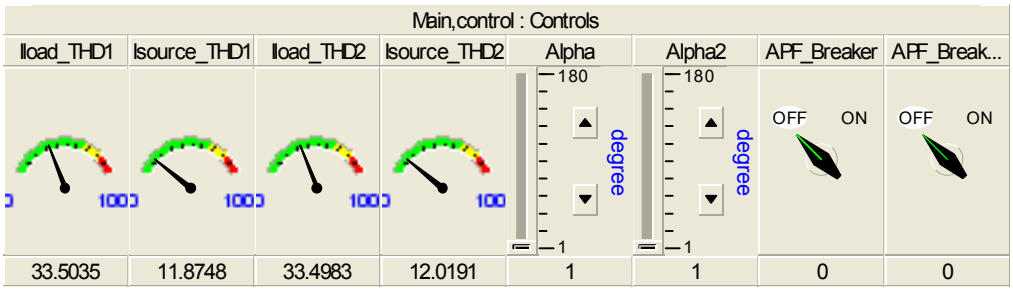


Figure 8.57. The THD levels on both sides of OHL

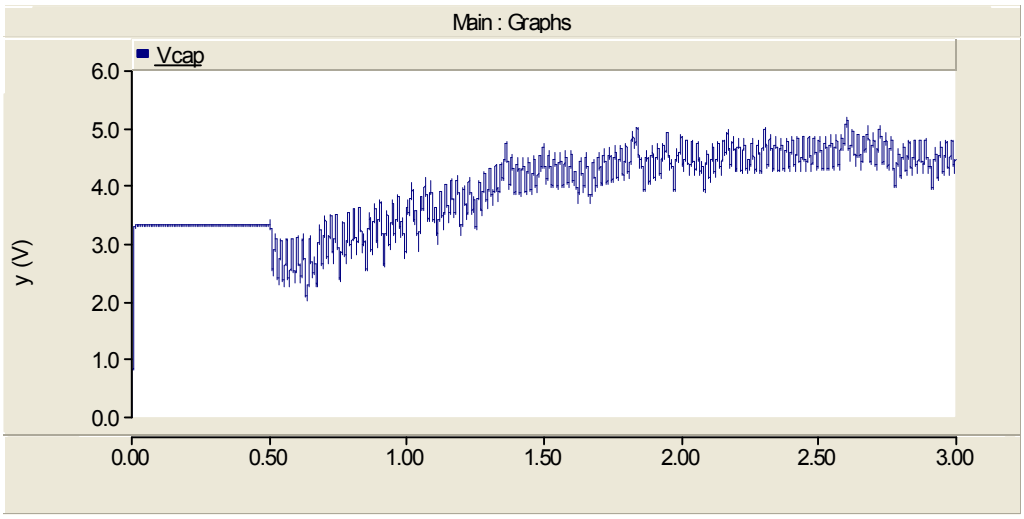


Figure 8.58.The DC link capacitor voltage characteristic

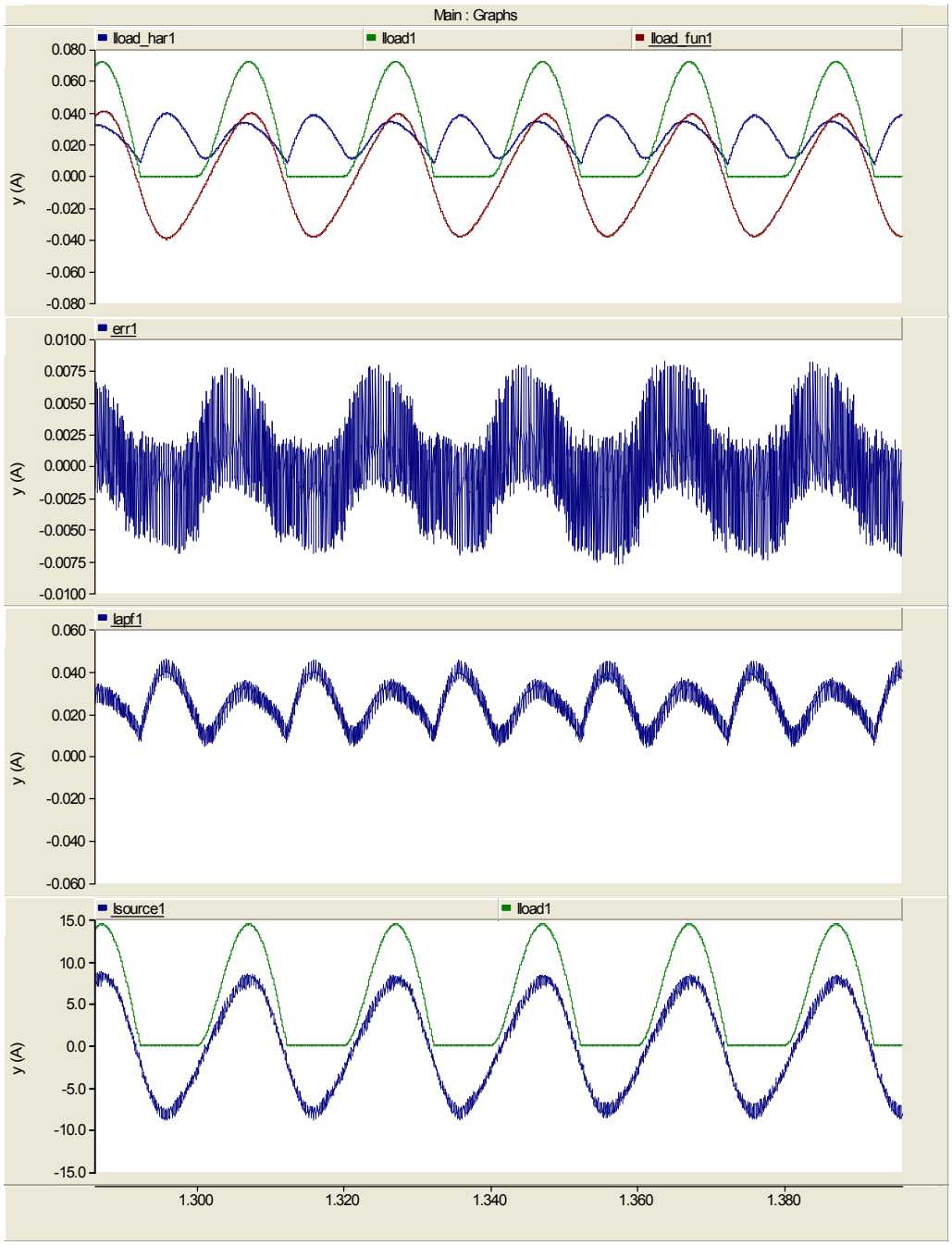


Figure 8.59.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

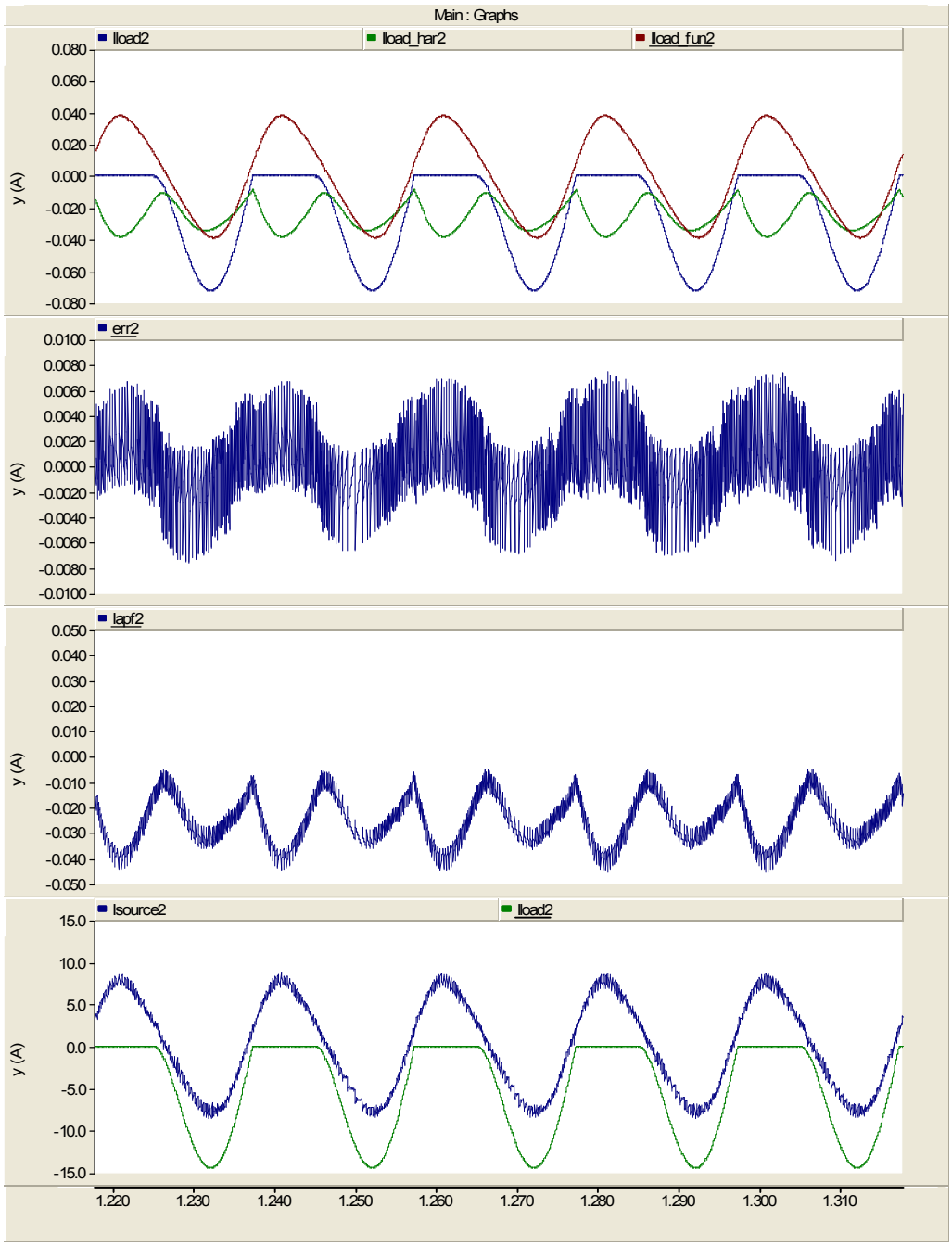


Figure 8.60.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

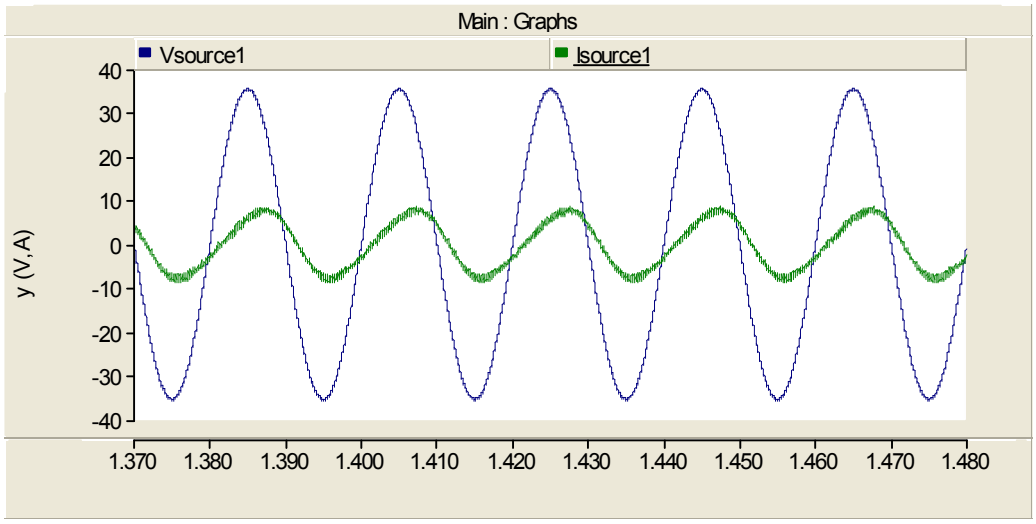


Figure 8.61.The phase difference between voltage and current (lagging) due to reactive power

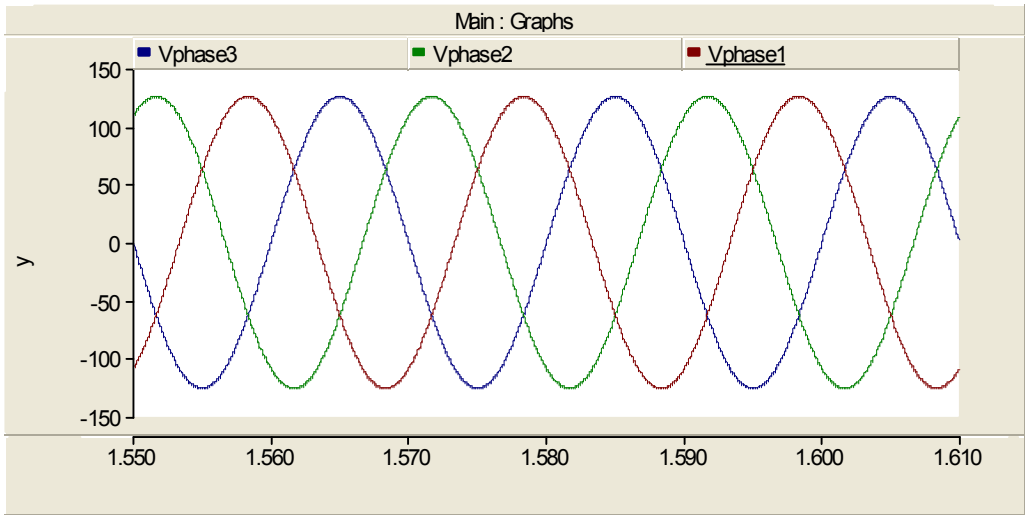


Figure 8.62.The voltage characteristic of utility network

8.4.2.Case 4 –b

The graph of THD at 0^0 firing angle of vehicle converter. The line inductor is adjusted 0.008 H. Without reactive compensation .

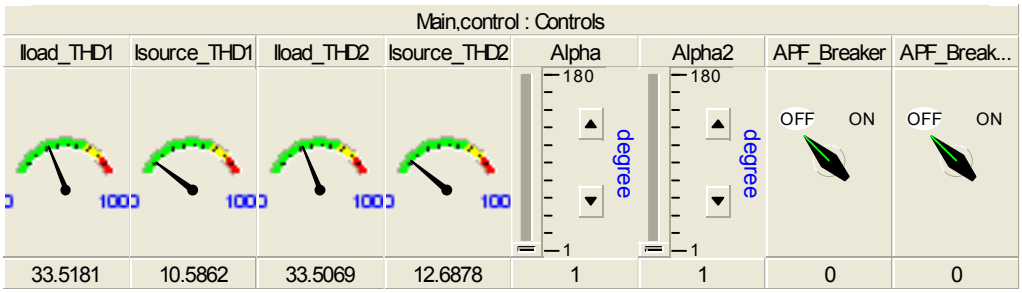


Figure 8.63.The THD levels on both sides of OHL

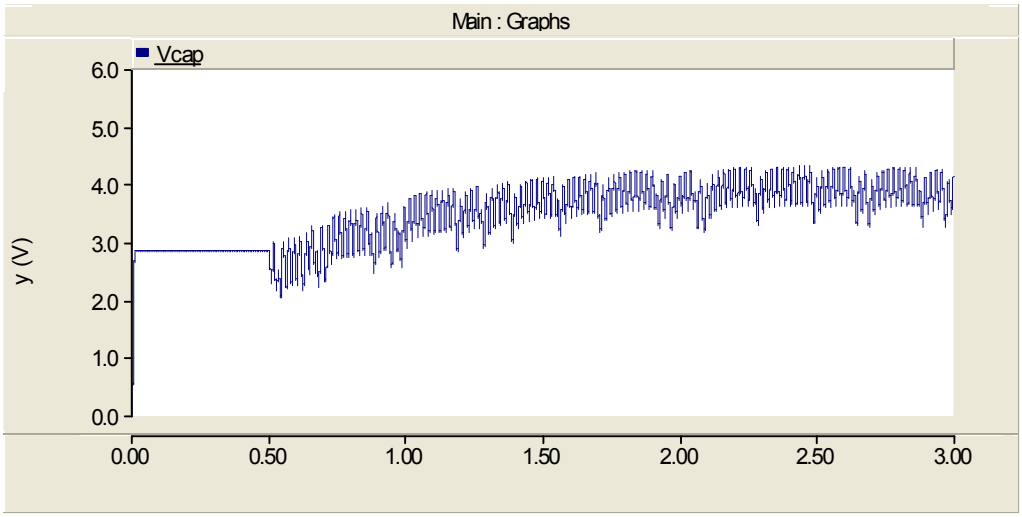


Figure 8.64.The DC link capacitor voltage characteristic

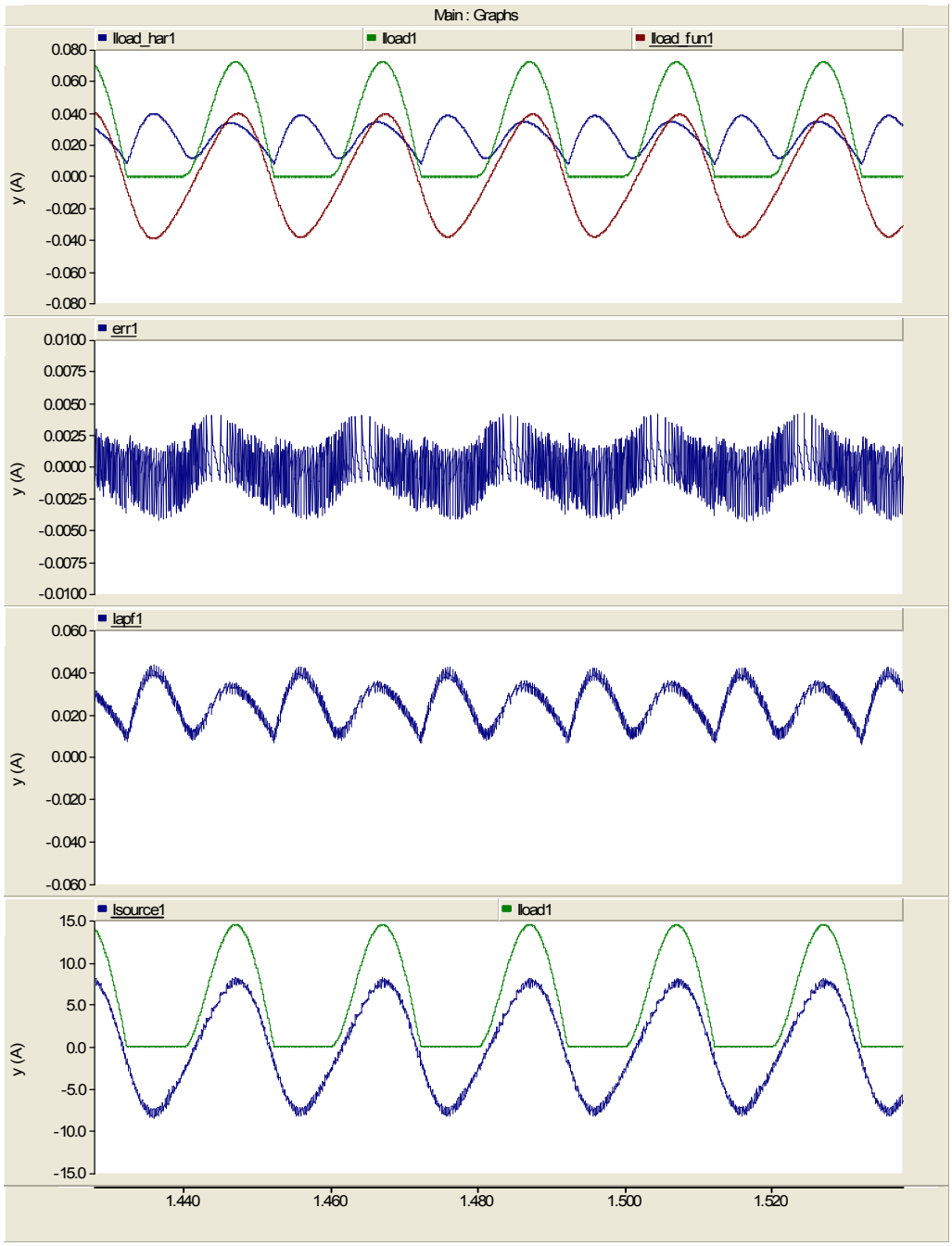


Figure 8.65.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

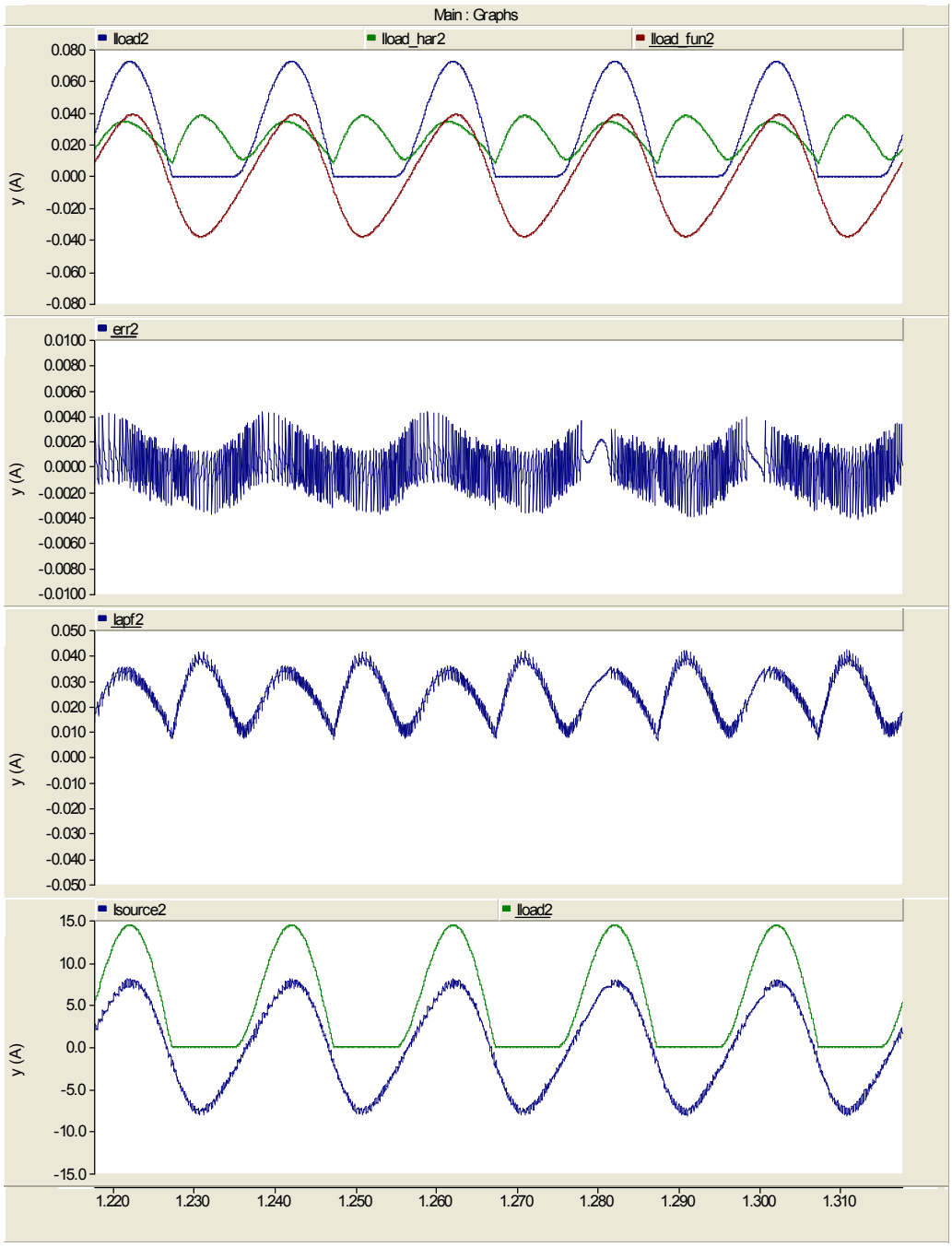


Figure 8.66.The simulation results of load 2 the current, the error signal that calculated by EPLL, harmonic signal and source signal

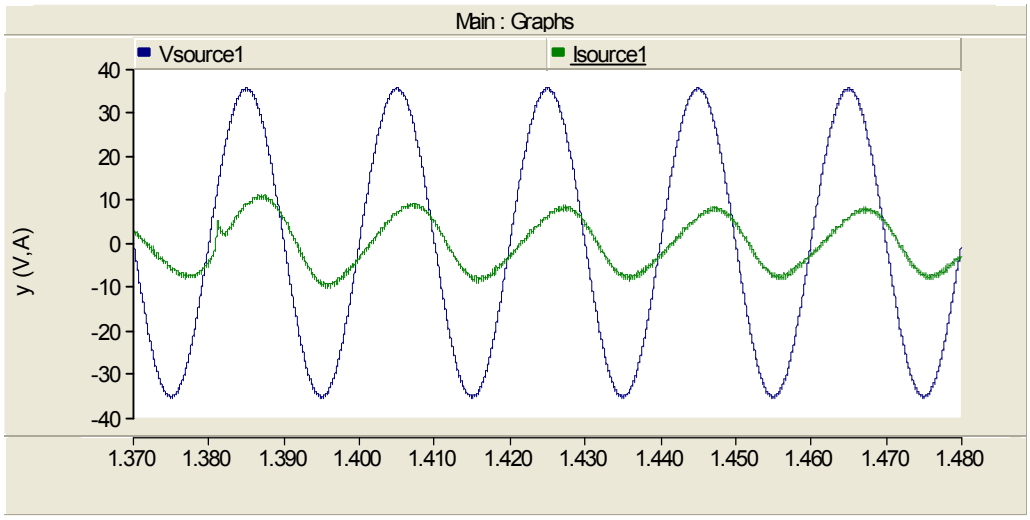


Figure 8.67.The phase difference between voltage and current (lagging) due to reactive power

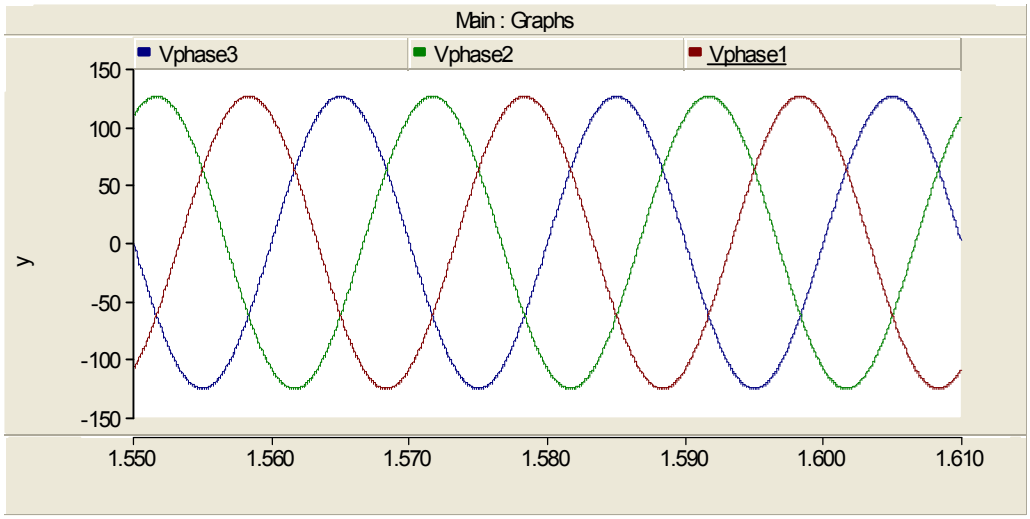


Figure 8.68.The voltage characteristic of utility network

8.4.3.Case 4 –c

The graph of THD at 0^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation .

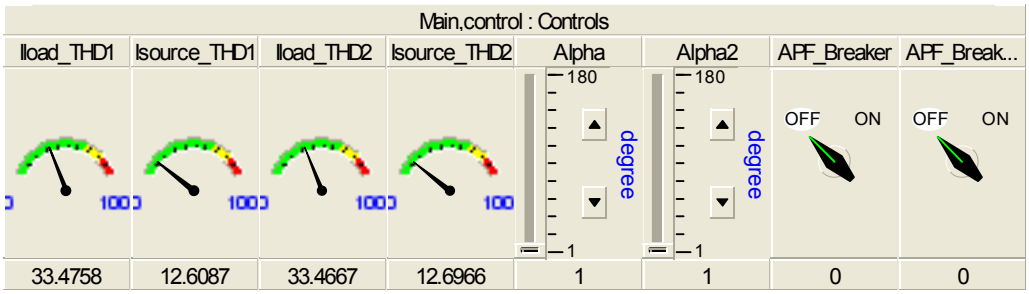


Figure 8.69.The THD levels on both sides of OHL

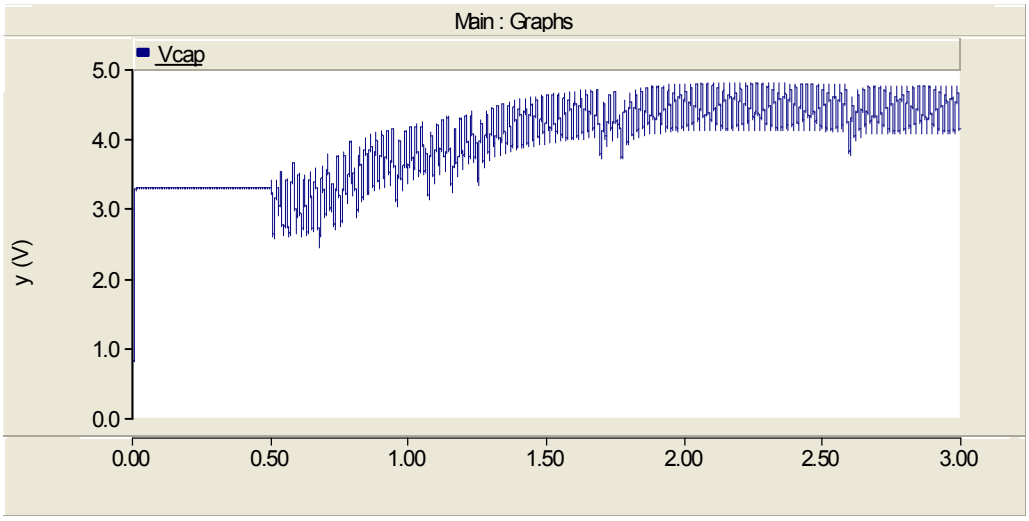


Figure 8.70.The DC link capacitor voltage characteristic

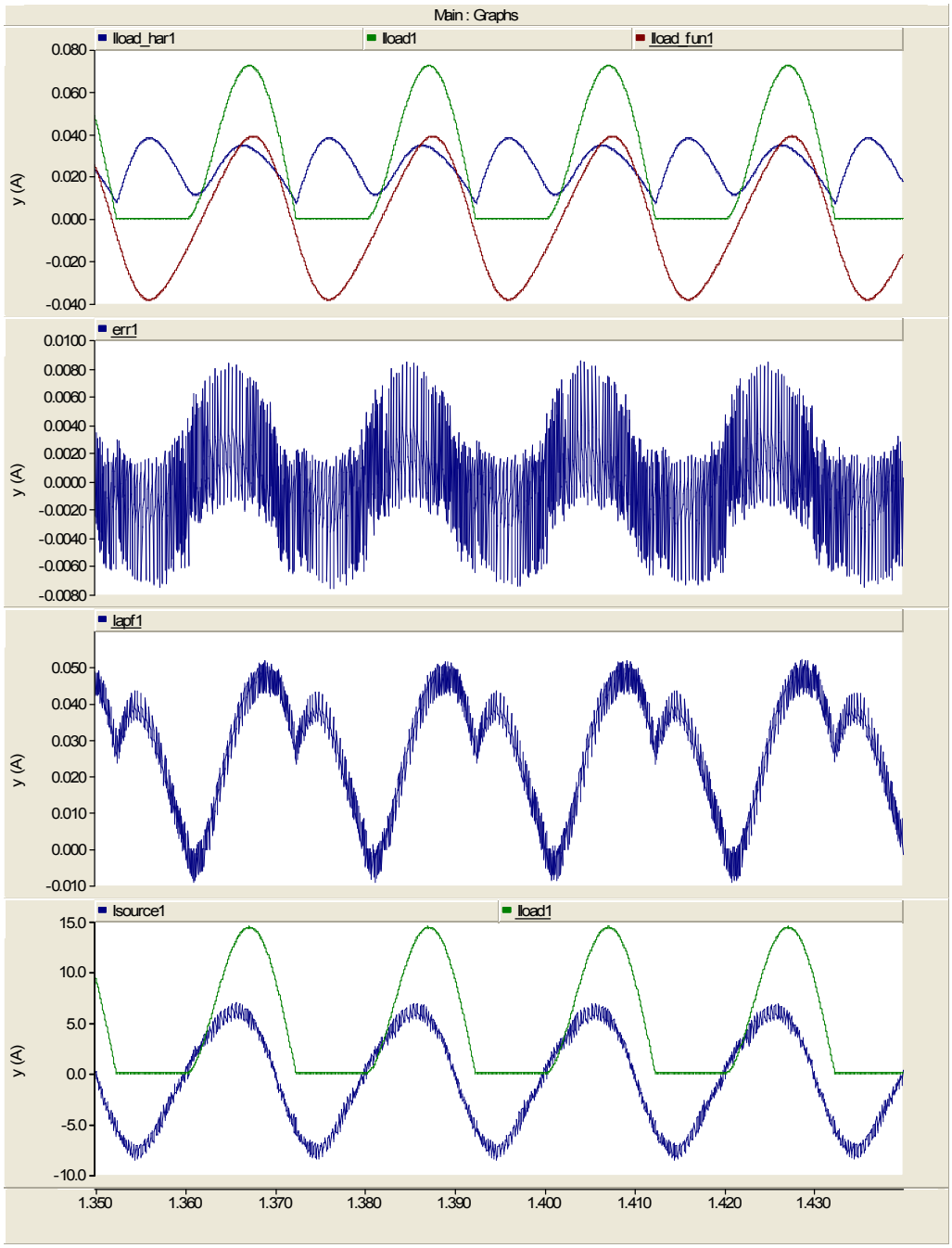


Figure 8.71.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

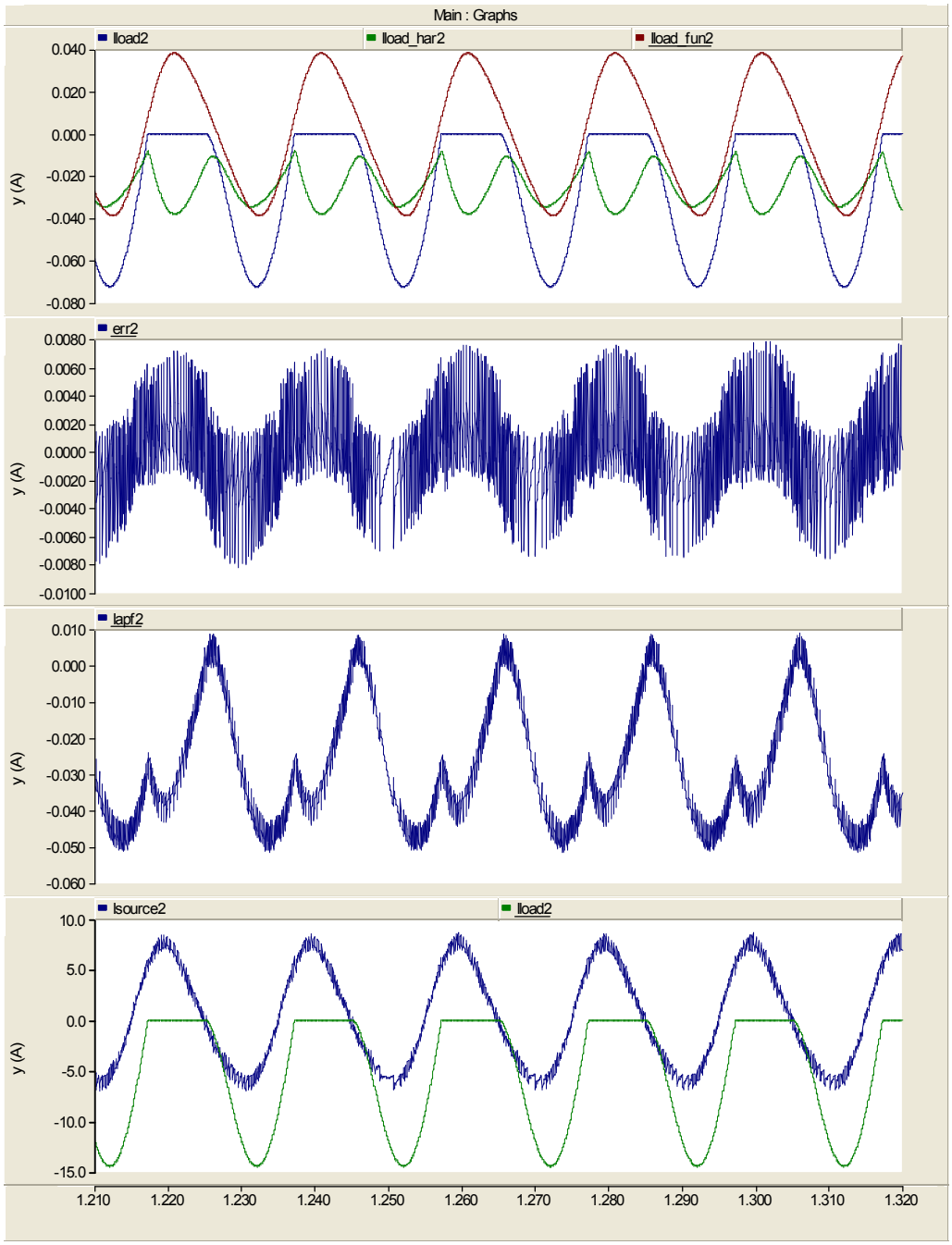


Figure 8.72.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

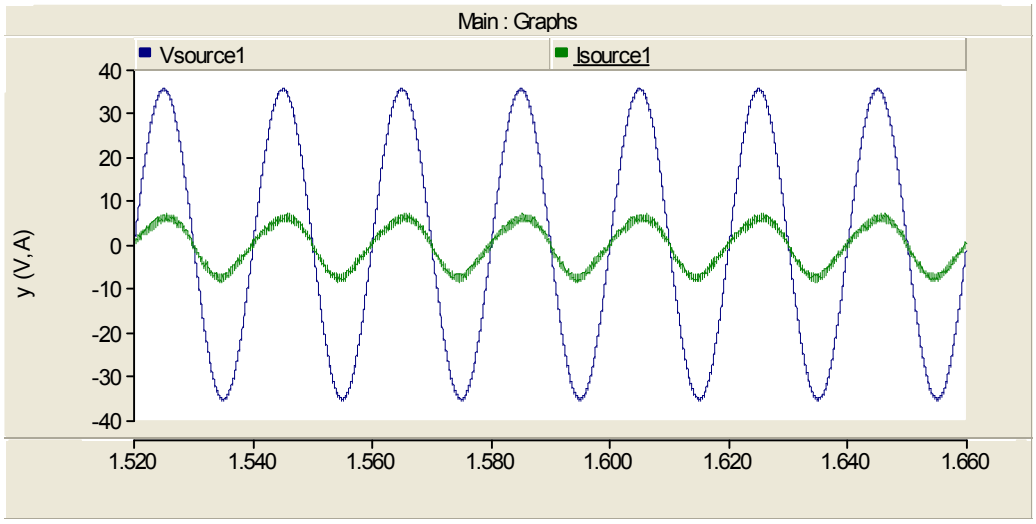


Figure 8.73.The phase difference between voltage and current (lagging) due to reactive power

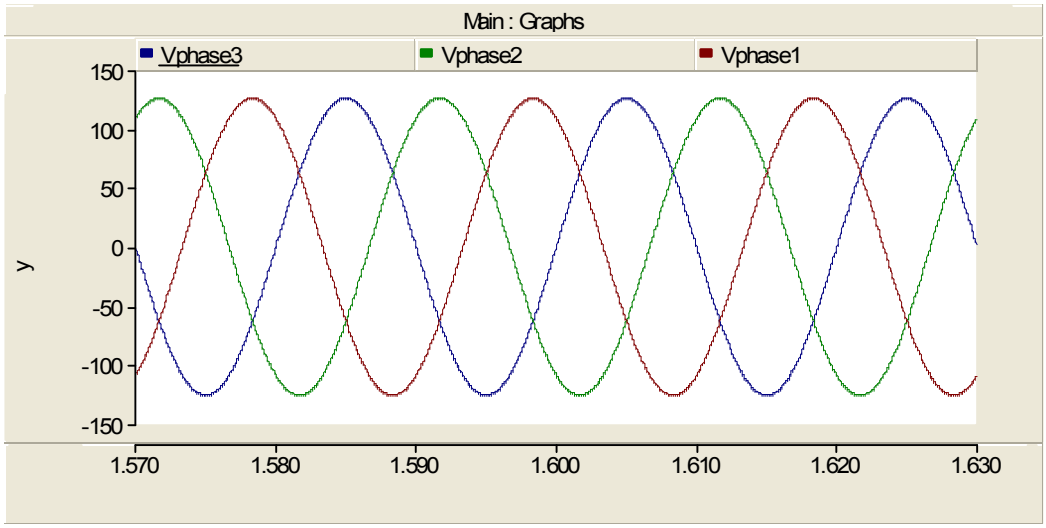


Figure 8.74.The voltage characteristic of utility network

8.5.Case 5

The aim of this case is monitoring the response of the APF to unbalanced load so the overview of the system has been changed .

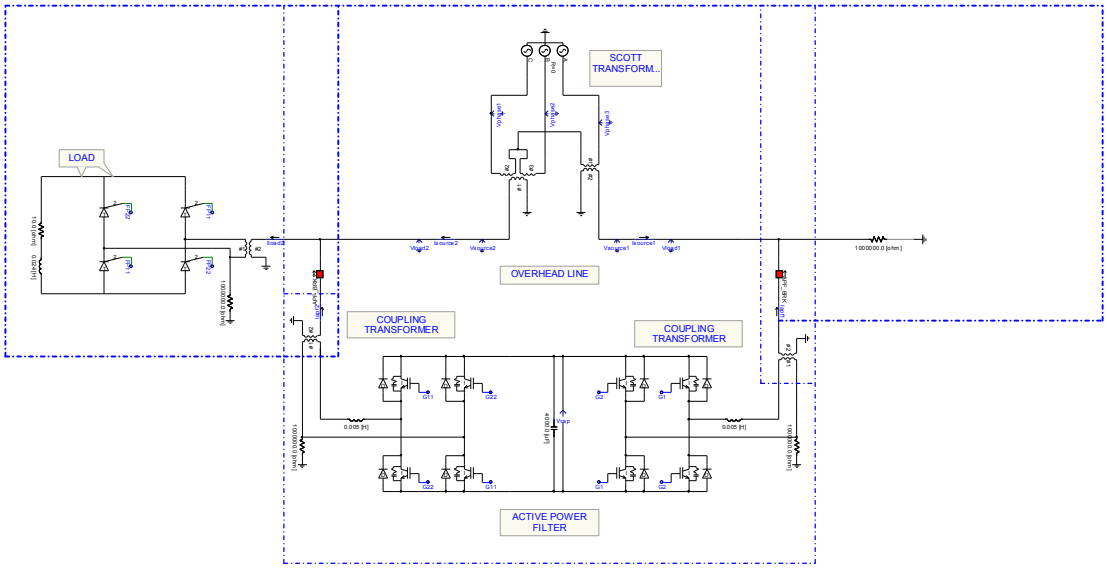


Figure 8.75. The overview of single side loaded system

8.5.1.Case 5-a

The graph of THD at 90^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation .

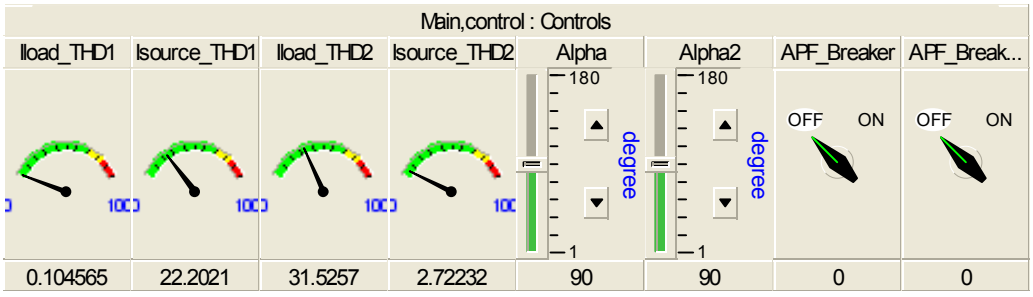


Figure 8.76.The THD levels on both sides of OHL

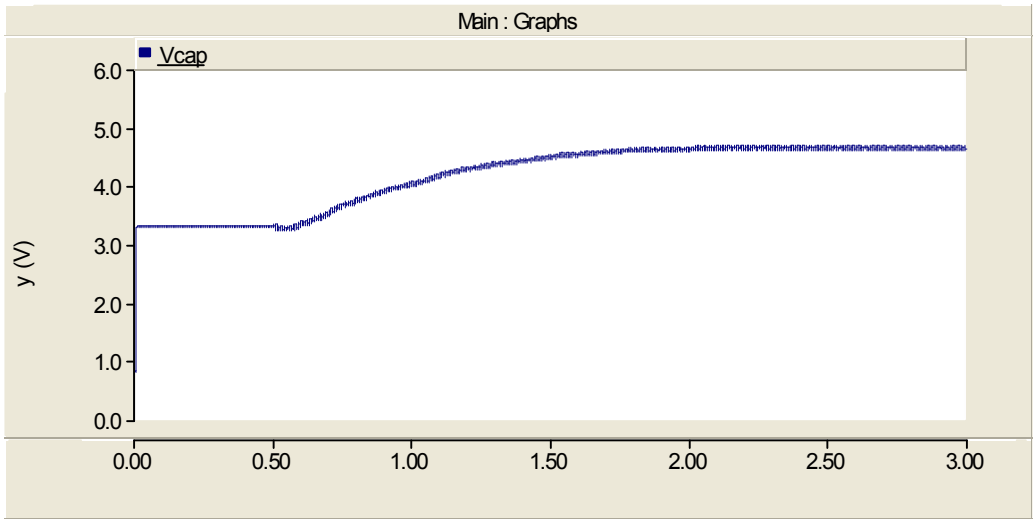


Figure 8.77.The DC link capacitor voltage characteristic

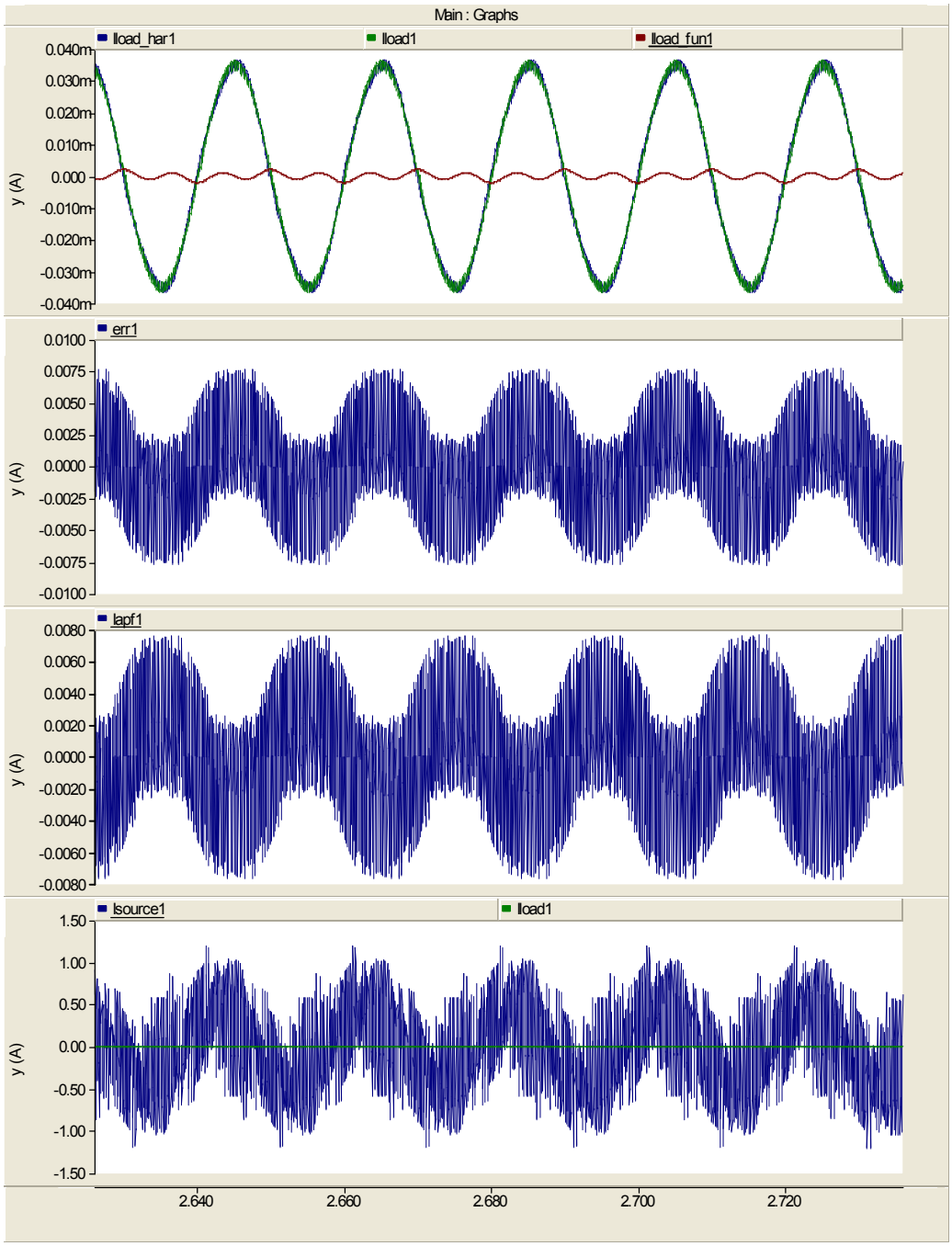


Figure 8.78.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

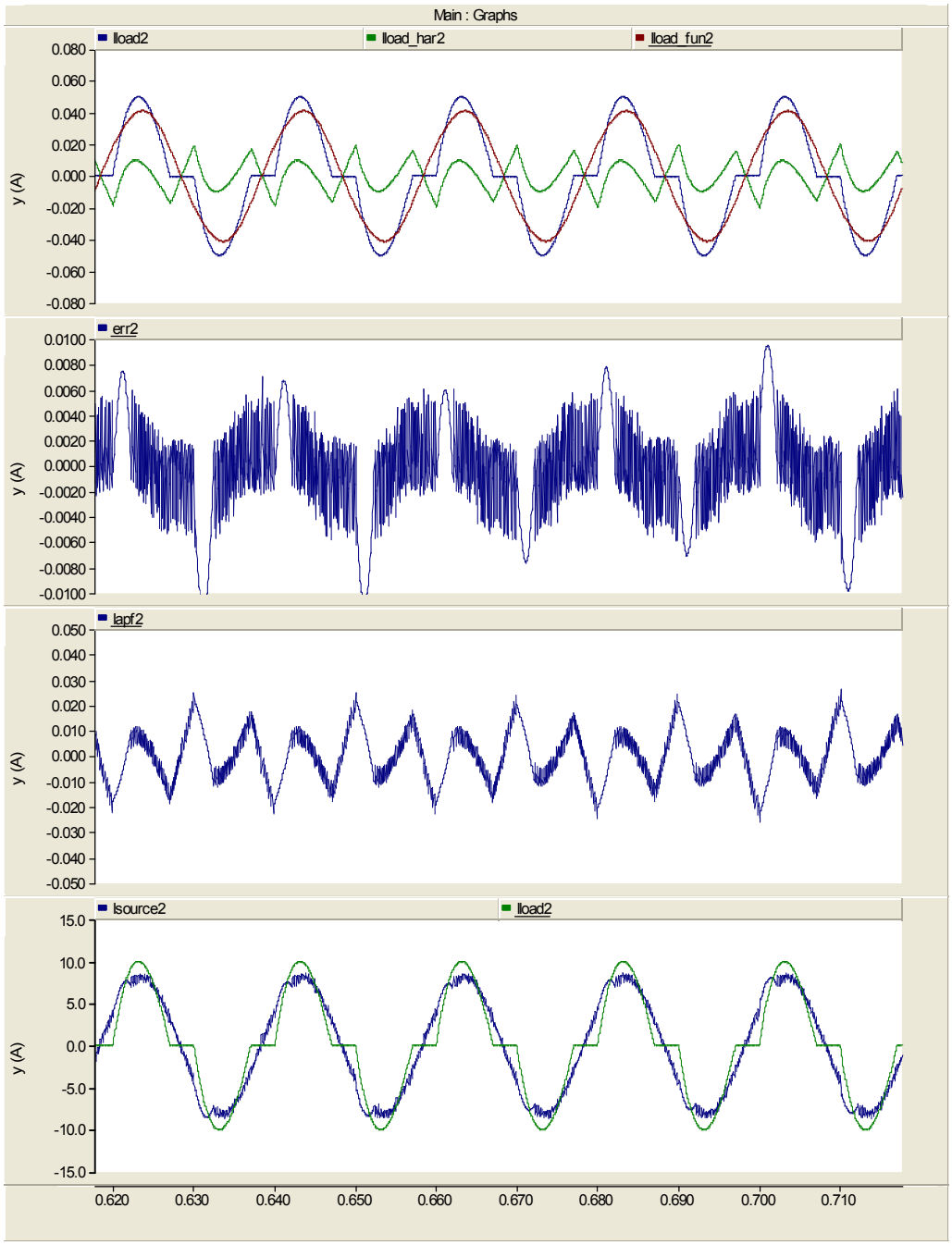


Figure 8.79.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

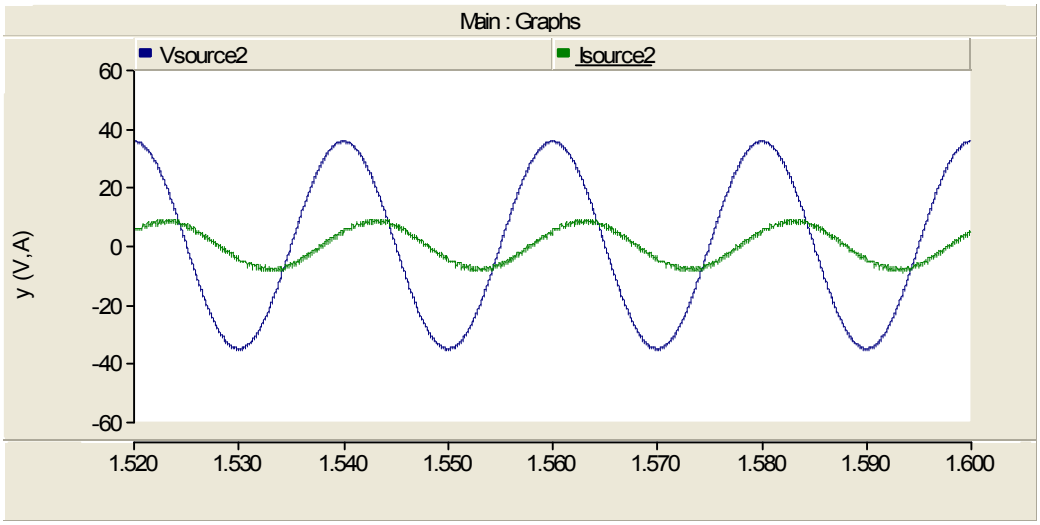


Figure 8.80.The phase difference between voltage and current (lagging) due to reactive power

8.5.2.Case 5-b

The graph of THD at 90^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation .

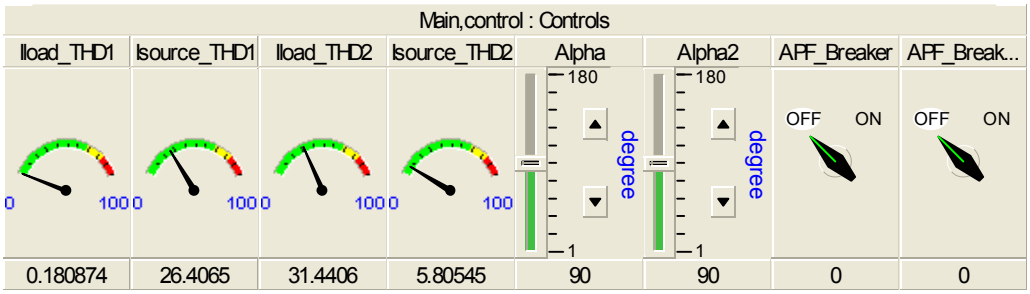


Figure 8.81.The THD levels on both sides of OHL

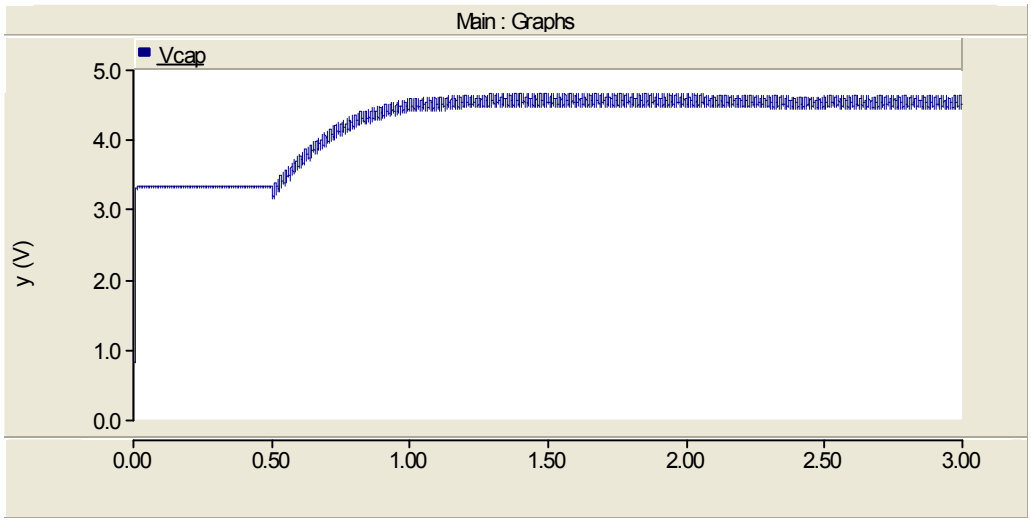


Figure 8.82.The DC link capacitor voltage characteristic

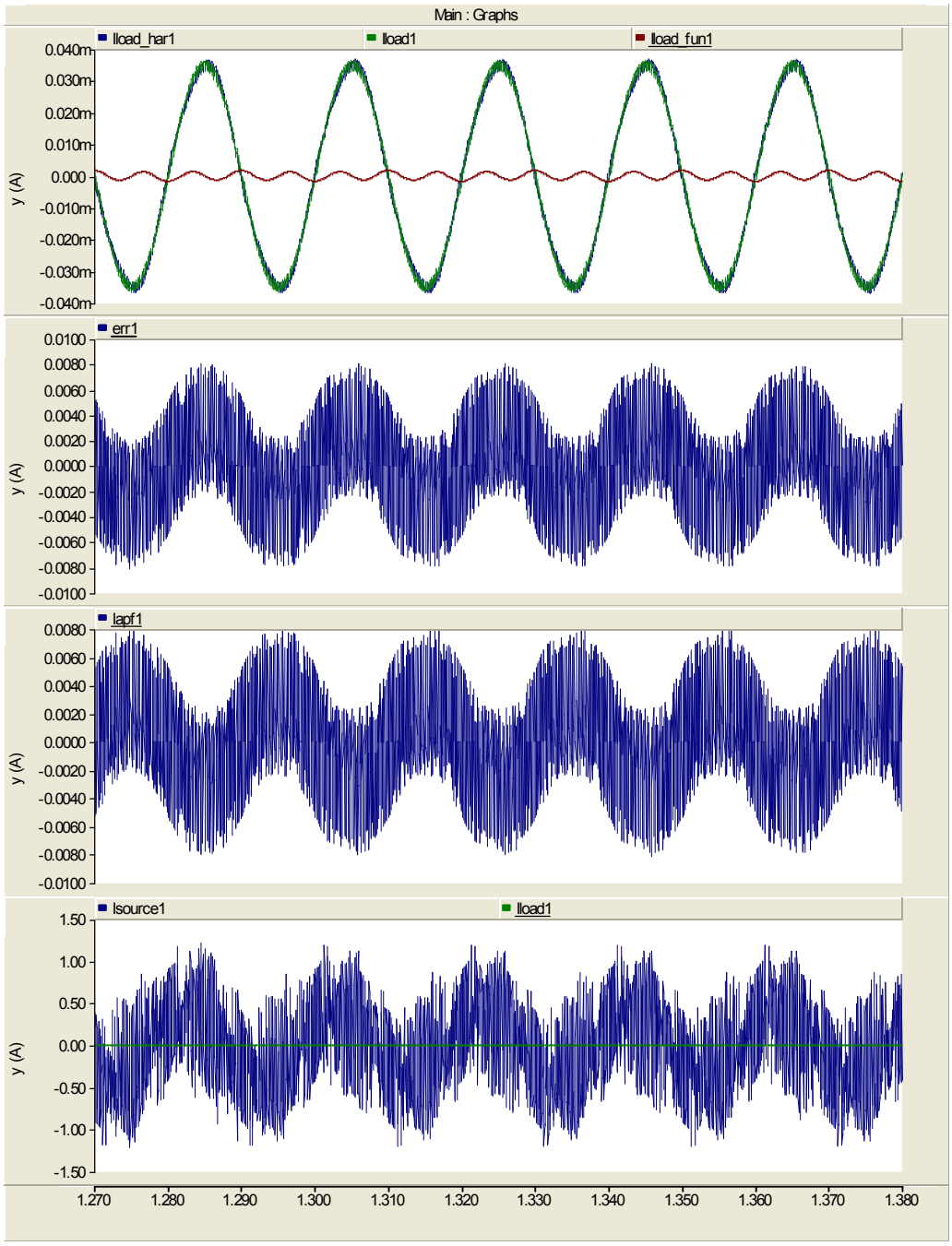


Figure 8.83.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

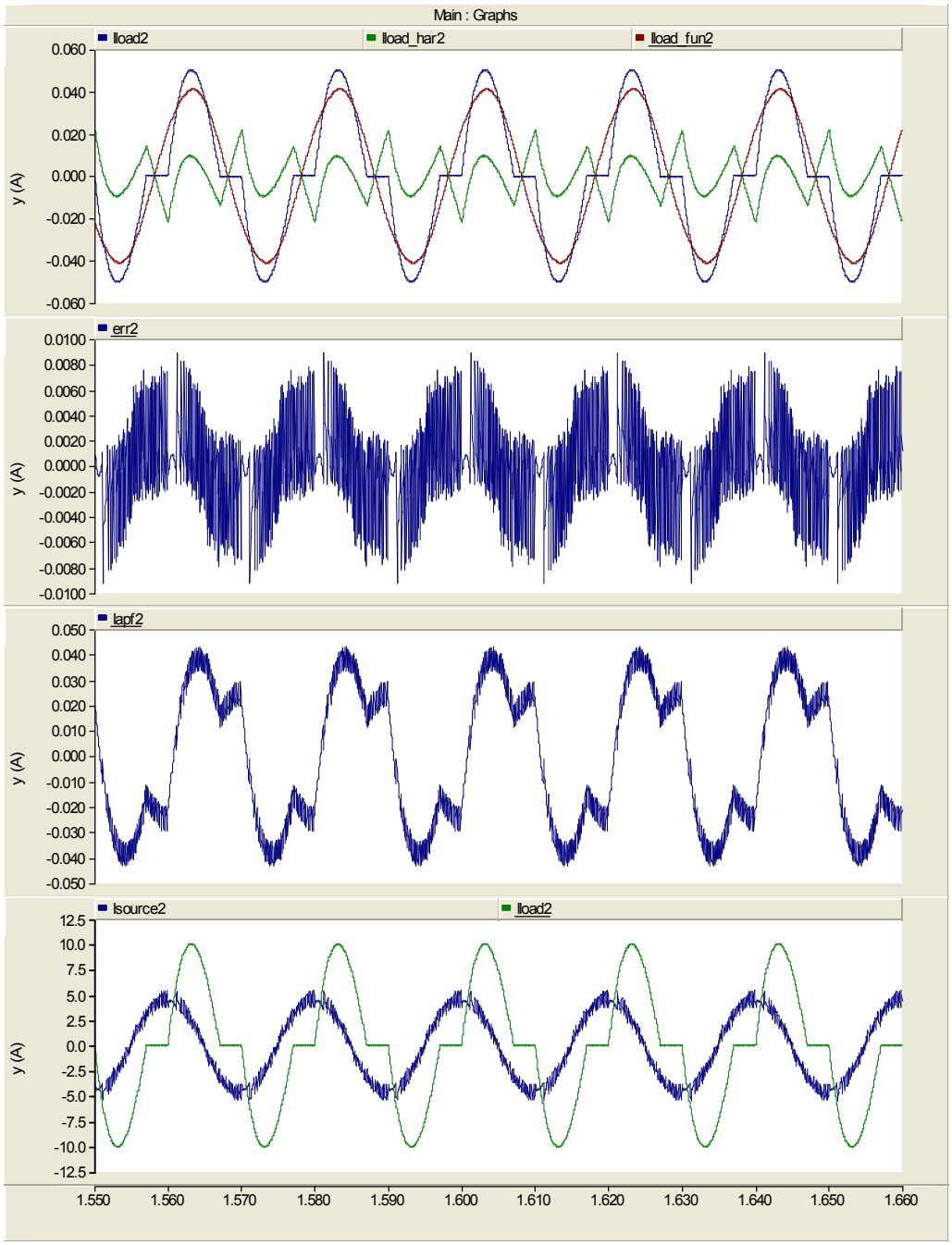


Figure 8.84.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

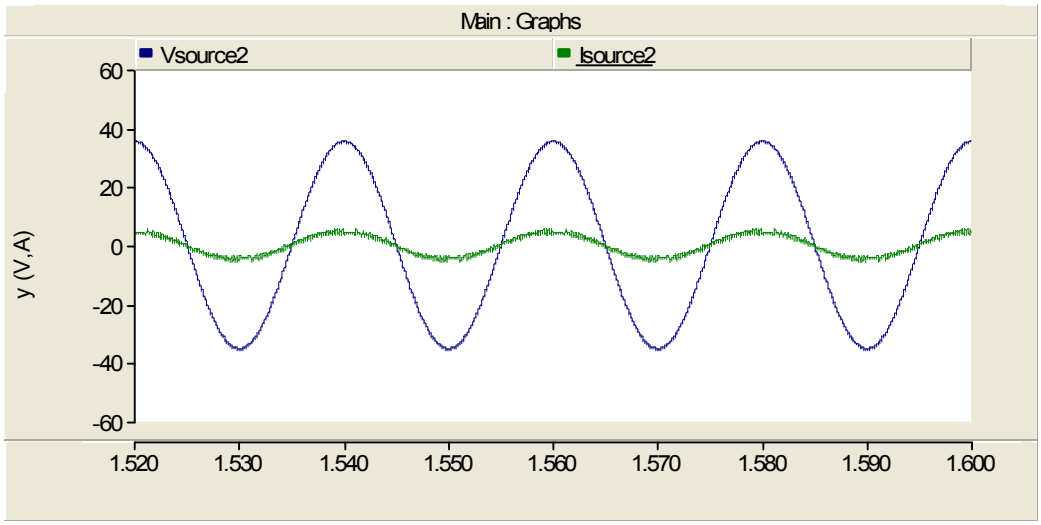


Figure 8.85.The phase difference between voltage and current (lagging) due to reactive power

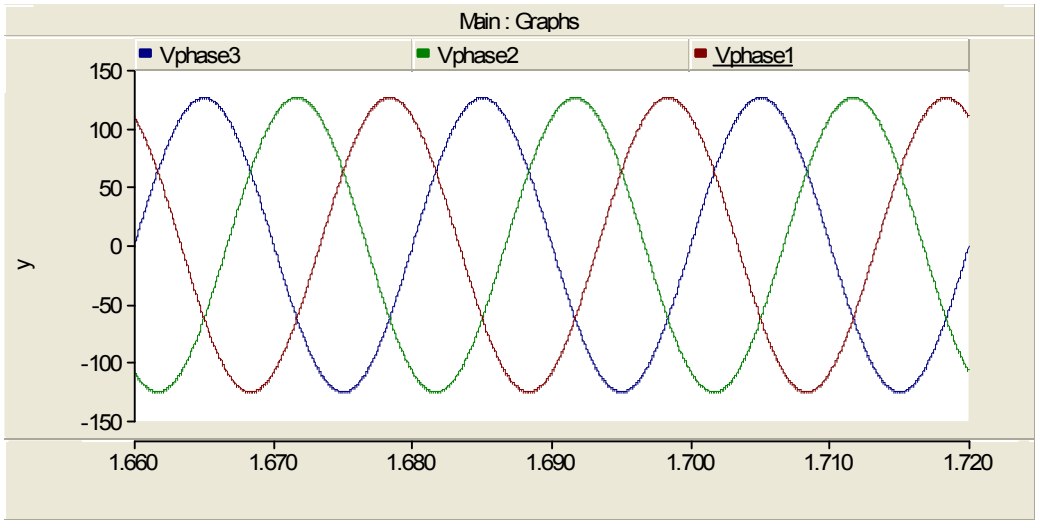
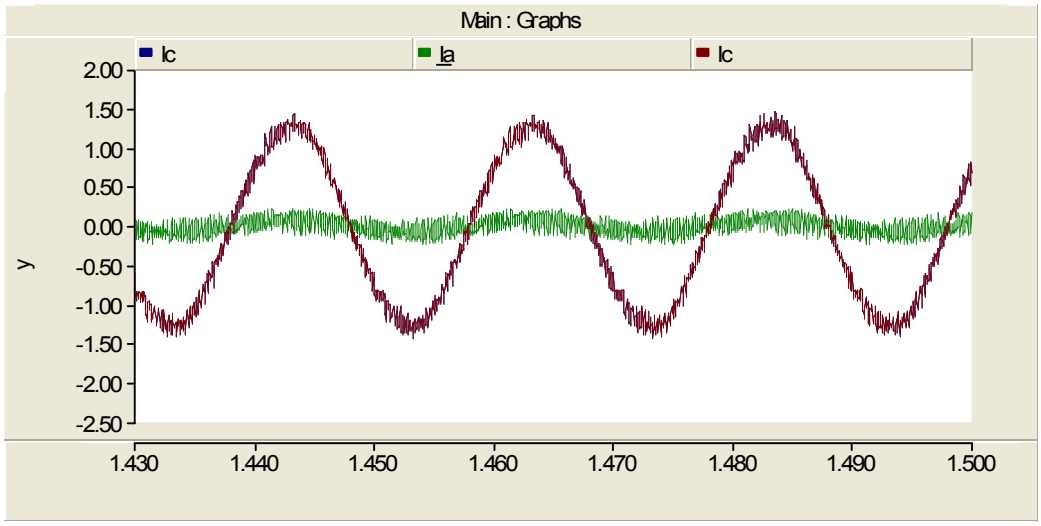


Figure 8.86.The voltage characteristic of utility network



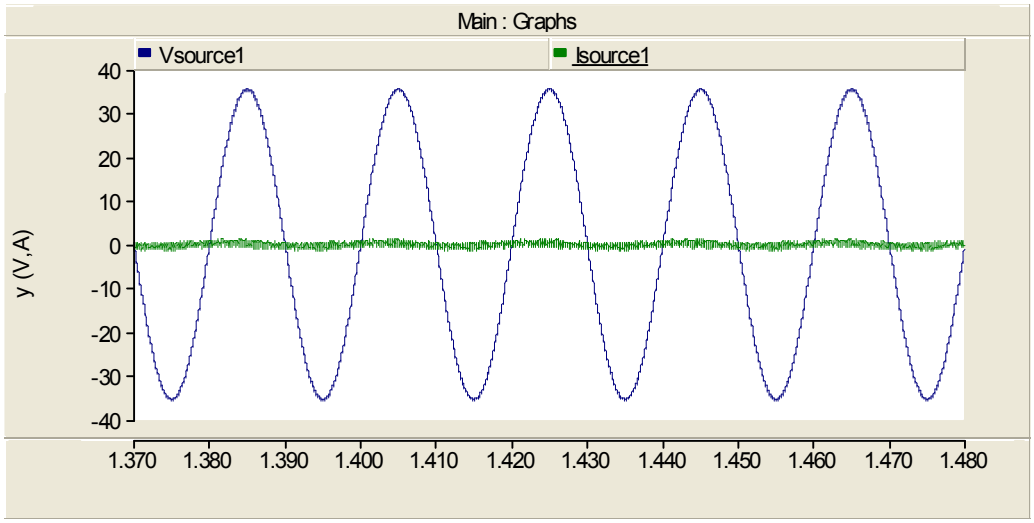


Figure 8.87. Voltage and current characteristic of unloaded side catenary

8.6.Case 6

The graph of THD at 60^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation.

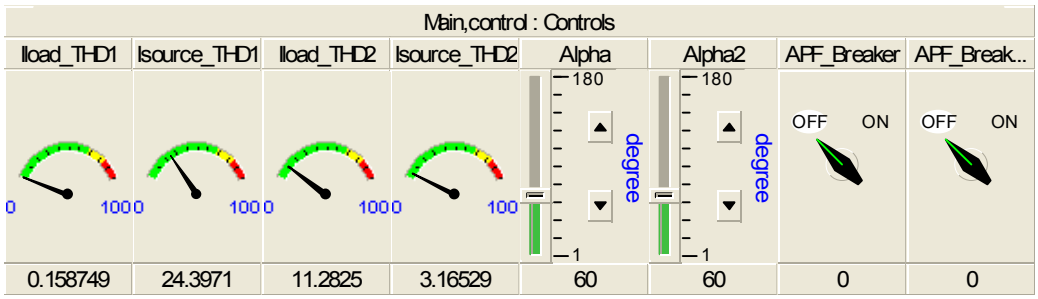


Figure 8.88.The THD levels on both sides of OHL

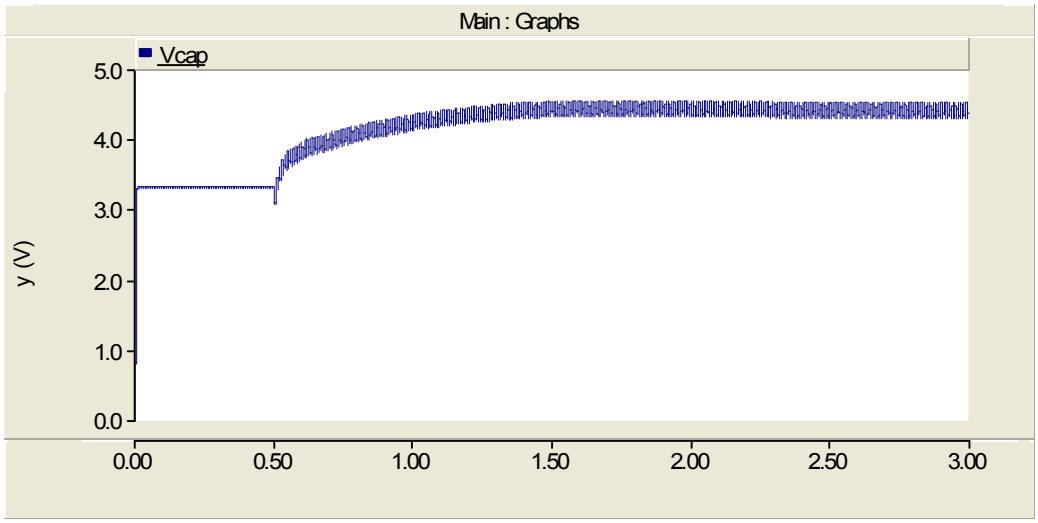


Figure 8.89.The DC link capacitor voltage characteristic

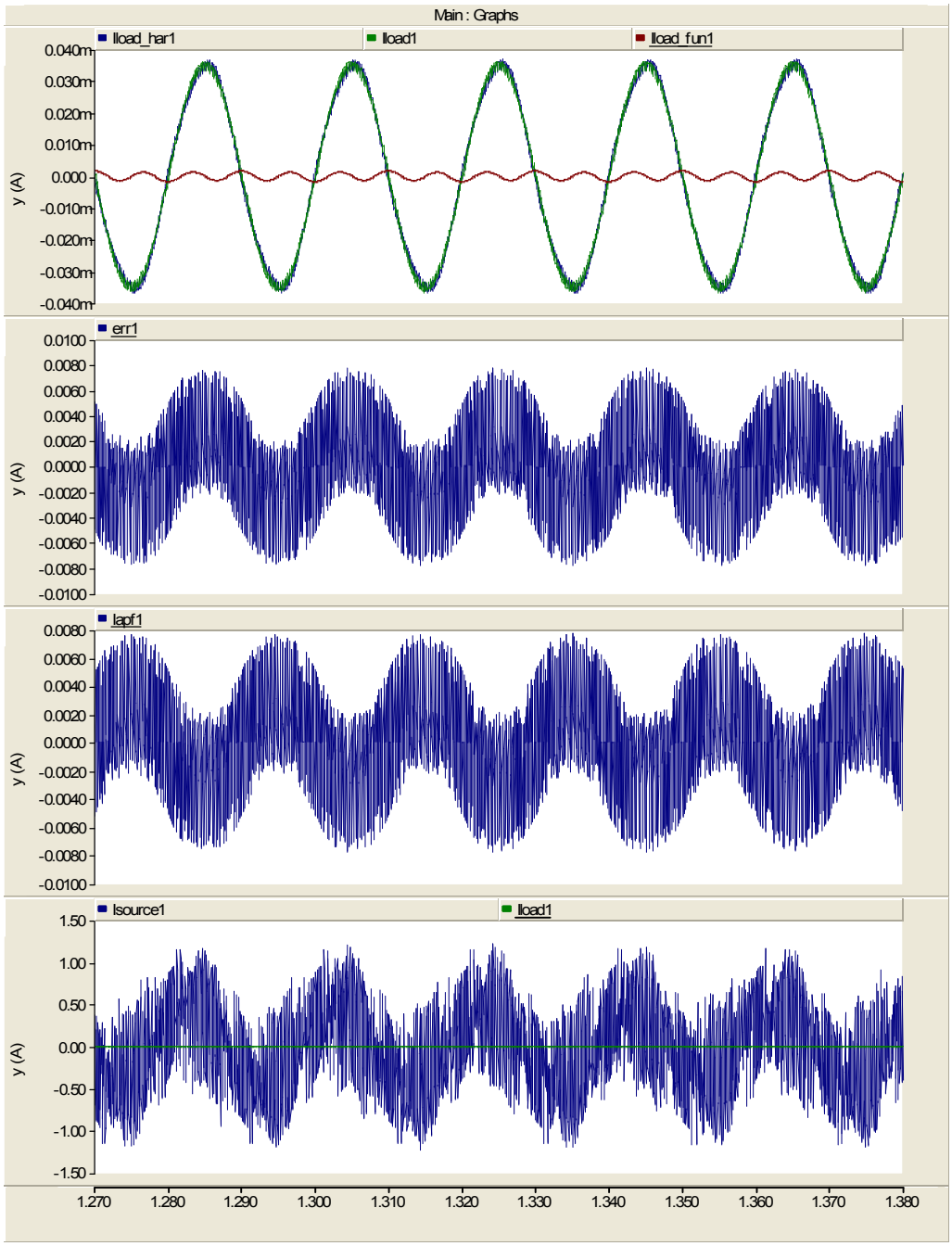


Figure 8.90.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

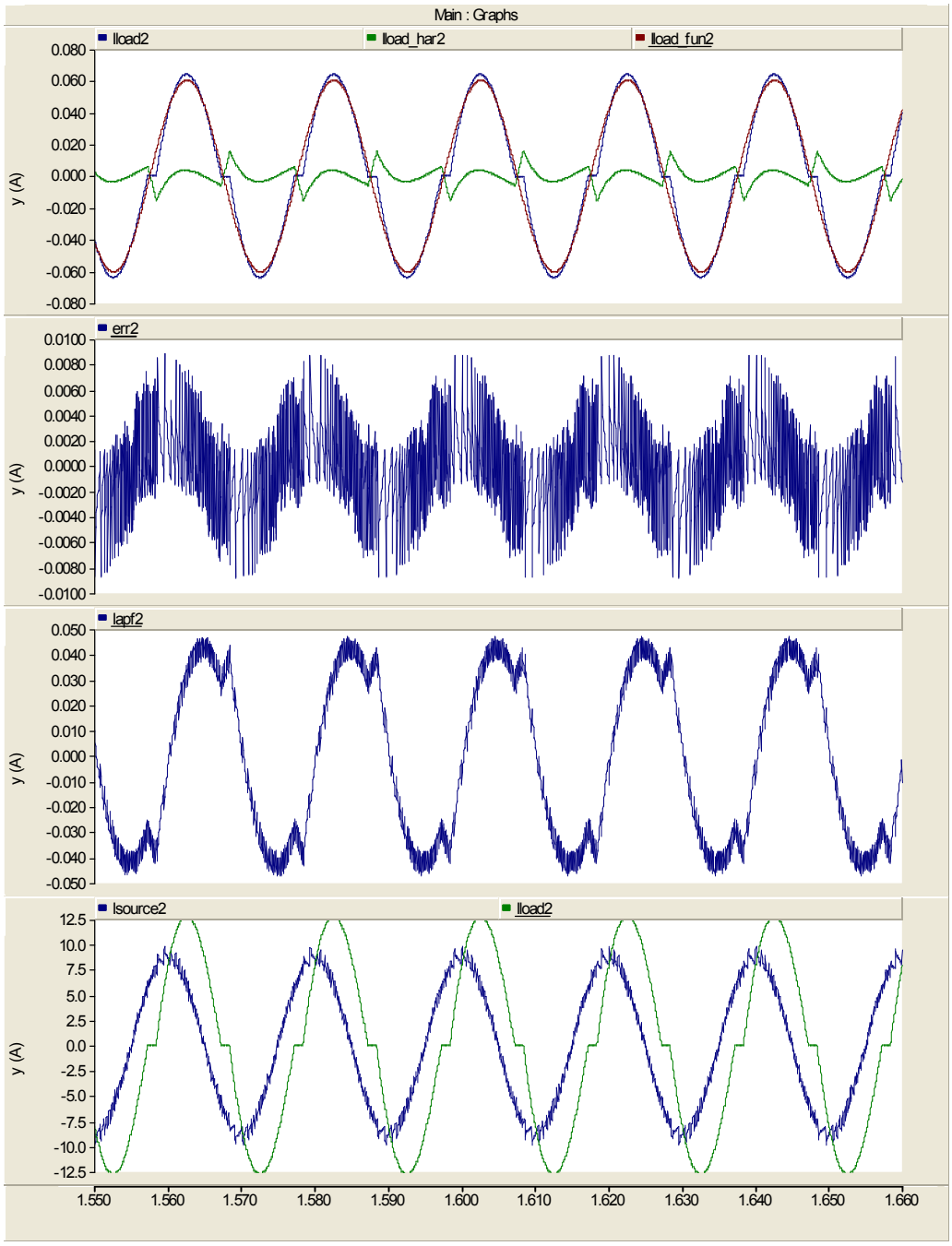


Figure 8.91.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

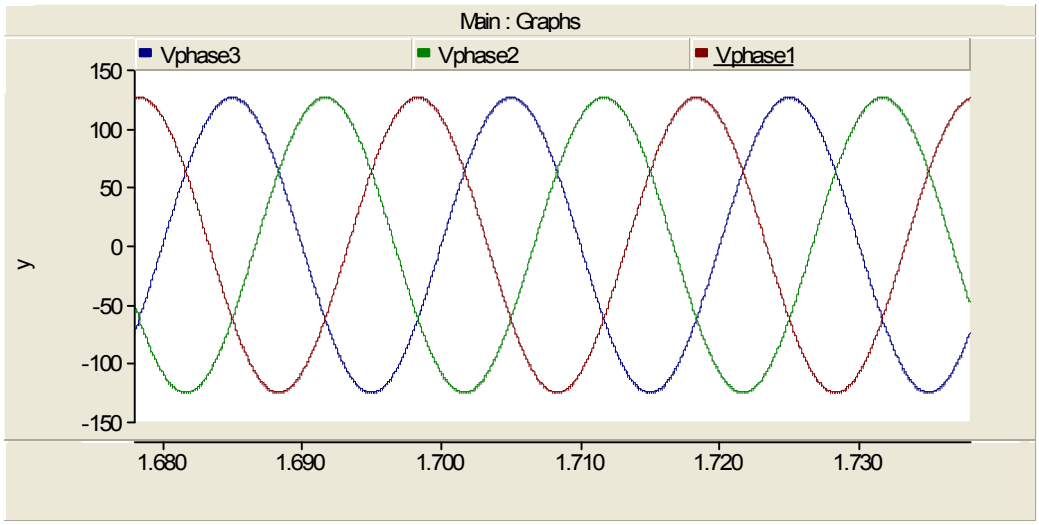


Figure 8.92.The voltage characteristic of utility network

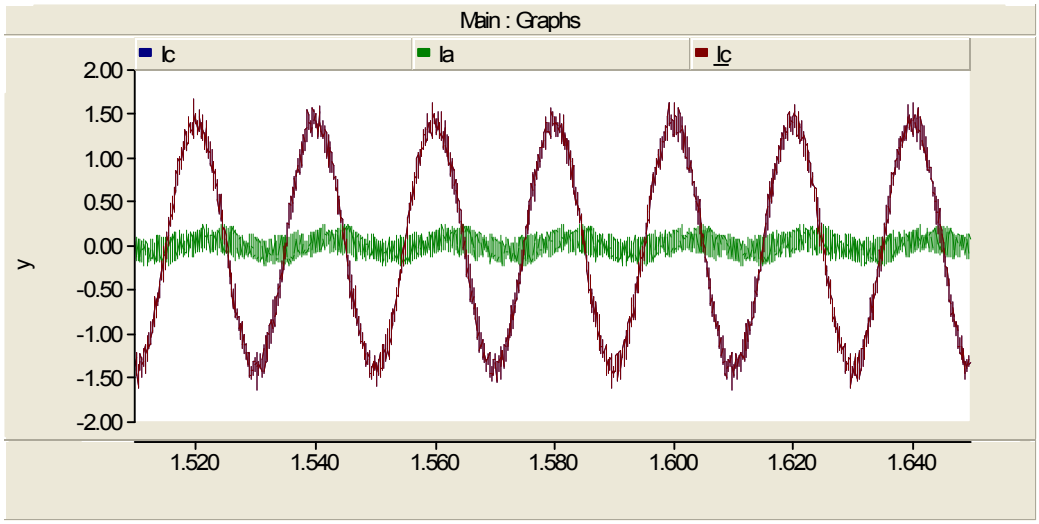


Figure 8.93. The currents characteristic of utility network

8.7.Case 7

8.7.1.Case 7- a

The graph of THD at 80^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. Without reactive compensation.

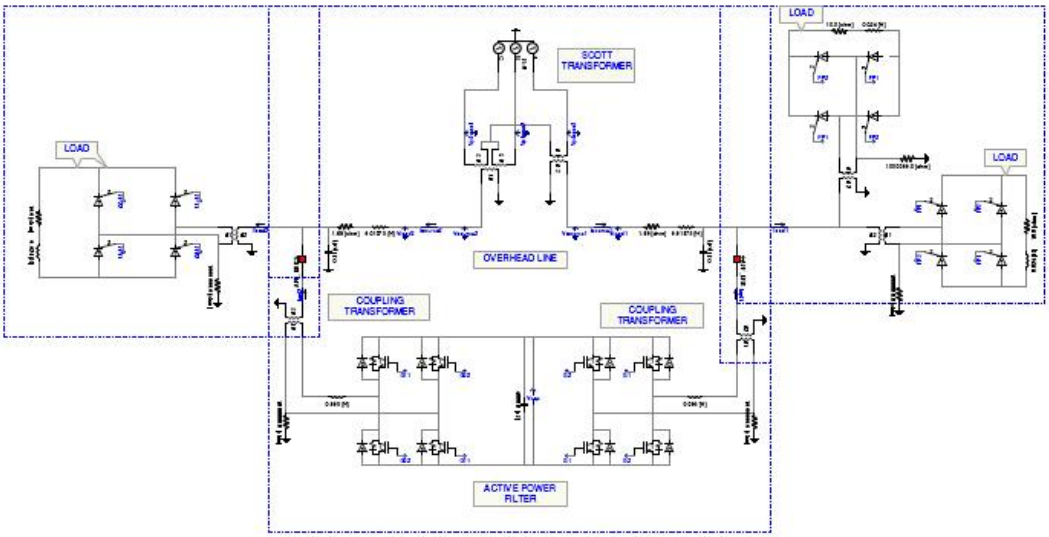


Figure 8.94.The overview of the model that is differently loaded

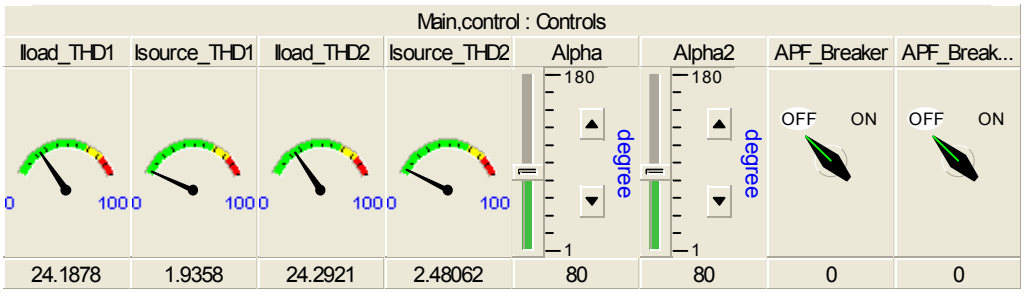


Figure 8.95.The THD levels on both sides of OHL

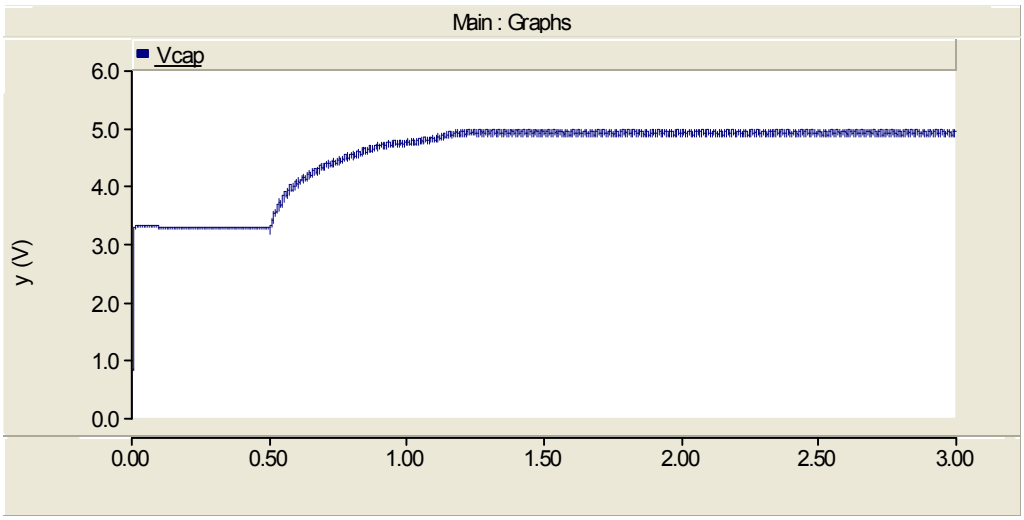


Figure 8.96.The DC link capacitor voltage characteristic

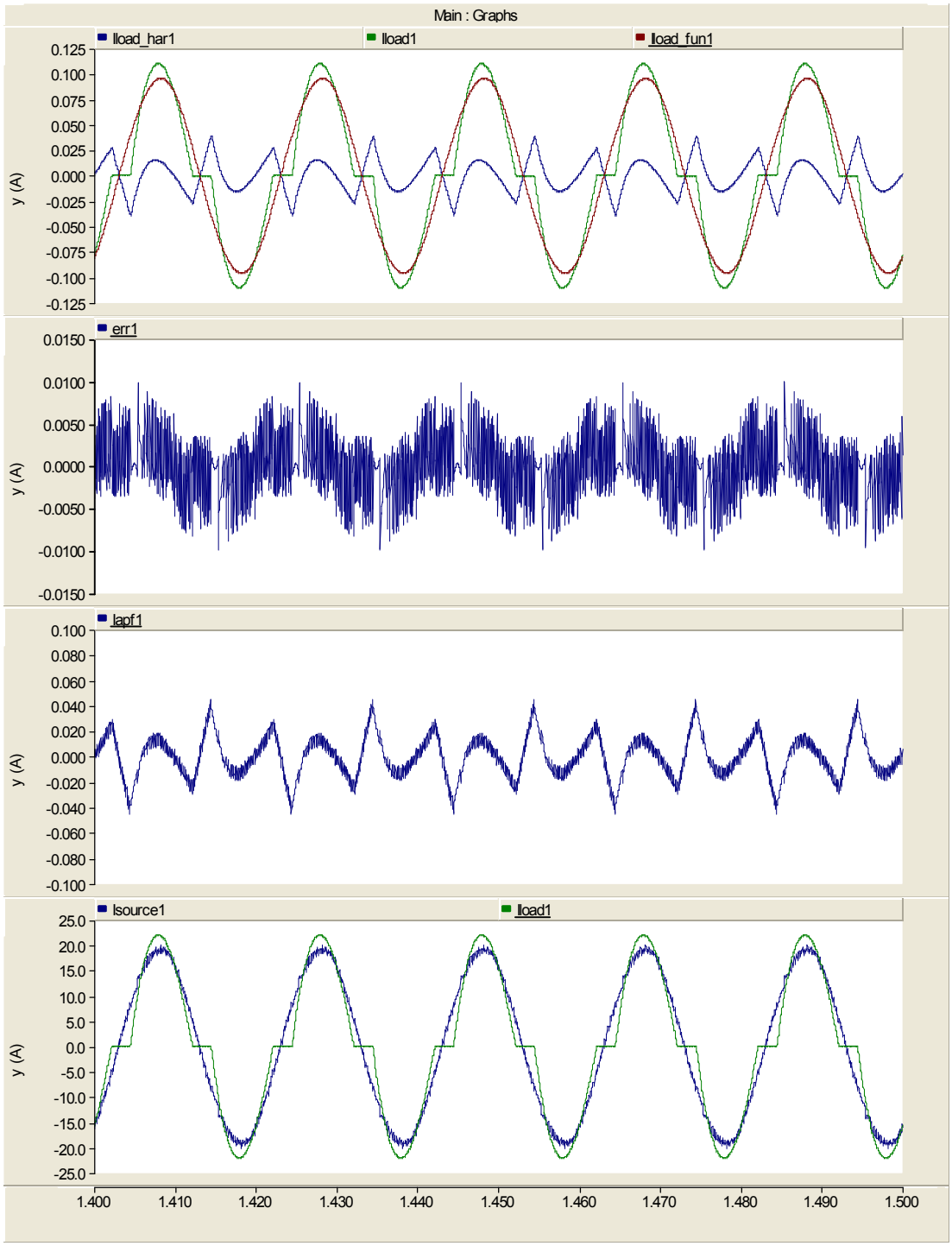


Figure 8.97.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

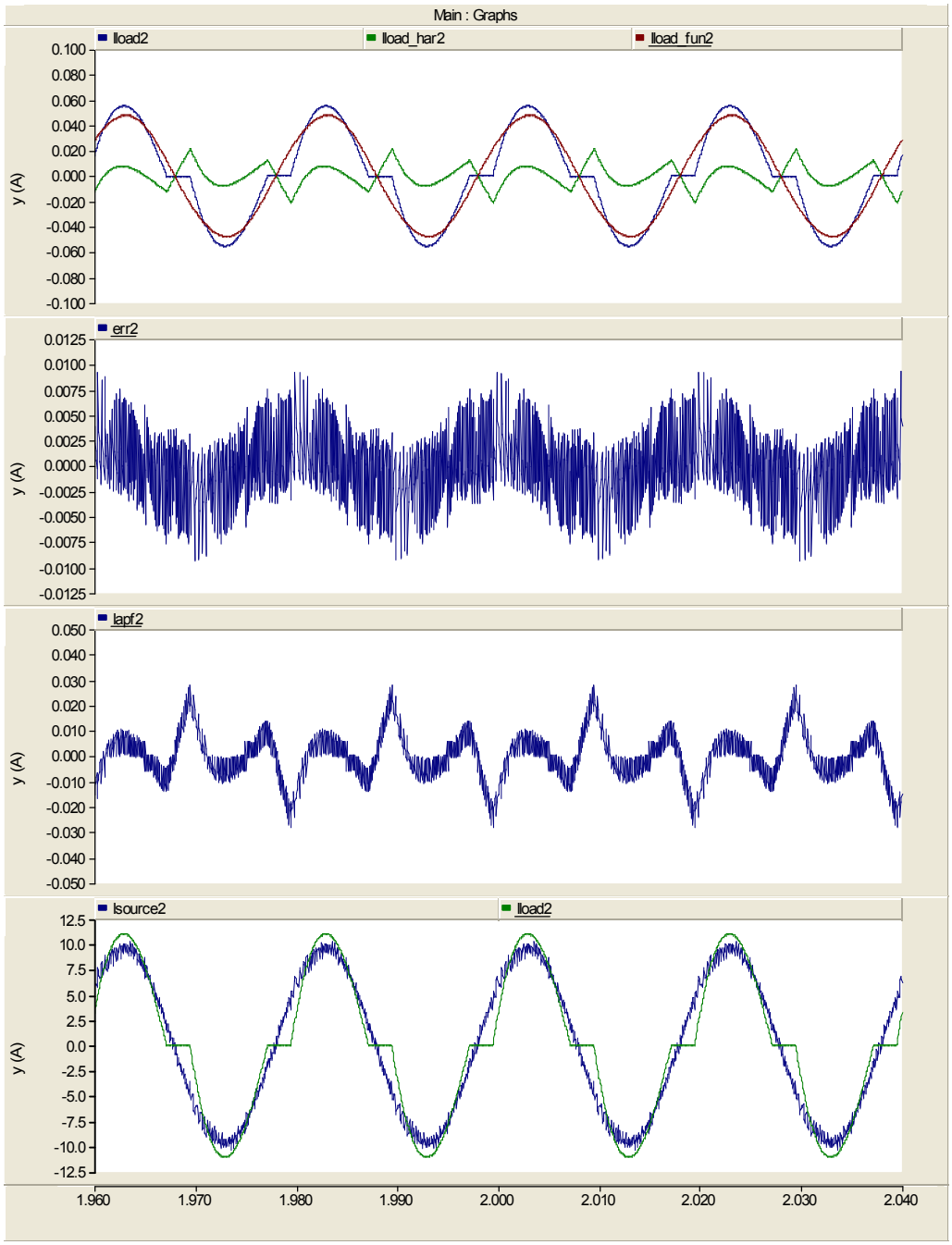


Figure 8.98.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

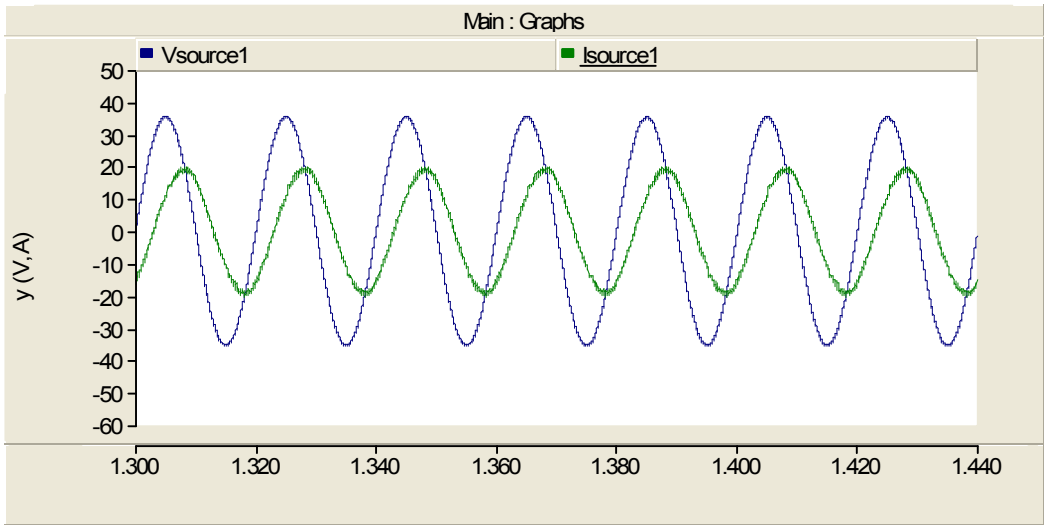


Figure 8.99.The phase difference between voltage and current (lagging) due to reactive power

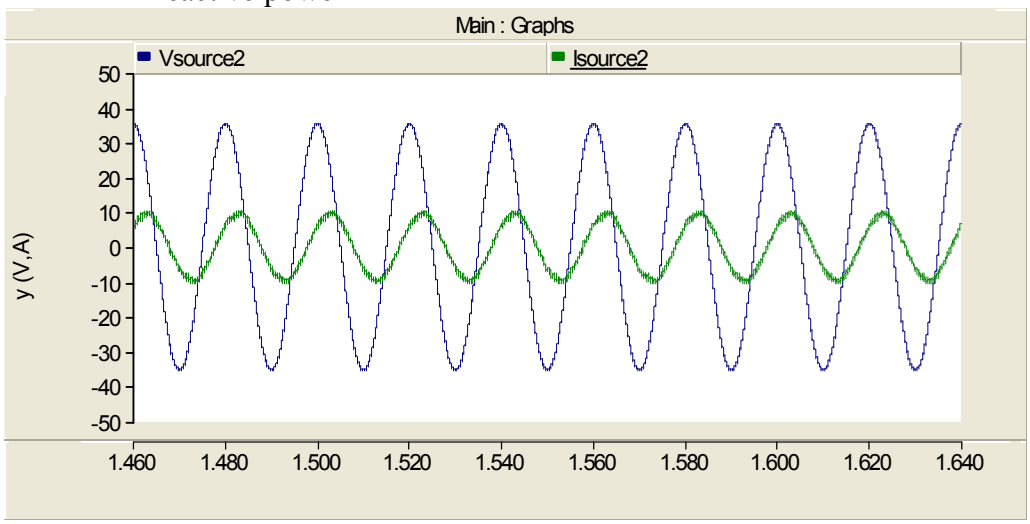


Figure 8.100.The phase difference between voltage and current (lagging) due to reactive power

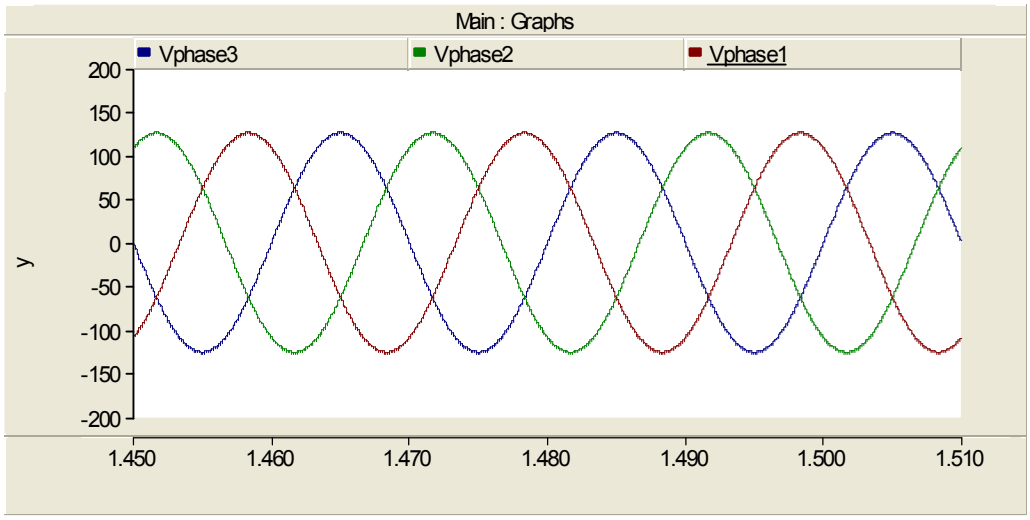


Figure 8.101.The voltage characteristic of utility network

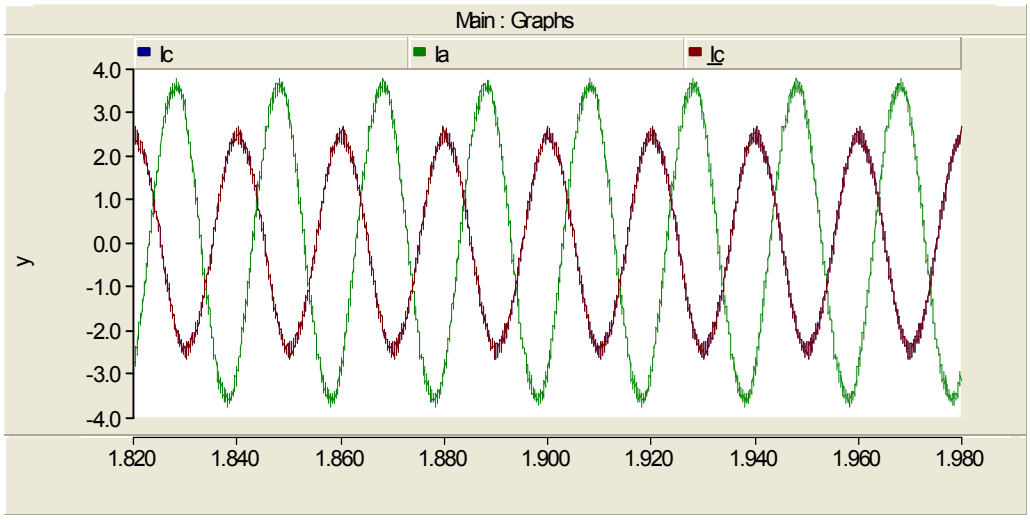


Figure 8.102.The current characteristic of utility network

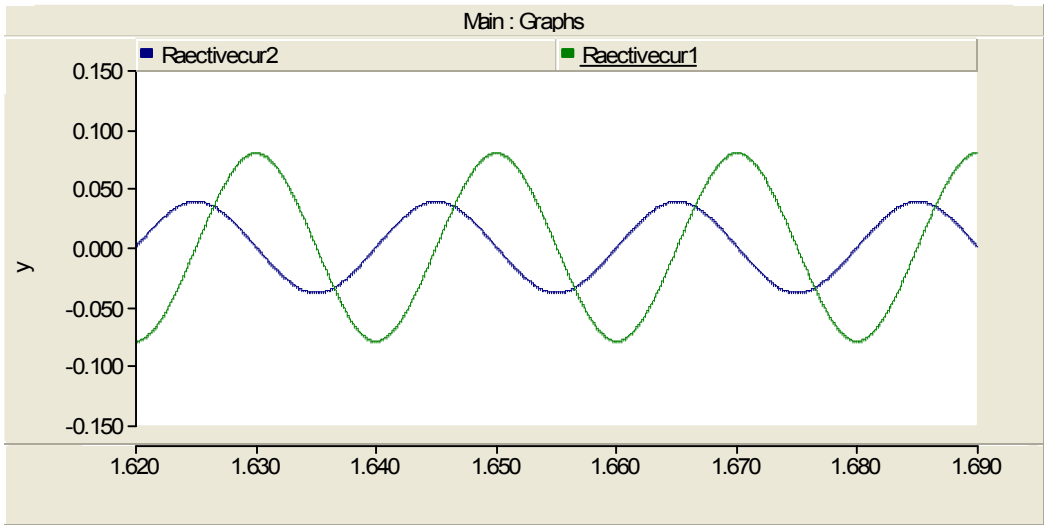


Figure 8.103. Reactive current charateristics on both catenary lines

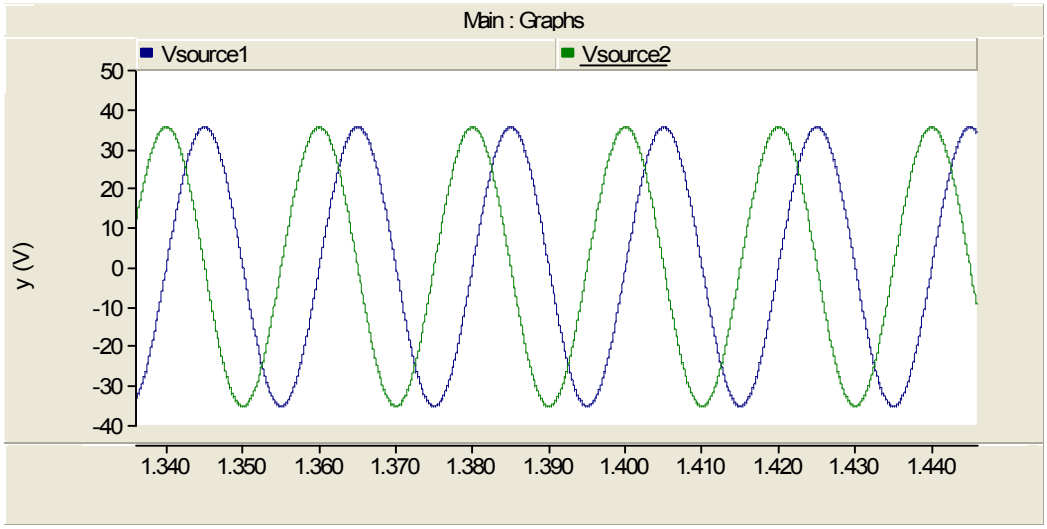


Figure 8.104. The voltage signal applied to catenary from Scott Transformer

8.7.2.Case 7- b

The graph of THD at 80^0 firing angle of vehicle converter. The line inductor is adjusted 0.005 H. With reactive compensation .

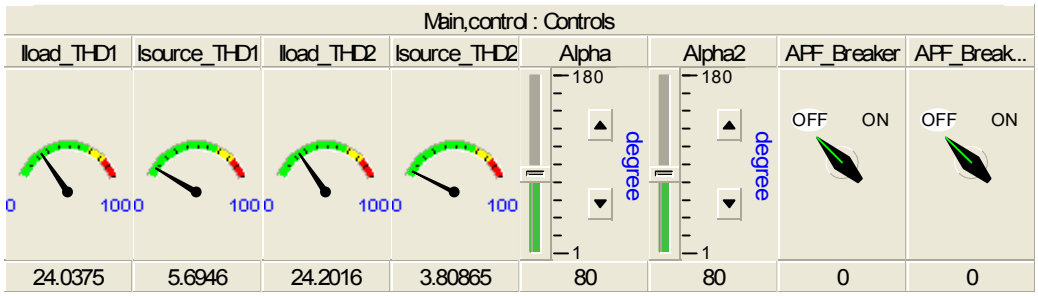


Figure 8.105.The THD levels on both sides of OHL

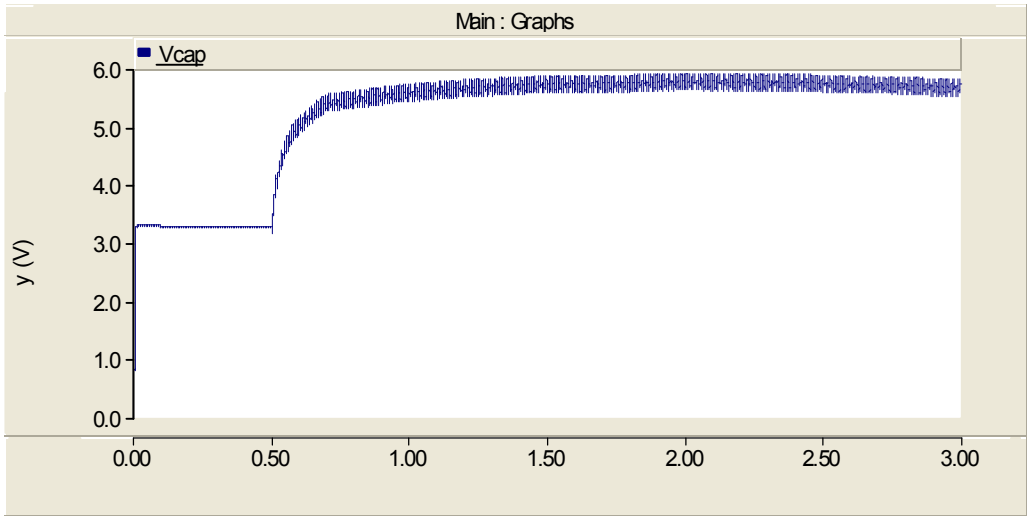


Figure 8.106. The DC link capacitor voltage characteristic

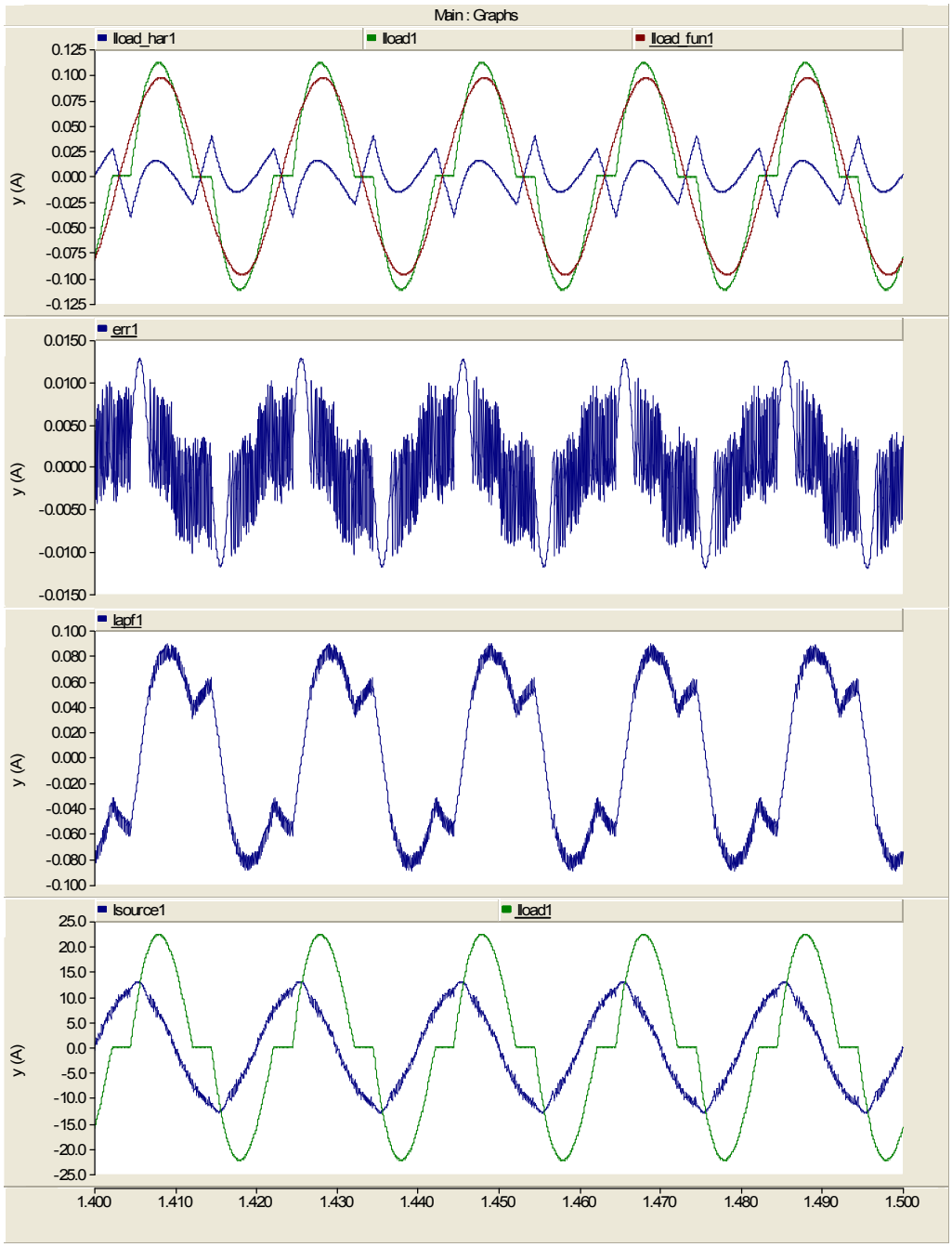


Figure 8.107.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

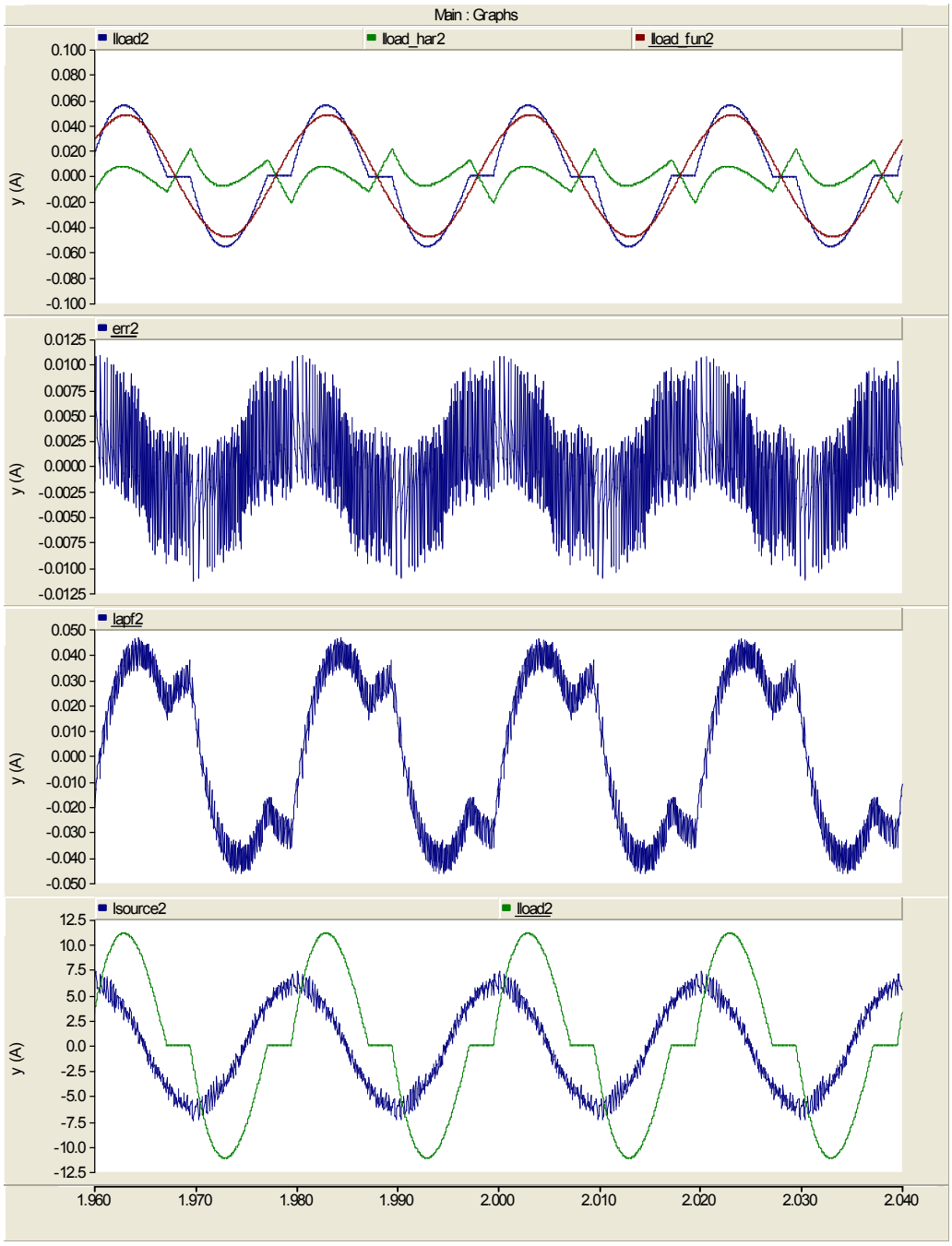


Figure 8.108.The simulation results of load 1 the current, the error signal that calculated by EPLL, harmonic signal and source signal

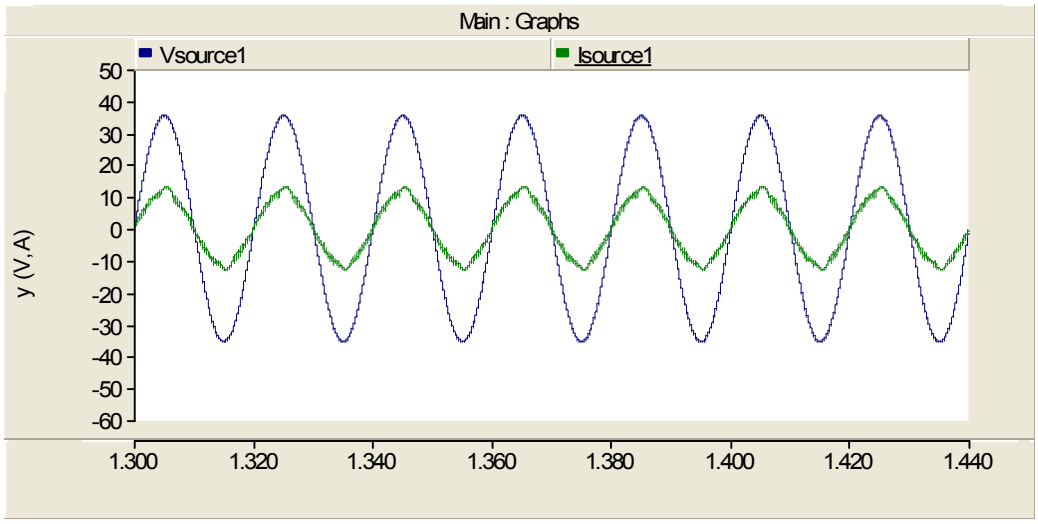


Figure 8.109.The phase difference between voltage and current (lagging) due to reactive power

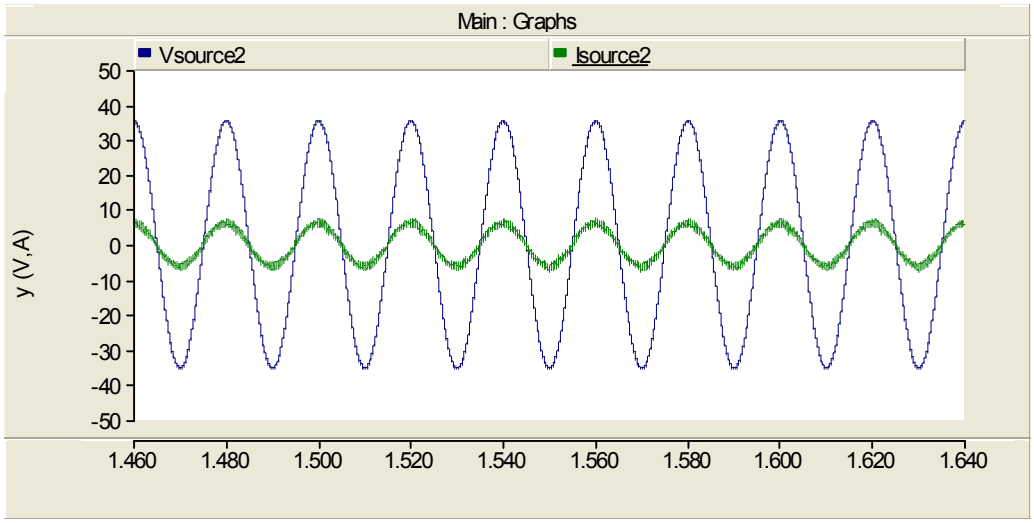


Figure 8.110.The phase difference between voltage and current (lagging) due to reactive power

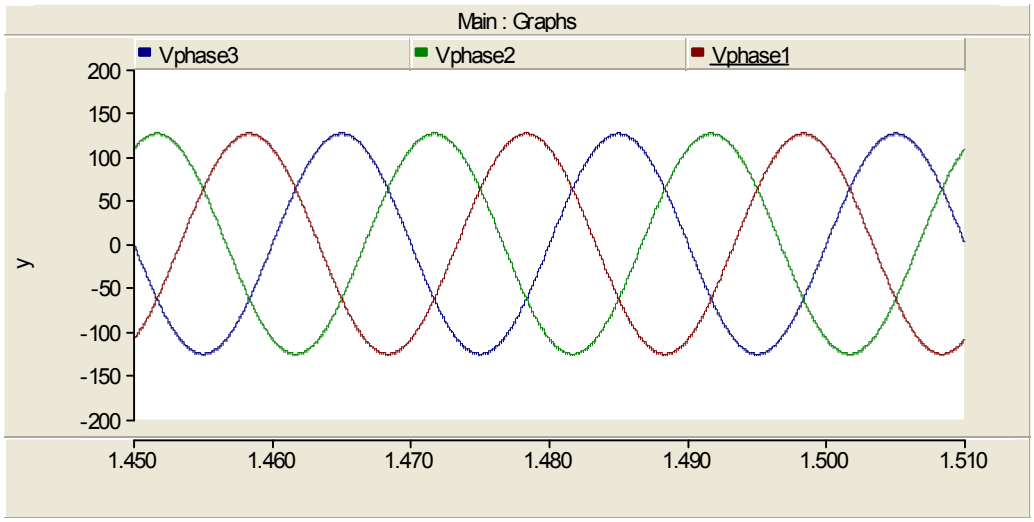


Figure 8.111.The voltage characteristic of utility network

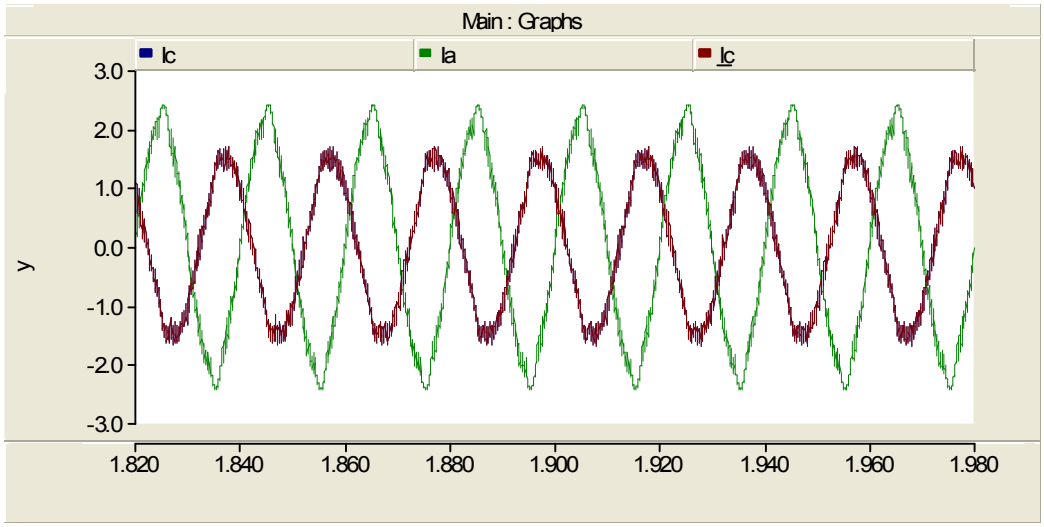
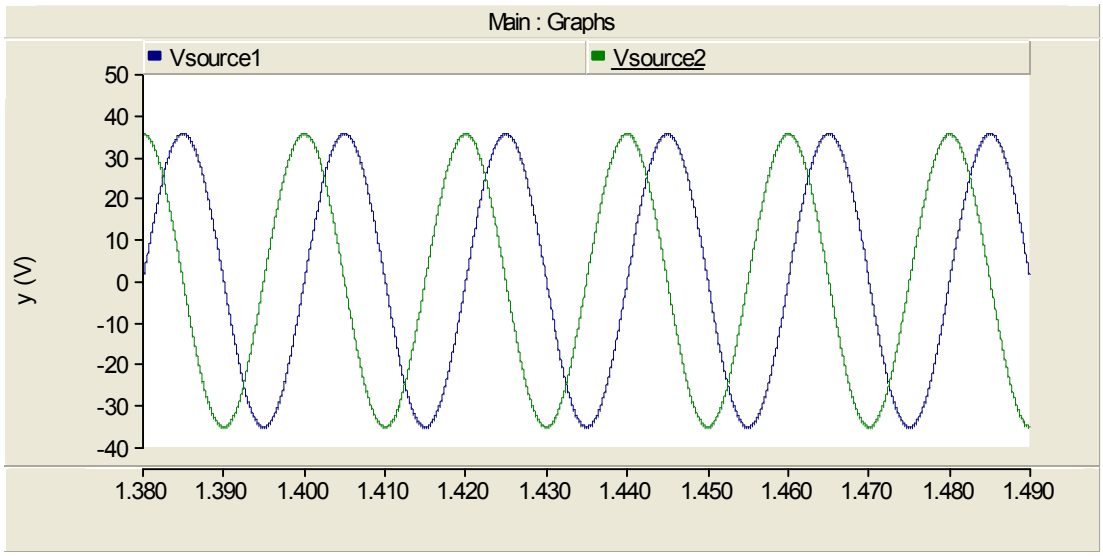
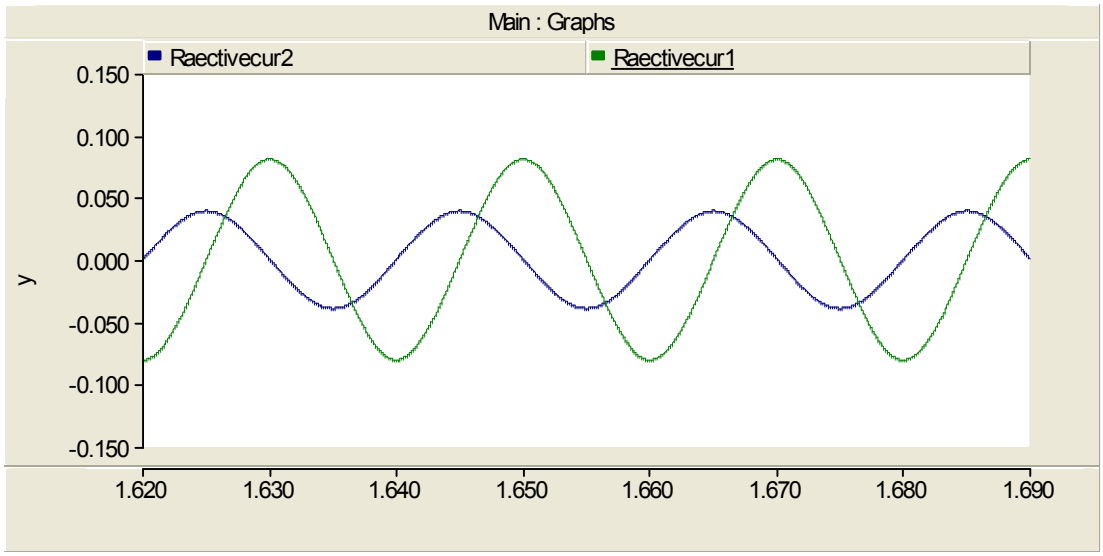


Figure 8.112. The currencts caharacteristic on utility network





When the active power filter is on , the voltage , current total harmonic distortions are measured for both side of the catenary line again. The results show that the total harmonic distortions is decreasing approximately 2% or 1% on both side of the catenary and this is a super harmonic level. But unfortunately the current levels have differences so this results are not satisfying .

9.CONCLUSIONS

The aim of the thesis is to introduce the electrified railway system and develop the power quality concern on 25kV AC railway system with a new application method.

The electrified railway system is spreading all over the world day by day because of traffic congestion , energy efficiency, environmental problems and expensive fossil fuel. Therefore the comprehensive literature research was carried out in order to introduced the electrified railway from chapter one to six chapter. Due to increasing interests to electrified railway, the power quality has also become an important concern in electrified railway system. In chapter six the power quality and its problems have been investigated by inclusive survey to identify and understand major problems which met in the applications, and also to find appropriate and satisfactory solutions.

As a result of the investigation power quality concern the new method of power quality conditioner has been proposed as a solution and it was introduced in chapter seven . The proposed single active power filter is appropriate to railway power supply system based on the asymmetrical transformer such as the Scott transformer . Most important role of Scott transformer in this study is minimizing the voltage unbalancing and converting three phase utility network voltage into two phase with 90^0 phase difference. The two single phase shunt active power filter fed by same voltage source is employed to compensate harmonic and reactive current generated by trains on the catenary line . In order to increase performance of active power enhanced phase loop lock (EPLL) technique has been used to track distortion and generate reference signal for pulse width modulator (PWM).

The simulation has been performed under the carefully chosen seven cases in seventeen different conditions by using PSCAD/EMTDC to verify the performance and operation of proposed model. The simulation results show that full reactive power compensation and proper elimination of harmonics is achieved. The current total harmonic distortion values that have been obtained by simulation are in a very good level and less than required standarts. Using PSCAD/EMTDC as a simulation

tool gives many advantages and the most important advantages were rapid simulation response and very easy operation due to visuality .

In the first case the loads thyristor rectifiers gate firing angles were assumed 90^0 and the system harmonic and reactive current compensation has been achieved very satisfactorily , the total harmonic distortion is decreased approximately % 2.8 . But the harmonic filtering performance of the active power filter was better while the interface reactor size was increasing. Reactive power compensation is achieved properly. The voltage characteristics at the utility and overhead line system were far beyond than expected. Depending on result the Scott transformer was achieved great success .

In the second case the loads thyristor rectifiers gate firing angles were 60^0 and the system harmonic and reactive current compensation has been achieved very satisfactorily , the total harmonic distortion is decreased approximately % 1.2 . But the harmonic filtering performance of the active power filter was increased when interface reactor size was adjusted to 8mH and THD was decreased to %0.9 .When the reactive power control was activated by EPLL of active filter , the THD level has increased to 2.8% . But it was still better than expected. The voltage characteristics at the utility and overhead line system were far beyond than expected. Depending on result the Scott transformer was achieved great success .

In the third case the loads thyristor rectifiers gate firing angles were 30^0 and the system harmonic and reactive current compensation has been achieved satisfactorily , the total harmonic distortion is decreased approximately % 3.3. The harmonic filtering performance of the active power filter was decreased when interface reactor size was adjusted to 8mH and THD was increased to %4.4 .When the reactive power control was activated by EPLL of active filter , the THD level was 3.9% and it was very good compensation. The voltage characteristics at the utility and overhead line system were far beyond than expected . The Scott transformer was managed to be successful depending on this results.

In the fourth case the loads thyristor rectifiers gate firing angles were 0^0 and unfortunately the system harmonic and reactive current compensation was not in bad status but it has not been achieved satisfactorily , the total harmonic distortion is

increased approximately % 11. The harmonic filtering performance of the active power filter was not changed when interface reactor size was adjusted to 8mH and THD was still at same level so it was not helpful adjustment .When the reactive power control was activated by EPLL of active filter, the THD level was still at same level but incredibly it was well compensation for reactive current. The Scott Transformer was achieved great success because the voltage characteristics at the utility and overhead line system were far beyond than expected .Basically THD level could be better with adjustment of EPLL.

Basically the following chapters five , six and seven simulation has been done to investigate the performance and response of system under unbalance load conditions.

In the fifth and sixth case one side of the transformer substation was loaded so the model has been simulated for different firing angles. The thyristor rectifiers gate firing angles were 90^0 and the system harmonic and reactive current compensation has been achieved satisfactorily in case five . The total harmonic distortion was approximately % 2.7. When the reactive power control was activated by EPLL of active filter, the THD level was 5.6 % and it was very good compensation. The Scott Transformer was achieved great success because the voltage characteristics at the utility and overhead line system were far beyond than expected . The thyristor rectifiers gate firing angles were 60^0 and the system harmonic and reactive current compensation has been achieved satisfactorily in case six also . When the reactive power control was activated by EPLL of active filter, the THD level was 3.1% and the model has achieved very good compensation.

In the seven case both side of transformer substation was loaded but the number of loads were different between the sections. Two trains were located as a load at section one and one train was located at section two. The thyristor rectifiers gate firing angles were 80^0 and the system harmonic and reactive current compensation has been achieved very satisfactorily in both end of substation. The total harmonic distortions were decreased approximately 1.9% and 2.2 % . When the reactive power control was activated by EPLL of active filter , the THD level were 3.9% and 5.6 % and these results were very good compensation. The voltage

characteristics at the utility and overhead line system were better than expected . The Scott transformer was managed to be successful depending on this results.

As reference current generator EPLL has achieved great success to for extracting harmonic and reactive current components from the load current. Its performance is evaluated when employed in a single-phase active power filter. Investigations show that the EPLL method can achieve its steady-state response in about two cycles. The important features of the EPLL are performance robustness with respect to noise and distortions, insensitivity to the uncertainties of the parameters, frequency- adaptivity and simplicity of the structure.

Finally according to all literature research and simulation results , proposed model is very suitable for implementation to 25kV AC electrified railway system . The new studies can be modelling the asynchronous motor with IGBT AC/DC drive technology as a load to evaluated the performance with AC motor or Auto-transformer system to decrease Overhead line effect to current characteristic.

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