

**UNIVERSITY OF ÇUKUROVA  
INSTITUTE OF NATURAL AND APPLIED SCIENCE**

**PhD THESIS**

**Mehmet Emin MERAL**

**VOLTAGE QUALITY ENHANCEMENT  
WITH CUSTOM POWER PARK**

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**

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**UNIVERSITY OF ÇUKUROVA  
INSTITUTE OF NATURAL AND APPLIED SCIENCE**

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**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**

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ÖZ

DOKTORA TEZİ

ÖZEL GÜÇ PARKI YARDIMIYLA GERİLİM KALİTESİNİN  
ARTTIRILMASI

Mehmet Emin MERAL

ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI  
FEN BİLİMLERİ ENSTİTÜSÜ  
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Tüketici ekipmanının hatalı çalışmasına veya devre dışı kalmasına neden olan her türlü gerilim ve akım sapması, güç kalitesi problemi olarak adlandırılır. Güç kalitesi problemleri sebeplerine göre iki sınıfa ayrılırlar. Birinci sınıfa, çoğunlukla; güç sistemindeki arızaların sebep olduğu ani gerilim düşümleri/yükselmeleri ve kesintiler gibi gerilim kalitesi problemleri dahildir. İkinci sınıf ise doğrusal olmayan yüklerden kaynaklanan düşük kaliteli yük akımı ile ilgili problemleri kapsar.

Son yıllarda, güç kalitesi problemlerine çözüm getiren ve Özel Güç Donanımları olarak adlandırılan güç elektroniği tabanlı cihazlara olan ilgi artmaktadır. Bununla birlikte, bahsedilen Özel Güç Donanımlarının bir endüstriyel/ticari güç parkına entegre edilmesiyle parkın güç kalitesi artırılabilir ve bu park Özel Güç Parkı olarak adlandırılır. Özel Güç Parkı, hassas yüklere sahip tüketicilere sürekli ve yüksek güç kalitesinde elektrik enerjisi sağlar.

Bu tezde, yukarıda birinci sınıfta belirtilen problemleri azaltmak ve gerilim kalitesini arttırmak amacıyla bir Özel Güç Parkı tasarlanmış, benzetim çalışmaları ve deneysel çalışmalar yapılmıştır. Bu amaçla modellenen, deneysel olarak kurulan ve bir alçak gerilim prototip güç parkında bir araya getirilen Özel Güç Donanımları; Dinamik Gerilim İyileştiricisi (DVR) ve Statik Transfer Anahtarıdır (STS). DVR için yeni bir gerilim kompanzasyon metodu önerilmiştir. Bununla birlikte kısa süreli gerilim düşümü ve kesintilerin tespit edilmesi amacıyla yeni bir hata tespit metodu sunulmuştur. Aynı hata tespit metodu STS için de önerilmiştir. Her iki donanım için önerilen metotlar benzetim çalışmaları ve deneysel çalışmalarda kullanılmış ve başarılı sonuçlar alınmıştır. Son olarak; bu iki cihaz bir yedek güç kaynağıyla birlikte, bir güç parkına entegre edilerek Özel Güç Parkı oluşturulmuştur. Bu Özel Güç Parkında, çeşitli hata senaryoları için gerilim kalitesinin artırılması incelenmiştir.

Bu çalışmayla birlikte, elektrik gerilim kalitesi problemlerine çözüm getiren çeşitli donanımların ülkemizde kullanımının yaygınlaştırılmasına, ülkemizin bilimsel literatürde isminin duyurulmasına ve ülke çapında yeni bir atılım olan “elektrik güç kalitesi problemlerine çözüm arama” konusunda bilinçlenmeye katkıda bulunulması hedeflenmiştir.

**Anahtar Kelimeler:** Güç Kalitesi, Özel Güç, Özel Güç Parkı, Statik Transfer Anahtarı, Dinamik Gerilim İyileştiricisi.

## ABSTRACT

### PhD THESIS

# VOLTAGE QUALITY ENHANCEMENT WITH CUSTOM POWER PARK

**Mehmet Emin MERAL**

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING  
INSTITUTE OF NATURAL AND APPLIED SCIENCES  
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A power quality problem is any voltage, current deviations that results in failure or misoperation of customer equipment. There are two classes of power quality problems according to causes. The first class covers voltage sags/swells and momentary interruptions mostly caused by faults in the power system. The second covers problems due to low quality of current drawn by the load caused by nonlinear loads.

In the recent years, power electronics based Custom Power (CP) devices that solve these problems attract attention. However, the system formed by putting together the CP devices in an industrial/commercial power park is known as Custom Power Park (CPP). The CPP provides continuous and high quality power to the customers having sensitive loads.

In this thesis, a CPP is designed, simulated and made experimental analysis to mitigate the first class problems mentioned above and enhance the voltage quality. The CP devices which are modeled, made experimental analysis and put together in a prototype low voltage power park are Dynamic Voltage Restorer (DVR) and Static Transfer Switch (STS). A new voltage compensation method is proposed for the DVR. However, a new sag detection method is presented for the DVR. The same detection method is also proposed for the STS. The proposed control methods are used for both devices in simulations and experimental setup and get successful results. Finally, the STS and the DVR are integrated to a power park prototype and the CPP is set up. The voltage quality improvements with the help of this CPP are examined against various fault scenarios.

The publications made as a result of these studies will contribute to scientific literature. Besides, it will also contribute to become conscious about a new country wide progress “finding solutions to the electric power quality problems” and this will also contribute to the using of power quality devices in our country.

**Keywords:** Power Quality, Custom Power, Custom Power Park, Static Transfer Switch, Dynamic Voltage Restorer.

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## LIST OF SYMBOLS

|               |                                       |
|---------------|---------------------------------------|
| $U_n$         | Nominal voltage                       |
| $h$           | Harmonic order                        |
| $I_{SC}$      | Maximum short circuit current         |
| $I_L$         | Maximum demand load current           |
| $P_{st}$      | Mean short term flicker severity      |
| $P_{lt}$      | Long term flicker severity            |
| $C_{STS}$     | Cost of the STS                       |
| $C_{int}$     | Cost of a production interruption     |
| $n_{int}$     | Interruption number                   |
| $T_{payback}$ | Pay-back time for the investment      |
| $C_{DVR}$     | Cost of the DVR                       |
| $V_d$         | d component of voltage                |
| $V_q$         | q component of voltage                |
| $G_I$         | Gate signal for the first IGBT signal |
| $Tr\_A$       | Injection transformer for phase A     |
| $L_f$         | Filter inductance                     |
| $C_f$         | Filter capacitance                    |
| $Ed$          | Nominal DC source voltage             |
| $V_s$         | Output voltage of the PWM inverter    |
| $I_s$         | Source current                        |
| $I_c$         | Capacitor current                     |
| $I_o$         | Load current                          |
| $V_o$         | Load voltage                          |
| $k$           | Modulation index                      |
| $K$           | Filter factor                         |
| $f_s$         | Switching frequency                   |
| $f_r$         | Fundamental frequency                 |
| $V_{oav}$     | Total harmonic of the load voltage    |
| $u(t)$        | Input signal to the PLL               |

|             |                                           |
|-------------|-------------------------------------------|
| $y(t)$      | Output of the PLL                         |
| $Mag(t)$    | Amplitude                                 |
| $\theta(t)$ | Phase angle of the tracked signal         |
| $e(t)$      | Represent the error signal                |
| $\omega_o$  | Angular frequency                         |
| $V_a$       | Phase A voltage                           |
| $V_b$       | Phase B voltage                           |
| $V_c$       | Phase C voltage                           |
| $V_p$       | Voltage phasor                            |
| $F_o$       | Cutoff frequency                          |
| $V_{phase}$ | Phase voltage                             |
| $V_{dif}$   | Real reference voltage for the PLL        |
| $x(t)$      | p.u. sinusoidal voltage output of the PLL |
| $V_{error}$ | Ideal reference voltage value for the PLL |
| $PhA$       | Phase A                                   |
| $PhB$       | Phase B                                   |
| $PhC$       | Phase C                                   |
| $V_{rms}$   | RMS value of voltage                      |
| $V_{peak}$  | Peak value of voltage                     |
| $V_{dc}$    | DC offset voltage                         |
| $\alpha$    | Alpha component                           |
| $\beta$     | Beta component                            |
| $V_{ab_p}$  | Preferred Feeder line to line AB voltage  |
| $V_{ab_a}$  | Alternate Feeder line to line AB voltage  |
| $I_{a_p}$   | Preferred Feeder phase A current          |
| $I_{a_a}$   | Alternate Feeder phase A current          |
| $R_s$       | Snubber Resistance                        |
| $C_s$       | Snubber Capacitance                       |
| $V_{pref}$  | Preferred feeder fault signal             |
| $V_{alt}$   | Alternate feeder fault signal             |
| $ZC$        | Detection of zero current transtition     |

|                  |                                                        |
|------------------|--------------------------------------------------------|
| $V_{pref\_prop}$ | Preferred feeder fault signal with proposed method     |
| $V_{pref\_conv}$ | Preferred feeder fault signal with conventioanl method |
| $ms$             | milliseconds                                           |
| $\Omega$         | Ohm                                                    |
| $F$              | Farad                                                  |
| $H$              | Henry                                                  |
| $k$              | Kilo                                                   |
| $M$              | Mega                                                   |
| $m$              | mili                                                   |
| $\mu$            | micro                                                  |
| $STS\_a$         | Alternate side of the STS                              |
| $BRK$            | Breaker                                                |
| $VT$             | Voltage Transducer                                     |
| $CT$             | Current Transducer                                     |
| $Z\_a$           | Load A impedance                                       |

## **LIST OF ABBREVIATIONS**

|       |                                                          |
|-------|----------------------------------------------------------|
| CP    | Custom Power                                             |
| STS   | Static Transfer Switch                                   |
| DVR   | Dynamic Voltage Restorer                                 |
| CPP   | Custom Power Park                                        |
| IEEE  | Institute of Electrical and Electronics Engineers        |
| IEC   | International Electrotechnical Commission                |
| POC   | Point of Connection                                      |
| USA   | United States of America                                 |
| HVDC  | High Voltage Direct Current                              |
| ASD   | Adjustable speed drive                                   |
| EPRI  | Electric Power Research Institute                        |
| US    | United States                                            |
| GDP   | Gross Domestic Product                                   |
| SARFI | System Average RMS Frequency Index                       |
| ANSI  | American National Standards Institute                    |
| EMC   | Electromagnetic Compatibility                            |
| NVE   | Norwegian Water Resources and Energy Directorate         |
| CEER  | Council of European Energy Regulators                    |
| LV    | Low Voltage                                              |
| MV    | Medium Voltage                                           |
| HV    | High Voltage                                             |
| IT    | Information Technology                                   |
| TEK   | Turkish Electric Authority                               |
| TEİAŞ | Turkey Transmission Co. Inc.                             |
| TETAŞ | The Turkish Electricity Trading and Contracting Co. Inc. |
| UCTE  | West European Electrical System                          |
| JEC   | Japanese Electro Technical Committee                     |
| EPDK  | Energy Market Regulatory Authority                       |
| TDD   | Total Demand Distortion                                  |

|          |                                                       |
|----------|-------------------------------------------------------|
| PCC      | Point of Common Coupling                              |
| THD      | Total Harmonic Distortion                             |
| RMS      | Root Mean Square                                      |
| GTO      | Gate Turn Off Thristor                                |
| SCL      | Static Current Limiter                                |
| SCB      | Static Circuit Breaker                                |
| DSTATCOM | Distribution Static Compensator                       |
| UPQC     | Unified Power Quality Conditioner                     |
| APF      | Active Power Filter                                   |
| MTS      | Mechanical Transfer Switch                            |
| CBEMA    | Computer and Business Equipment Manufacturers' Assoc. |
| VSC      | Voltage Source Converter                              |
| UPS      | Uninterruptible Power Supplies                        |
| PFC      | Power Factor Correction                               |
| SMES     | Magnetic Energy Storage                               |
| PQ       | Power Quality                                         |
| CVT      | Constant Voltage Transformer                          |
| USD      | American Dollars                                      |
| DSP      | Digital Signal Processor                              |
| FPGA     | Field Programmable Gate Array                         |
| PWM      | Pulse Width Modulation                                |
| PLL      | Phase Locked Loop                                     |
| EMTS     | Electromechanical Transfer Switches                   |
| SCR      | Silicon Controlled Rectifier                          |
| BBM      | Break Before Make                                     |
| MBB      | Make Before Break                                     |
| PPP      | Premium Power Park                                    |
| PPQP     | Premium Power Quality Park                            |
| CPPL     | Custom Power Plaza                                    |
| SSTS     | Solid State Transfer Switches                         |
| SSB      | Solid State Breaker                                   |

|         |                                   |
|---------|-----------------------------------|
| FASTRAN | Fast Transfer Switc               |
| SSVC    | Solid State VAr Compensator       |
| BG      | Backup Generator                  |
| PQCC    | Power Quality Control Centre      |
| AC      | Alternating Current               |
| DC      | Direct Current                    |
| Hz      | Hertz                             |
| VA      | Voltamper                         |
| W       | Watt                              |
| V       | Volt                              |
| A       | Amper                             |
| J       | Joule                             |
| CH1     | Measurement Channel 1 of Analyzer |
| CH2     | Measurement Channel 2 of Analyzer |
| CH3     | Measurement Channel 3 of Analyzer |

## 1. INTRODUCTION

### 1.1. General Information

Power Quality is “the ability of the electrical power system to transmit and deliver electrical energy to the customers within the specified limits. Power quality phenomena includes all possible situations in which the waveform of the supply voltage (voltage quality) or load current (current quality) deviate from the sinusoidal waveform at rated frequency with amplitude corresponding to the rated rms value for all three phases of a three-phase system. There are two classes of power quality problems according to sources of problems. The first covers voltage disturbances (voltage quality problems) caused by faults in the power system. The second covers phenomena due to low quality of current (current quality problems) drawn by the load caused by nonlinear loads (Sannino et al, 2003).

The most significant and critical power quality problems are voltage quality problems such as voltage sags or complete interruptions of the energy supply (Arora et al, 1998). These problems may cause tripping of “sensitive” electronic equipment with disastrous and may cause shutdown of the production with high costs associated.

The concept of Custom Power (CP) is the employment of power electronic or static controllers in medium or low voltage distribution systems for the purpose of supplying a level of power quality that is needed by electric power customers that are sensitive to rms voltage variations and voltage transients. CP devices, or controllers, are devices that include static switches, power converters, injection transformers, master control modules and/or energy storage modules that have the ability to perform current interruption and voltage regulation functions in a distribution system to improve power quality (IEEE P1409, 2003).

The CP devices are basically of two types - network reconfiguring type and compensating type (Ghosh et al, 2002a). Static Transfer Switch (STS) belongs to network configuring type. STS is usually a thyristor based device that is used to protect sensitive loads from voltage sags or interruptions. It can perform a sub-cycle

transfer of the sensitive load from a supplying feeder to an alternate feeder. STS is connected to a bus coupler between two incoming feeders.

The compensating devices are used for voltage regulation, active filtering, or power factor correction. Dynamic Voltage Restorer (DVR) is a series connected voltage compensating device. The main purpose of this device is to protect sensitive loads from voltage sags in the supply side. This is accomplished by rapid series voltage injection to compensate for the drop in the supply voltage. Since this is a series device, it can also be named as a “series active power filter”.

As a new CP concept of improving power quality, attention has been paid to Custom Power Park (CPP), which is able to offer customers high quality of power. The concept requires integration within a power park of multiple CP devices (such as STS and DVR), which have previously been deployed independently. These devices compensate for power quality disturbances to protect sensitive process loads as well as improve service reliability.

## **1.2. Contributions of the Thesis**

An estimated 50% of customers suffer from power quality problems that cost European industry well over 10 billion euro per year. It is similar in Turkey with respect to industrial capacity. The most significant and critical power quality problems are voltage sags or complete interruptions of the energy supply. CP Devices provides an integrated solution to the present problems that are faced by the customers and power distributors. However, in a CPP; all customers of the park benefit from high-quality power supply and did not suffer from power quality problems.

There is no enough study about CPP which is a relatively new concept in the literature. There are only a few theoretical studies and there are no experimental studies related to CPP. This study gives some help to literature. The publications made as a result of this study will contribute to scientific literature.

However, there is no enough background on power quality, voltage quality issues and CP devices in Turkey. This study will also contribute to the concept

“finding solutions to the electric power quality problems” and this will also pioneer the using of related devices in Turkey.

### 1.3. Objectives of the Thesis

The objectives of this thesis are as follows:

- To describe the power quality definitions and power quality problems,
- To describe main sources and effects of the power quality problems,
- To present the power quality standards,
- To describe standards related to power quality in Turkey,
- To describe CP concept, CP devices and CPP,
- To discuss the economical payback of the CP devices,
- To describe design and modeling of the DVR,
- To evaluate performance of the modeled DVR with simulation studies,
- To describe experimental setup of the DVR,
- To evaluate performance of the DVR with experimental analysis,
- To describe design and modeling of the STS,
- To evaluate performance of the modeled STS with simulation studies,
- To describe experimental setup of the STS,
- To evaluate performance of the STS with experimental analysis,
- To describe the design and modeling of the CPP,
- To evaluate performance of the modeled CPP with simulation studies,
- To describe experimental setup of the CPP,
- To evaluate performance of the CPP with experimental analysis.

### 1.4. Outline of the Thesis

In this study;

According to performed studies, the structure of this thesis is formed as follows:

After this introductory chapter, in Chapter 2; power quality definitions, types of the power quality problems, main sources of the power quality problems, negative effects of the power quality problems, power quality standards, standards related to power quality in Turkey are described.

Chapter 3 defines Custom Power concept, the CP devices namely DVR and STS and also CPP. Comparisons for application of various power quality devices and various economic evaluations for CP devices are presented in this chapter.

In Chapter 4, DVR with a new sag detection method is presented. Literature review, modeling and experimental setup of the proposed DVR are explained. The proposed DVR is evaluated through simulation studies and experimental results.

In Chapter 5, STS system which employs a new sag detection method is presented. Literature review, modeling and experimental setup of the proposed STS are explained. It is evaluated with simulation studies and experimental results.

There are a few simulation studies on CPP in the literature. But, this CPP study is the first experimental study in the literature. In Chapter 6, the CPP concept is presented, and then modeling and experimental setup are explained. Simulation and experimental results are also presented.

In Chapter 7, the most important conclusions of the study are explained and the suggestions for future work are given. Finally, references used for this study and biography of the author are presented.

## 2. POWER QUALITY

### 2.1. Introduction

Electrical power is the most essential raw material used by commerce and industry today. It is an unusual commodity because it is required as a continuous flow -it cannot be conveniently stored in quantity- and it cannot be subject to quality assurance checks before it is used. In reality, of course, electricity is very different from any other product. It is generated far from the point of use and is fed to the grid together with the output of many other generators and arrives at the point of use via several transformers and many kilometers of overhead and possibly underground cabling. Assuring the quality of delivered power at the point of use is no easy task (Chapman, 2001a).

Both electric utilities and end customers of electric power are becoming increasingly concerned about the quality of electric power. The term “power quality” has become one of the most prolific buzzwords in the power industry since the late 1980s (Dugan et al, 2003). Everybody does not agree with the use of the term power quality, but they do agree that it has become a very important aspect of power delivery especially in the second half of the 1990s. There is a lot of disagreement about what power quality actually incorporates. Various sources use the term power quality with different meanings. Other sources use similar but slightly different terminology like “quality of power supply” or “voltage quality” (Bollen, 2001).

Within the The Institute of Electrical and Electronics Engineers (IEEE), the term “Power Quality” has gained some official status already. But the international standards setting organization; International Electrotechnical Commission (IEC) does not yet use the term power quality in any of its standard documents. Instead it uses the term “Electromagnetic Compatibility”, which is not the same as power quality but there is a strong overlap between the two terms. Below, a number of different terms will be discussed (Bollen, 2001).

The definition of power quality given in the IEEE dictionary originates in IEEE Std. 1100: “Power quality is the concept of powering and grounding sensitive

equipment in a manner that is suitable to the operation of that equipment”. However, the following definition is given in IEC 61000-1-1: “Electromagnetic compatibility is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment” (Bollen, 2001).

From the many publications on this subject and the various terms used, the following terminology has been extracted. The reader should realize that there is no general consensus on the use of these terms. The most common terms about power quality are given below with their definitions (Bollen, 2001);

**Voltage quality:** It is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant frequency and constant magnitude. The limitation of this term is that it only covers technical aspects and that even within those technical aspects it neglects the current distortions. The term voltage quality is regularly used, especially in European publications. It can be interpreted as the quality of the product delivered by the utility to the customers.

**Current quality:** It would be a complementary definition. Current quality is concerned with deviations of the current from the ideal. The ideal current is again a single-frequency sine wave of constant frequency and magnitude. An additional requirement is that this sine wave is in phase with the supply voltage. Thus where voltage quality has to do with what the utility delivers to the consumer, current quality is concerned with what the consumer takes from the utility. Of course, voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal.

**Power quality:** Technically, in engineering terms, power is the rate of energy delivery and is proportional to the product of the voltage and current. It would be difficult to define the quality of this quantity in any meaningful manner. The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits. AC power systems are designed to operate at a sinusoidal voltage of a given frequency and magnitude. Any significant deviation in the waveform magnitude, frequency, or

purity is a potential power quality problem. Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage (Dugan et al, 2003). Power quality is often considered as a combination of voltage and current quality. In most of the cases, it is considered that the network operator is responsible for voltage quality at the point of connection (POC) while the customer's load often influences the current quality at the POC (Bhattacharyya et al, 2007).

**Power quality problem:** It is defined as “any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment”.

After this introductory section, power quality problems are explained and main sources of the problems are investigated. Also the effects of these problems to both customer and utilities are defined. Especially the costs related to power quality problems for customers and utilities are discussed. However, the IEEE and IEC power quality standards using around the world are explained. Power quality standards for Turkey, Europe and United States of America (USA) are also mentioned.

## 2.2. Power Quality Problems

Power quality has acquired intensified interest and importance during the last twenty years. On one hand, because of the widely use of non-linear loads and various faults in power system, power quality is seriously disturbed. For example, the distorted voltage, voltage sag, voltage fluctuation, flicker and other dynamic processes are caused. On the other hand, the mass use of the controlling equipment and electronic devices based on computer technology demand higher levels of power quality. This kind of devices are sensitive to small changes of power quality, a short-time change on power quality, that is power quality problems can cause great economical losses (Chengyong et al, 2004). Figure 2.1 shows main power quality problems as waveform.

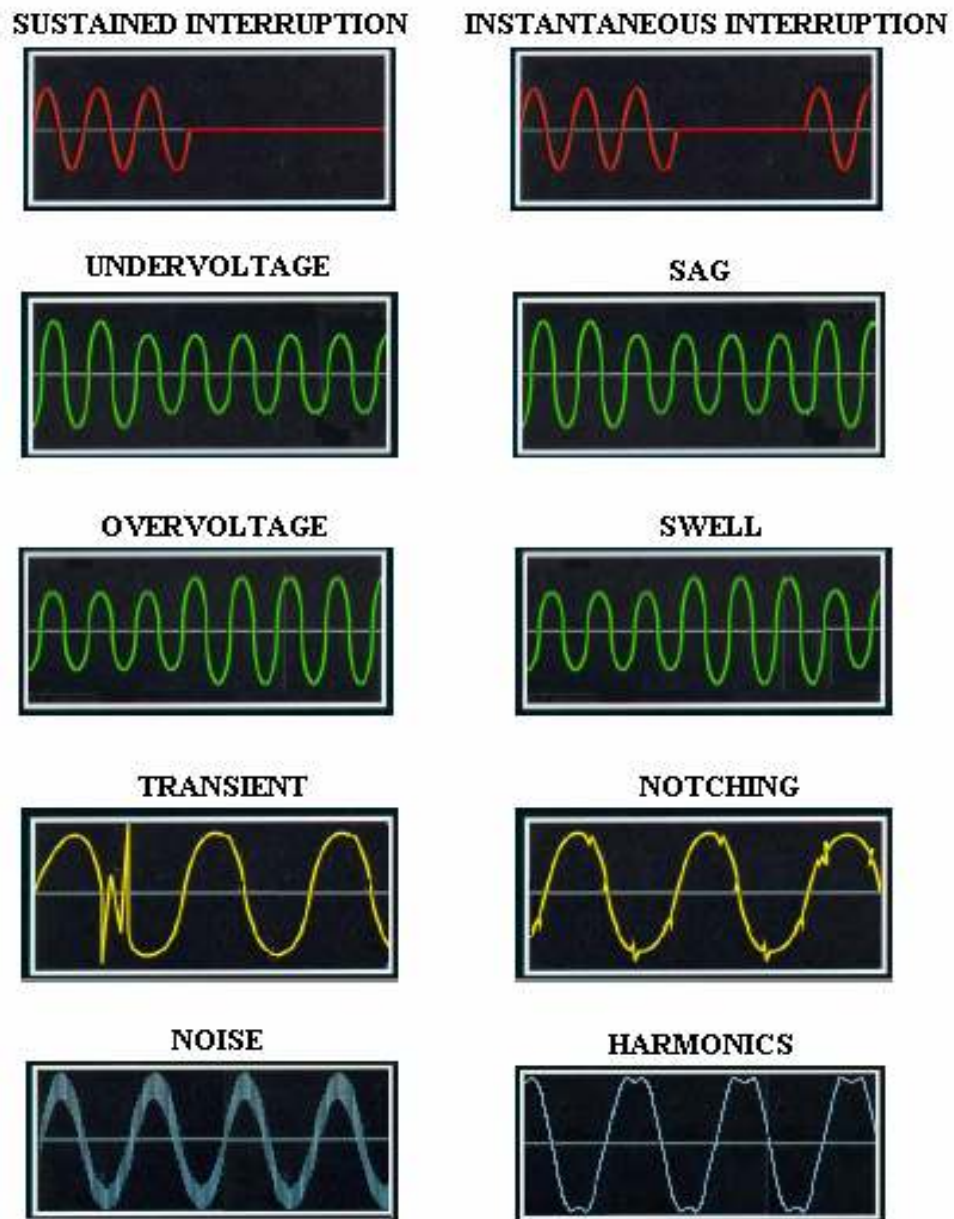


Figure 2.1. Main power quality problems as waveform

Table 2.1 also presents information regarding typical spectral content, duration and magnitude in per unit (pu). The categories in Table 2.1 provide a means to clearly describe the main power quality problems.

Table 2.1. Categories of power quality problems according to durations and magnitudes (Ceati, 2007)

| Categories of the power quality problems | Typical spectral content      | Typical duration | Typical voltage magnitude |
|------------------------------------------|-------------------------------|------------------|---------------------------|
| 1. Transients                            |                               |                  |                           |
| 1.1 Impulsive                            |                               |                  |                           |
| 1.1.1 Nanosecond                         | 5-ns rise                     | <50 ns           |                           |
| 1.1.2 Microsecond                        | 1- $\mu$ s rise               | 50 ns-1 ms       |                           |
| 1.1.3 Millisecond                        | 0.1-ms rise                   | >1 ms            |                           |
| 1.2 Oscillatory                          |                               |                  |                           |
| 1.2.1 Low frequency                      | <5 kHz                        | 0.3-50 ms        | 0-4 pu                    |
| 1.2.2 Medium frequency                   | 5-500 kHz                     | 20 $\mu$ s       | 0-8 pu                    |
| 1.2.3 High frequency                     | 0.5-5 MHz                     | 5 $\mu$ s        | 0-4 pu                    |
| 2. Short-duration events                 |                               |                  |                           |
| 2.1 Instantaneous                        |                               |                  |                           |
| 2.1.1 Interruption                       |                               | 0.5-30 cycles    | <0.1 pu                   |
| 2.1.2 Sag (dip)                          |                               | 0.5-30 cycles    | 0.1-0.9 pu                |
| 2.1.3 Swell                              |                               | 0.5-30 cycles    | 1.1-1.8 pu                |
| 2.2 Momentary                            |                               |                  |                           |
| 2.2.1 Interruption                       |                               | 30 cycles-3 s    | <0.1 pu                   |
| 2.2.2 Sag (dip)                          |                               | 30 cycles-3 s    | 0.1-0.9 pu                |
| 2.2.3 Swell                              |                               | 30 cycles-3 s    | 1.1-1.4 pu                |
| 2.3 Temporary                            |                               |                  |                           |
| 2.3.1 Interruption                       |                               | 3 s-1 min        | <0.1 pu                   |
| 2.3.2 Sag (dip)                          |                               | 3 s-1 min        | 0.1-0.9 pu                |
| 2.3.3 Swell                              |                               | 3 s-1 min        | 1.1-1.2 pu                |
| 3. Long-duration events                  |                               |                  |                           |
| 3.1 Interruption, sustained              |                               | >1 min           | 0.0 pu                    |
| 3.2 Undervoltages                        |                               | >1 min           | 0.8-0.9 pu                |
| 3.3 Overvoltages                         |                               | >1 min           | 1.1-1.2 pu                |
| 4. Voltage unbalance                     |                               | Steady state     | 0.5-2%                    |
| 5. Waveform distortion                   |                               |                  |                           |
| 5.1 DC offset                            |                               | Steady state     | 0-0.1%                    |
| 5.2 Harmonics                            | 0-100 <sup>th</sup> harmonics | Steady state     |                           |
| 5.3 Interharmonics                       | 0-6 kHz                       | Steady state     |                           |
| 5.4 Notching                             |                               | Steady state     |                           |
| 5.5 Noise                                | Broadband                     | Steady state     | 0-1%                      |
| 6. Voltage fluctuations                  | <25 Hz                        | Intermittent     | 0.1-7%                    |

### 2.2.1. Types of Power Quality Problems

Power quality problems can be divided into two types, which need to be treated in a different way (Bollen, 2001):

- **Variations:** A characteristic of voltage or current (e.g., frequency or power factor) is never exactly equal to its nominal or desired value. The small deviations from the nominal or desired value are called, “voltage variations” or “current variations”. A property of any variation is that it has a value at any moment in time; e.g., the frequency is never exactly equal to 50 Hz or 60 Hz, the power factor is never exactly unity. Monitoring of a variation thus has to take place continuously.

- **Events:** Occasionally the voltage or current deviates significantly from its normal or ideal wave shape. These sudden deviations are called “events”. Examples are a sudden drop to zero of the voltage due to the operation of a circuit breaker (a voltage event) and a heavily distorted over current due to switching of a nonleaded transformer (a current event). Monitoring of events takes place by using a triggering mechanism where recording of voltage and/or current starts the moment a threshold is exceeded.

#### 2.2.1.1. Voltage and Current Variations

A detailed overview of voltage and current variations is given below:

##### i) Voltage Magnitude Variation

Increase and decrease of the voltage magnitude due to;

- Variation of the total load of a distribution system or a part of it,
- Actions of transformer tap-changers,
- Switching of capacitor banks or reactors.

The IEC uses the term “voltage variation” instead of “voltage magnitude variation”. The IEEE does not appear to give a name to this phenomenon. Very fast

variation of the voltage magnitude is referred to as voltage fluctuation (Bollen, 2001).

## **ii) Voltage Frequency Variation**

Like the magnitude, also the frequency of the supply voltage is not constant. Voltage frequency variation is due to unbalance conditions between load and generation. Short-duration frequency transients due to short circuits and failure of generator stations are also included in voltage frequency variations, although they would better be described as events.

The IEC uses the term “power frequency variation”; the IEEE uses the term “frequency variation” (Bollen, 2001).

## **iii) Current Magnitude Variation**

On the load side, the current is normally not constant in magnitude. The variation in voltage magnitude is mainly due to variation in current magnitude. The variation in current magnitude plays an important role in the design of power distribution systems. The system has to be designed for the maximum current, where the revenue of the utility is mainly based on average current. The more constant the current, is the cheaper the system per delivered energy unit. Neither IEC nor IEEE gives a name for this phenomenon (Bollen, 2001).

## **iv) Current Phase Variation**

Ideally, voltage and current waveforms are in phase. In that case the power factor of the load equals unity and the reactive power consumption is zero. That situation enables the most efficient transport of (active) power and thus the cheapest distribution system.

Neither IEC nor IEEE give a name for this power quality phenomenon. But the terms “power factor” and “reactive power” may describe this phenomenon (Bollen, 2001).

#### **v) Voltage and Current Unbalance**

Unbalance or three-phase unbalance is the phenomenon in a three-phase system, in which the rms values of the voltages or the phase angles between consecutive phases are not equal. The severity of the voltage unbalance in a three-phase system can be expressed in a number of ways;

- The ratio of the negative-sequence and the positive-sequence voltage component,
- The ratio of the difference between the highest and the lowest voltage magnitude and the average of the three voltage magnitudes,
- The difference between the largest and the smallest phase difference between consecutive phases.

These three severity indicators can be referred to as “negative-sequence imbalance”, “magnitude unbalance” and “phase unbalance”, respectively.

The primary source of voltage unbalance is unbalanced load (thus current unbalance). This can be due to an uneven spread of (single-phase) low-voltage customers over the three phases, but more commonly unbalance is due to a large single-phase load. Examples of the latter can be found among railway traction supplies and arc furnaces. Three-phase voltage unbalance can also be the result of capacitor bank anomalies, such as a blown fuse in one phase of a three-phase bank.

The IEEE mainly recommends the term “voltage unbalance” although some standards use the term “voltage imbalance” (Bollen, 2001).

#### **vi) Voltage Fluctuation**

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes. Arc furnaces are the most common cause of

voltage fluctuations on the transmission and distribution system (Martinez, 1998). If the voltage variations are large enough or in a certain critical frequency ranges, the performance of equipment can be affected. Cases in which voltage variation affects load behavior are rare, with the exception of lighting load. If the illumination of a lamp varies with frequencies between about 1 Hz and 10 Hz, our eyes are very sensitive to it and above a certain magnitude the resulting light flicker can become rather disturbing. The fast variation in voltage magnitude is called “voltage fluctuation”; the visual phenomenon as perceived by our brain is called “light flicker” or “voltage flicker”.

The terms “voltage fluctuation” and “light flicker” are used by both IEC and IEEE (Bollen, 2001). Sources of voltage fluctuations are as follows:

It can be seen that the primary cause of voltage changes is the time variability of the reactive power component of fluctuating loads. Such loads include, for example, arc furnaces, rolling mill drives, main winders, etc. – in general, loads with a high rate of change of power with respect to the short circuit capacity at the point of connection to the supply.

It is very important to note that small power loads such as starting of induction motors, welders, boilers, power regulators, electric saws and hammers, pumps and compressors, cranes, elevators etc. can also be the sources of flicker. Other causes are capacitor switching and on-load transformer tap changers, which can change the inductive component of the source impedance (Leonardo, 2009).

#### **vii) DC Offset**

The presence of a DC voltage or current in an AC power system is termed DC offset. This phenomenon can occur as the result of a geomagnetic disturbance or due to the effect of half-wave rectification. Incandescent light bulb life extenders, for example, may consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification (Dugan et al, 2003).

**viii) Harmonic Voltage Distortion**

The voltage waveform is never exactly a single frequency sine wave. This phenomenon is called “harmonic voltage distortion”. When we assume a waveform to be periodic, it can be described as a sum of sine waves with frequencies being multiples of the fundamental frequency (Bollen, 2001).

There are three contributions to the harmonic voltage distortion:

- The voltage generated by a synchronous machine is not exactly sinusoidal due to small deviations from the ideal shape of the machine.
- The power system transporting the electrical energy from the generator stations to the loads is not completely linear, although the deviation is small. The classical example is the power transformer, where the nonlinearity is due to saturation of the magnetic flux in the iron core of the transformer. A more recent example of a nonlinear power system component is the High Voltage Direct Current (HVDC) link. The transformation from AC to DC and back takes place by using power-electronics components which only conduct during part of a cycle.
- The main contribution to harmonic voltage distortion is due to nonlinear load. A growing part of the load is fed through power-electronics converters drawing a non-sinusoidal current. The harmonic current components cause harmonic voltage components and thus a non-sinusoidal voltage, in the system.

Within the IEEE and IEC, the term “distortion” is used to refer to harmonic distortion (Bollen, 2001).

**ix) Harmonic Current Distortion**

As harmonic voltage distortion is mainly due to non-sinusoidal load currents, harmonic voltage and current distortion are strongly linked. Harmonic current distortion requires over-rating of series components like transformers and cables. As the series resistance increases with frequency, a distorted current will cause more losses than a sinusoidal current of the same rms value (Bollen, 2001).

Types of equipments that generate harmonic currents are (Chapman, 2001b):

- Switched mode power supplies (SMPS)
- Electronic fluorescent lighting ballasts
- Small and/or large Uninterruptible Power Supplies (UPSs)
- Variable speed drives

#### **x) Interharmonics**

Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz) are called interharmonics. Interharmonics can be found in networks of all voltage classes. The main sources of interharmonics waveform distortion are static frequency converters, cyclo-converters, induction motors and arcing devices (Omniverter, 2009).

#### **xi) Notching**

A notch is a periodic voltage disturbance of opposite polarity from the waveform. It is caused by the normal operation of power electronics devices when current is commutated from one phase to another, or caused by switching operations. Voltage notching represents a special case that falls between transients and harmonic distortion (Barros et al, 2009). For example, in three-phase rectifiers the commutation from one diode or thyristor to the other creates a short circuit with a duration less than 1 ms, which results in a reduction in the supply voltage called “voltage notching” or simply “notching”.

#### **xii) Noise**

The supply voltage contains components which are not periodic at all. These can be called “noise”. Noise is an unwanted electrical signal of high frequency from other equipments. Noise in power systems can be caused by control circuits, electromagnetic interference, micro-wave and radar transmission. Improper

grounding often exacerbates noise problems. Noise consists of any unwanted distortion of the power signal that can not be classified as harmonic distortion or transients (IEEE1159, 1995).

#### **2.2.1.2. Events**

Events are phenomena which only happen every once in a while. A momentary interruption of the supply voltage is the best-known example.

##### **i) Transients**

A transient is “that part of the change in a variable that disappears during transition from one steady state operating condition to another”. Another word in common usage that is often considered synonymous with transient is “surge”. A utility engineer may think of a surge as the transient resulting from a lightning stroke for which a surge arrester is used for protection. Transients can be classified into two categories: “impulsive” and “oscillatory” (Dugan et al, 2003).

An impulsive transient is a sudden, non-power frequency change in the steady-state condition of voltage or current, that includes unidirectional in polarity. Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. For example, a “1.2-50 $\mu$ s, 2000 impulsive transient” nominally rises from zero to its peak value of 2000 V in 1.2  $\mu$ s and then decays to half its peak value in 50  $\mu$ s. The most common cause of impulsive transients is lightning.

An oscillatory transient is a sudden, non-power frequency change in the steady-state condition of voltage or current, that includes both positive and negative polarity values. Oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds (or several cycles of the principal frequency) are considered high-frequency transients. These transients are often the result of a local system response to an impulsive transient.

## ii) Interruptions

A “voltage interruption” (IEEE100, 1992) or “supply interruption” (EN50160, 1999), is a condition in which the voltage at the supply terminals is close to zero. Close to zero is by the IEC defined as “lower than 1% of the declared voltage” and by the IEEE as “lower than 10%” (IEEE100, 1992) for a period of time not exceeding 1 min (Bollen, 2001).

Interruptions durations are subdivided into three categories-instantaneous, momentary and temporary which coincide with the three categories of sags and swells. Interruptions can be the result of power system faults, equipment failures, control malfunctions, switching operations or very short power loss. The duration of an interruption due to a fault on the utility system is determined by the operating time of utility protective devices. Delayed re-closing of the protective device may cause a momentary or temporary interruption (Dugan et al, 2003).

## iii) Voltage Sags

A “voltage sag” is a decrease to between 0.1 and 0.9 pu in rms voltage at the power frequency for durations from 0.5 cycles to 1 min. Voltage sags are usually associated with system faults but can also be caused by energization of heavy loads or starting of large motors and overloaded wiring.

The power quality community has used the term “sag” for many years to describe a short-duration voltage decrease. Although the term has not been formally defined, it has been increasingly accepted and used by utilities, manufacturers and end users. The IEC definition for this phenomenon is “dip”. Terminology used to describe the magnitude of voltage sag is often confusing. A “20 percent sag” can refer to a sag which results in a voltage of 0.8 or 0.2 pu. The preferred terminology would be one that leaves no doubt as to the resulting voltage level: “a sag to 0.8 pu” or “a sag whose magnitude was 20 percent”. When not specified otherwise, a 20 percent sag will be considered an event during which the rms voltage decreased by

20 percent to 0.8 pu. The nominal, or base, voltage level should also be specified (Dugan et al, 2003).

#### **vi) Voltage Swells**

A “voltage swell” is defined as an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min. As with sags, swells are usually associated with system fault conditions, but they are not as common as voltage sags (Dugan et al, 2003).

Swells can also be caused by switching off a large load or energizing a large capacitor bank, insulation breakdown, sudden load reduction and open neutral connection.

#### **v) Sustained Interruptions**

When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a “sustained interruption”. Voltage interruptions longer than 1 min are often permanent and require human intervention to repair the system for restoration. The term sustained interruption refers to specific power system phenomena and, in general, has no relation to the usage of the term “outage”. Utilities use outage to describe phenomena of similar nature for reliability reporting purposes. However, this causes confusion for end users who think of an outage as any interruption of power that shuts down a process. This could be as little as one-half of a cycle. Outage, as defined in IEEE (IEEE100, 1992) does not refer to a specific phenomenon, but rather to the state of a component in a system that has failed to function as expected. Also, use of the term interruption in the context of power quality monitoring has no relation to reliability or other continuity of service statistics. Thus, this term has been defined to be more specific regarding the absence of voltage for long periods (Dugan et al, 2003).

Sustained interruptions are caused by malfunction of customer equipment, operations of protective devices in response to faults that occur due to nature or accidents.

#### **vi) Undervoltages**

An “undervoltage” is a decrease in the rms ac voltage to less than 0.9 pu for duration longer than 1 min (Dugan et al, 2003). Switching on of large loads, overloaded customer wiring loose, unbalanced phase loading and incorrect tap setting can cause an undervoltage.

#### **vii) Overvoltages**

An “overvoltage” is an increase in the rms ac voltage greater than 110% at the power frequency for a duration longer than 1 min. Overvoltages are usually the result of load switching that are the opposite of the events that cause undervoltages. (e.g., switching off a large load or energizing a capacitor bank). The overvoltages result because either the system is too weak for the desired voltage regulation or voltage controls are inadequate. Incorrect tap settings on transformers or improper application of power factor correction capacitors can also result in system overvoltages (Dugan et al, 2003).

### **2.2.2. Main Sources of Power Quality Problems**

Recent studies conducted by the Edison Electrical Institute show that 80-90 % of all power quality issues result from onsite problems, rather than utility problems. But, more importantly, the studies indicate that power quality problems are on the rise for industrial and commercial customers. These problems can range from improper grounding and bonding to code violations and internally generated power disturbances (Walawalkar et al, 2002). Main sources of power quality problems can be summarized below (Stones et al, 2001):

**i) Load Switching**

The effect of heavy load switching on the local network is a fairly common problem causing transients to propagate through to other “electrically close” equipment. These transients can be of surprisingly large voltage magnitude but have very little energy due to their short duration, which is normally measured in terms of milliseconds.

**ii) Power Electronic Devices**

Power electronic devices are non-linear loads that create harmonic distortion and can be susceptible to voltage sags if not adequately protected. The most common “economically damaging” power quality problem encountered involves the use of variable-speed drives. Variable-speed motor drives or inverters are highly susceptible to voltage sag disturbances and cause particular problems in industrial processes where loss of mechanical synchronism is an issue.

**iii) IT and Office Equipment**

IT (Information Technology) equipment power supplies consist of a switched mode DC power supply and are the cause of a significant increase in the level of 3<sup>rd</sup>, 5<sup>th</sup> and 7<sup>th</sup> harmonic voltage distortion in recent years. Because the 3<sup>rd</sup> harmonic is a ‘triple’ harmonic it is of zero order phase sequence and therefore adds in the neutral of a balanced three-phase system. The increasing use of IT equipment has led to concern of the increased overloading of neutral conductors and also overheating of transformers. Recent developments have seen the use of switched mode power supplies in fluorescent lighting applications; these lighting applications typically represent in the region of 50% of a modern building’s load.

**iv) Arcing Devices**

Electric arc furnaces, arc welders and electric discharge lamps are all forms of electric arcing device. These devices are highly non-linear loads. The current waveform drawn is characterized by an increasing arc current limited only by the network impedance. All arcing devices are sources of harmonic distortion. The arcing load can be represented as a relatively stable source of voltage harmonics. Arc welders commonly cause transients in the local network due to the intermittent switching and therefore some electronic equipment may require protection from the impulsive spikes generated.

**v) Embedded Generation**

Increasing levels of embedded generation predicted in the future are likely to have an effect on power quality. An increased amount of embedded generation at substation level and below will lead to increased fault current levels in the feeders.

**vi) Large Motor Starting**

The dynamic nature of induction machines means that they draw current depending on the mode of operation; during starting this current can be as high as six times the normal rated current. This increased loading on the local network has the effect of causing a voltage sag, the magnitude of which is dependent on the system impedance.

**vii) Storm and Environment Related Damage**

Lightning strikes are a cause of transient over voltages often leading to faults on the electricity supply network.

**viii) Wiring and Grounding**

Grounding and wiring problems account for up to 80% of all power quality problems, making them the most important consideration for successful operation of sensitive electronic equipment.

**ix) Saturated Transformers**

The operation of transformers closer to the saturation region of magnetization characteristics can cause harmonic distortions on sinusoidal waveform.

**x) Other Sources of Power Quality Problems**

Other sources of power quality problems are compressors, battery chargers, circuit breaker switching, electronic power supplies, lighting ballasts, insulator flashover, lightning strike, silicon-controlled rectifiers, X-Ray machines and tree damage to wires.

**2.2.3. Effects of Power Quality Problems**

In this section, the damage of equipment and the economic costs of these damages due to the power quality problems are defined.

**2.2.3.1. Effects of Most Common Power Quality Problems on the Electrical and Electronic Equipments****i) Effects of Voltage Sags**

Voltage sags are the most common power disturbance which certainly gives affecting especially in industrial and large commercial customers such as the damage of the sensitivity equipments and loss of daily productions and finances. Also, it

causes system halts, loss of data and shutdown hardware damage, motor stalling and reduced life of motors (Wahab et al, 2006), (Ceati, 2007). An example of the sensitivity equipments to the voltage sag are Programmable Logic Controller (PLC), computers, controller power supplies, motor starter contactors, control relays, adjustable speed drive (ASD) and chiller control. Typical voltage sag problems in industrial equipment include (Eberhard et al, 2007):

- Relays opening, due to the sag affecting the relay's coil voltage,
- Undervoltage sensors on the ac mains operating unnecessarily,
- Incorrect reports from sensors, such as air flow sensors or water pressure sensors,
- Circuit breakers or fuses operating, either due to the increase in current on non-dipped phases or (more often) due to a large increase in current immediately after the sag; or a small section of highly-sensitive electronics that responds incorrectly to the sag.

## **ii) Effects of Voltage Swells**

Voltage swells can affect the performance of sensitive electronic equipment, cause data errors, produce equipment shutdowns, may cause equipment damage and reduce equipment life. It causes nuisance tripping and degradation of electrical contacts. Also it causes most of the problems as voltage sag which explains above (Bangor, 2009).

## **iii) Effects of Harmonics**

Harmonics cause problems both on the supply system and within the installation. The effects and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa. There are several common problem areas caused by harmonics. Harmonic voltage distortion can lead to control errors and malfunction of equipment.

This can especially be a big problem in industrial power systems, where there is a large concentration of distorting load as well as sensitive load (Bollen, 2001).

However, the problems caused by harmonic currents (Chapman, 2001b) are:

- Overloading of neutrals,
- Overheating of transformers,
- Tripping of circuit breakers,
- Over-stressing of power factor correction capacitors.

Problems caused by harmonic voltages are:

- Voltage distortion,
- Zero-crossing noise.

#### **iv) Effects of Fluctuations (Flickers)**

Voltage fluctuations in power systems cause a number of harmful technical effects resulting in disruption to production processes with substantial costs. However, the physiological effect of flicker is the most important because it affects the ergonomics of the production environment, causing operator fatigue and reduced concentration levels. In addition, irregular operation of contactors and relays can cause severe disruption to production processes. Illustrative examples of the adverse effects of voltage fluctuation are presented below (Hanzelka et al, 2006).

- Voltage fluctuations at the terminals of an induction motor cause changes in torque and slip and consequently affect the production process.
- The usual effect of voltage fluctuation in phase-controlled rectifiers with dc-side parameter control is a reduction of power factor and the generation of non-characteristic harmonics and inter-harmonics.
- Any change in supply voltage magnitude results in a change in the luminous flux of a light source and this is known as flicker.

#### **v) Effects of Transients**

Some of the effects of transients are below (Stedi, 2008):

- Electronic devices may operate erratically. Equipment could lock up or produced garbled results. Integrated circuits (sometimes called “electronic chips”) may fail immediately or fail prematurely. Most of the time, the failure is attributed to age of the equipment.

- Motors will run at higher temperatures when transient voltages are present. Transients can interrupt the normal timing of the motor. This type of disruption produces motor vibration, noise and excessive heat. Motor winding insulation is degraded and eventually fails. Transients produce hysteresis losses in motors that increase the amount of current necessary to operate the motor. Transients can cause early failures of electronic motor drives and controls.

- Transient activity causes early failure of all types of lights. Fluorescent systems suffer early failure of ballasts, reduced operating efficiencies and early bulb failures.

- The facility's electrical distribution system is also affected by transient activity. Transients degrade the contacting surfaces of switches, disconnect switches and circuit breakers. Intense transient activity can produce “nuisance tripping” of breakers by heating the breaker and “fooling” it into reacting to a non-existent current demand.

- Electrical transformers are forced to operate inefficiently because of the hysteresis losses produced by transients and can run hotter than normal.

#### **vi) Effects of Momentary Interruptions and Sustained Interruptions**

The main effects of momentary interruptions are system shut down, equipment trip off, loss of computer/controller memory. However, the main effects of sustained interruptions are product loss and loss of computer memory (Ceati, 2007).

**vii) Effects of Overvoltages and Undervoltages**

Overvoltage results in overheating and reduced life of electrical equipments. Undervoltages result in low efficiency and reduced life of electrical equipment, hardware damage and lengthening process time (Ceati, 2007).

**viii) Effects of Noises and Notching**

Noise disturbs sensitive electronic equipment but is usually not destructive. It can cause processing errors and data loss. Notching mainly results in high-order harmonics, which are often not considered in power engineering (Bollen, 2001). It also can be leads to processing errors and data loss.

**ix) Effects DC offset**

Direct current in alternating current networks can be detrimental due to an increase in transformer saturation, additional stressing of insulation and other adverse effects (P1433, 2009).

**ix) Effects of Voltage Unbalance and Current Unbalance**

Unbalance also leads to additional heat production in the winding of induction and synchronous machines; this reduces the efficiency of the machine (Bollen, 2001).

**2.2.3.2. Effect of Power Quality Problems to the Industries**

Effects of power quality problems can be shown up in many aspects of industrial operations. The aspects include loss of production, manufacturing interruptions, loss of revenue, decreased competitiveness, lost opportunities, product

damage, wasted energy, and decreased equipment life. Followings are brief explanations that define those aspects (Muhamad et al, 2007).

**i) Loss of Production**

Each time production is interrupted, the business loses the margin on the product that is not manufactured and not sold.

**ii) Manufacturing Interruption**

It is because some portion of certain manufacturing systems is affected by power quality disturbances, the whole system may not meet the performance requirements, product quality and production volume. There are some proactive manufacturers that have investigated these power quality linkages and invested in adequate backup or protection systems will have lower cost or product loss figures than the manufacturers that are uneducated inexperienced or completely ignore the need for proper backup or protection systems. Reacting to a voltage disruption can include everything involving restoring production, diagnosing and correcting the problem, clean up and repair and disposing of damaged product.

**iii) Loss of Revenue**

Any direct interruption to a manufacturing process can interrupt sales resulting in delayed production schedules. The loss of revenue from any kind of process is generally on observable.

**iv) Decreased Competitiveness**

Power quality problems in the manufacturing environment can often result in customer dissatisfaction and a poor quality product, as well as delayed production

schedules. These shortcomings almost certainly decrease competitiveness and can be very costly.

**v) Lost Opportunity**

Any power quality problems that impact any type of product processes can also mean lost opportunity sales because of two factors. One is the marketing of a new product at just the right time. Two is for the marketing of seasonal products at the peak of the season.

**vi) Product Damage**

Sometimes power quality problems in manufacturing processes can result in product damage. Occasionally, the damage can be directly observed and the damaged product is discarded or recycled. Product damage can be costly if the damage is subtle and the effects take some time to surface.

**vii) Wasted Energy**

Any interruption to a manufacturing process will result in a waste of energy in the restart process. In the case where product damage occurs because of a process stop or misoperation due to some type of disturbance, the energy up to that point is wasted.

**viii) Decreased Equipment Life Time**

Many systems that experience disturbances, both detected and undetected, have resulted in decreased equipment life. High energy, fast rise time transients can cause outright circuit board failure, even for systems protected by transient suppressors or can cause degradation over time such that burnout is only delayed.

Harmonic distortion and phase unbalance can combine to overstress motors and transformers and shortening their useful life times.

### **2.2.3.3. Various Research Studies about Costs Related to Voltage Quality Problems**

Several European countries have estimated customers' costs related to short and long interruptions over the past years and decades. These costs are normally based upon nation wide customer surveys. Very few countries have estimated customers costs related to poor voltage quality. Some surveys about different countries' costs related to voltage quality problems and short interruptions are described in below:

#### **i) In Norway**

A national research project finished in 2002 based on a nation wide customer survey including both long and short interruptions and some selected voltage quality problems (Ergeg, 2006). Results from the project have given the following costs for final customers in Norway related to large deviations for some voltage quality parameters and short interruptions:

- Supply voltage variations: Annual costs because of too high and too low stationary voltage, based on the response from seven companies within the process industry, are approximately 5375 € and 17875 € respectively per respondent.
- Transient overvoltages: Annual costs, based on the response from eight companies within the process industry, are approximately 3125 € per respondent.
- Supply voltage sags: Annual costs for Norwegian final customers are estimated to be between approximately 21.3 M€ and 41.3 M€.
- Short interruptions: Annual costs for Norwegian final customers is estimated to be between approximately 47.5 M€ and 66.3 M€.

**ii) In USA**

Various projects realized for USA:

- Clemmensen (Clemmensen, 1999) provided the first-ever power-quality cost estimate of \$26 billion for the U.S. manufacturing sector. This estimate was adopted by Electric Power Research Institute (EPRI) and subsequently widely cited throughout the 1990s. It is important to note that Clemmensen's estimate was for annual spending on industrial equipment to address power-quality problems; power-quality problems normally refer to a subset of reliability problems in which voltage drops (in some cases to zero) for a very short period of time, typically for only a few cycles or seconds (Gyuk et al, 2004).
- In 2001, EPRI commissioned and published a report from Primen. This report is the first systematic effort to estimate the national economic cost of power interruptions including power quality (Ceids, 2001). Primen estimates USA power interruption costs at \$119 billion per year.

**iii) In Bangladesh**

A survey study examined the economic impact of the quality of electricity delivered to the industrial installations in Bangladesh, including power interruptions, voltage fluctuations, and supply harmonics. The assessment consists of reviewing existing guidelines on power quality, analyzing poor power quality and its economic impact on a sample of industrial consumers, estimating self-generation costs and environmental impacts, and providing recommendations for power quality improvements. The investigation was carried out using a detailed nationwide survey sample of industries consisting of 208 installations covering main categories of industries contributing to the country's gross domestic product (GDP) growth. The survey was based on a structured questionnaire administered during August through October of 2002. The study data used are based on responses to the questionnaire concerning fiscal year 2001 (Nexant, 2003). Results are as follows:

- Industrial sector losses attributable to unplanned electric power interruptions average 0.83 US\$/kWh, while they are only 0.34 US\$/kWh for planned outages. Thus the unplanned interruptions result in economic losses that are nearly two and one-half times those of planned interruptions.

- These interruptions result in a substantial economic loss in the industrial sector amounting to US\$ 778 million a year. This translates into 11.54% of the industrial sector GDP or 1.72% of the national GDP in 2000.

#### **iv) In Sweden**

A research project finished in 2003 based on an earlier made customer survey, resulted in estimated annual costs for industrial customers related to short interruptions and voltage sags, from 105 M€ to 157 M€ (actual costs) (Ergeg, 2006).

### **2.3. Power Quality Standards**

The requirements of electricity customers have changed tremendously over the years. Equipment has become much more sensitive to power quality variations and some types of equipment can be the cause of power quality problems. Standards are needed to achieve coordination between the characteristics of the power supply system and the requirements of the end use equipment. This is the role of power quality standards. During the past 15 years much progress has been made in defining power quality phenomena and their effects on electrical and electronic equipment. In addition methods have been established for measuring these phenomena and in some cases defining limits for satisfactory performance of both the power system and connected equipment. In the international community, both IEEE and IEC have created a group of standards that addresses these issues from a variety of perspectives (McGranaghan et al, 2002).

### **2.3.1. Purpose of Standardization**

Standards that define the quality of the supply have been present for decades already. Almost any country has standards defining the margins in which frequency and voltage are allowed to vary. Other standards limit harmonic current and voltage distortion, voltage fluctuations and duration of an interruption. There are three main reasons for developing power quality standards (Bollen, 2001).

#### **i) Defining the Nominal Environment**

A hypothetical example of such a standard is: “The voltage shall be sinusoidal with a frequency of 50 Hz and an rms voltage of 230 V”. Such a standard is not very practical as it is technically impossible to keep voltage magnitude and frequency exactly constant. Therefore, existing standards use terms like “nominal voltage” in this context. A more practical version of the above standard text would read as: “The nominal frequency shall be 50 Hz and the nominal voltage shall be 230 V” which comes close to the wording in European standard EN 50160 (Bollen, 2001).

#### **ii) Defining the Terminology**

Even if a standard-setting body does not want to impose any requirements on equipment or supply, it might still want to publish power quality standards. A good example is IEEE Std.1346 which recommends a method for exchanging information between equipment manufacturers, utilities and customers. The standard does not give any suggestions about what is considered acceptable.

This group of standards aims at giving exact definitions of the various phenomena, how their characteristics should be measured and how equipment should be tested for its immunity. The aim of this is to enable communication between the various partners in the power quality field. It ensures, e.g., that the results of two power quality monitors can be easily compared and that equipment immunity can be compared with the description of the environment. Hypothetical examples are: “A

short interruption is a situation in which the rms voltage is less than 1% of the nominal rms voltage for less than 3 minutes” and “the duration of a voltage sag is the time during which the rms voltage is less than 90% of the nominal rms voltage” (Bollen, 2001).

### **iii) Limit the Number of Power Quality Problems**

Limiting the number of power quality problems is the final aim of all the work on power quality. Power quality problems can be mitigated by limiting the amount of voltage disturbances caused by equipment, by improving the performance of the supply and by making equipment less sensitive to voltage disturbances. All mitigation methods require technical solutions which can be implemented independently of any standardization. But proper standardization will provide important incentives for the implementation of the technical solutions. Proper standardization will also solve the problem of responsibility for power quality disturbances. Hypothetical examples are: The current taken by a load exceeding 4 kVA shall not contain more than 1% of any even harmonic. The harmonic contents shall be measured as a 1-second average and Equipment shall be immune to voltage variations between 85% and 110% of the nominal voltage. This shall be tested by supplying at the equipment terminals, sinusoidal voltages with magnitudes of 85% and 110% for duration of 1 hour (Bollen, 2001).

### **2.3.2. Power Quality Standards of IEEE**

Disturbances are events that do not occur on a regular basis but can impact the performance of equipment. They include transients, voltage variations (sags swells) and interruptions (McGranaghan, 2005).

### **2.3.2.1. IEEE Standards Related with Voltage Sags and Interruptions**

Voltage sags fall in the category of short duration voltage variations. According to IEEE Standard 1159 and IEC definitions, these include variations in the fundamental frequency voltage that last less than one minute. These variations are best characterized by plots of the rms voltage versus time but it is often sufficient to describe them by a voltage magnitude and a duration that the voltage is outside of specified thresholds. It is usually not necessary to have detailed waveform plots since the rms voltage magnitude is of primary interest (McGranaghan, 2005).

The voltage variations can be a momentary low voltage (voltage sag), high voltage (voltage swell) or loss of voltage (interruption). IEEE Standard 1159 specifies durations for instantaneous, momentary and temporary disturbances.

There is considerable standards work under way to define indices for characterizing voltage sag performance. In IEEE, this work is being coordinated by IEEE P1564. The most common index use is SARFIx (System Average RMS Frequency Index). This index represents the average number of voltage sags experienced by an end user each year with a specified characteristic. For SARFIx, the index would include all of the voltage sags where the minimum voltage was less than x. For example, SARFI70 represents the expected number of voltage sags where the minimum voltage is less than 70%. The SARFI index and other alternatives for describing voltage sag performance are being formalized in the IEEE Standard 1564 Working Group (McGranaghan, 2005).

### **2.3.2.2. IEEE Standards Related with Transients**

The term “transient” is normally used to refer to fast changes in the system voltage or current. The most well-known standard in the field of transient overvoltage protection is ANSI (American National Standards Institute) / IEEE C62.41-1991 and IEEE Guide for Surge Voltages in Low Voltage AC Power Circuits. This standard defines the transient environment that equipment may see and provides specific test waveforms that can be used for equipment withstand testing. The

transient environment is a function of the equipment or surge suppressor location within a facility as well as the expected transients from the supply system. (McGranaghan, 2005)

### **2.3.3. Electromagnetic Compatibility Standards of IEC**

Within the IEC a comprehensive framework of standards on electromagnetic compatibility is under development. Electromagnetic Compatibility (EMC) is defined as: the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

There are two aspects to EMC: (1) a piece of equipment should be able to operate normally in its environment and (2) it should not pollute the environment too much. In EMC terms: immunity and emission. There are standards for both aspects (Bollen, 2001).

#### **2.3.3.1. Immunity Requirements**

Immunity standards define the minimum level of electromagnetic disturbance that a piece of equipment shall be able to withstand. Before being able to determine the immunity of a device, a performance criterion must be defined. In other words, it should be agreed upon what kind of behavior will be called a failure. In practice it will often be clear when a device performs satisfactorily and when not, but when testing equipment the distinction may become blurred. It will all depend on the application whether or not a certain equipment behavior is acceptable.

The basic immunity standard IEC-61000-4-1 gives four classes of equipment performance:

- Normal performance within the specification limits.
- Temporary degradation or loss of function which is self-recoverable.
- Temporary degradation or loss of function which requires operator intervention or system reset.

- Degradation or loss of function which is not recoverable due to damage of equipment, components or software, or loss of data.

### 2.3.3.2. Emission Standards

Emission standards define the maximum amount of electromagnetic disturbance that a piece of equipment is allowed to produce. Within the existing IEC standards, emission limits for harmonic currents are IEC 61000-3-2 and 61000-3-6. For voltage fluctuations, standards are IEC 61000-3-3, 61000-3-5 and 61000-3-7. Most power quality phenomena are not due to equipment emission but due to operational actions or faults in the power system. As the EMC standards only apply to equipment, there are no “emission limits” for the power system. Events like voltage sags and interruptions are considered as a “fact-of-life” These events do, however, contribute to the electromagnetic environment (Bollen, 2001).

### 2.3.4. Standards of Events According to the IEEE and IEC

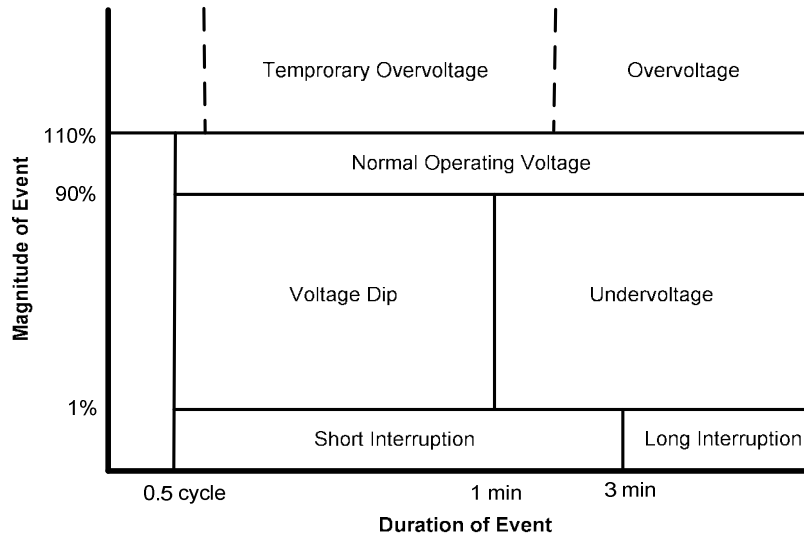


Figure 2.2. Definitions of voltage magnitude events as used in EN 50160

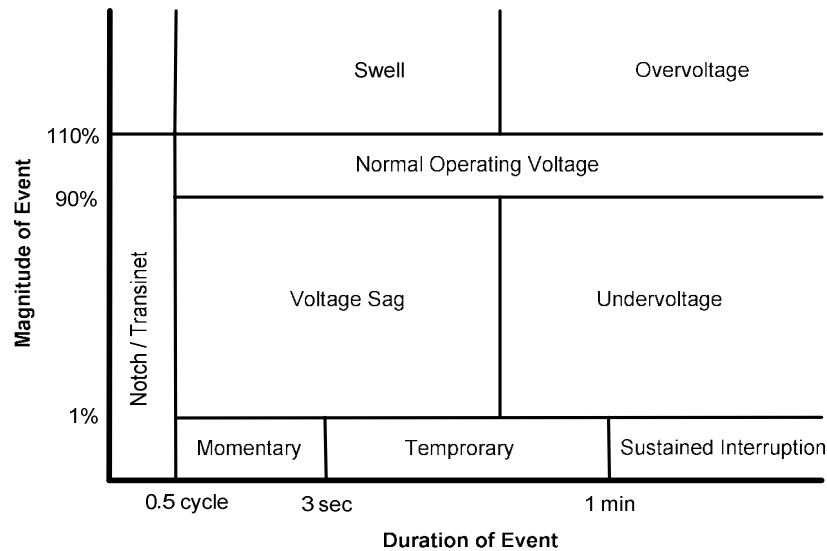


Figure 2.3. Definitions of voltage magnitude events as used in IEEE Std. 1159-1995

Both IEC and IEEE give different names to events in some of the regions of the magnitude-duration plane. The IEC definitions are summarized in Figure 2.2 and the IEEE definitions in Figure 2.3. The IEC definitions were obtained from CENELEC document EN 50160, the IEEE definitions from IEEE Std. 1159-1995 (Bollen, 2001).

### 2.3.5. The European Voltage Characteristics Standard: EN50160

The main document of IEC dealing with requirements concerning the supplier's side is standard EN 50160, which characterizes voltage parameters of electrical energy in public distribution systems. On the user's side, it is the quality of power available to the user's equipment that is important. Correct equipment operation requires the level of electromagnetic influence on equipment to be maintained below certain limits. Equipment is influenced by disturbances on the supply and by other equipment in the installation, as well as itself influencing the supply. These problems are summarized in the EN 61000 series of EMC standards, in which limits of conducted disturbances are characterized.

European standard 50160 describes electricity as a product, including its shortcomings. It gives the main characteristics of the voltage at the customer's supply terminals in public low-voltage and medium-voltage networks under normal operating conditions. Some disturbances are just mentioned below, for others a wide range of typical values are given and for some disturbances actual voltage characteristics are given (Bollen 2001).

#### 2.3.5.1. Standards for Voltage Variations

Standard EN 50160 gives limits for some variations. For each of these variations the value is given which shall not be exceeded for 95% of the time. The measurement should be performed with a certain averaging window. The length of this window is 10 minutes for most variations; thus very short time scales are not considered in the standard. The following limits for the low-voltage supply are given in the document (Bollen, 2001):

- **Voltage magnitude:** 95% of the 10-minute averages during one week shall be within  $\pm 10\%$  of the nominal voltage of 230 V.
- **Harmonic distortion:** For harmonic voltage components up to order 25, values are given which shall not be exceeded during 95% of the 10-minute averages obtained in one week. The total harmonic distortion shall not exceed 8% during 95% of the week.
- **Voltage fluctuation:** 95% of the 2-hour long-term flicker severity values obtained during one week shall not exceed 1. The flicker severity is an objective measure of the severity of light flicker due to voltage fluctuations
- **Voltage unbalance:** the ratio of negative- and positive-sequence voltage shall be obtained as 10 minute averages, 95% of those shall not exceed 2% during one week
- **Frequency:** 95% of 10 second averages shall not be outside the range 49.5-50.5 Hz.

### 2.3.5.2. Standards for Voltage Events

Standard EN 50160 does not give any voltage characteristics for events. Most event-type phenomena are only mentioned, but for some an indicative value of the event frequency is given. For completeness a list of events mentioned in EN 50160 is reproduced below (Bollen, 2001):

- **Voltage magnitude steps:** These normally do not exceed  $\pm 5\%$  of the nominal voltage, but changes up to  $\pm 10\%$  can occur a number of times per day.
- **Voltage sags:** Frequency of occurrence is between a few tens and one thousand events per year. Duration is mostly less than 1 second and voltage drops rarely below 40%. At some places sags due to load switching occur very frequently.
- **Short interruptions:** They occur between a few tens and several hundreds times per year. The duration is in about 70% of the cases less than 1 second.
- **Long interruptions:** Their frequency may be less than 10 or up to 50 per year.
- **Voltage swells:** They occur under certain circumstances. Over voltages due to short-circuit faults elsewhere in the system will generally not exceed 1.5 kV rms in a 230 V system.
- **Transient overvoltages:** They will generally not exceed 6 kV peak in a 230 V system.

### 2.3.6. Country Perspectives of Power Quality Standards

#### 2.3.6.1. Standards in Germany

The German national standard VDE 0100 states that the voltage parameters defined in DIN-EN-50160 reflect extreme situations in the network and are not representative of typical conditions. In planning networks the recommendations of VDE 0100 should be followed. The equipment standard VDE 0838 (EN 60555) is also quoted.

### 2.3.6.2. Standards in Norway

The Norwegian Water Resources and Energy Directorate (NVE) is subordinated to the Ministry of Petroleum and Energy, and is responsible for the administration of Norway's water and energy resources. NVE introduced absolute limits for several voltage quality parameters January 1st 2005. Those voltage quality parameters are the voltage frequency, supply voltage variations, rapid voltage changes, flicker severity, voltage unbalance and harmonic voltages.

One of NVE's aims making this regulation was to uphold the today's quality and not to cause a general increase in the quality of supply. For decades limits for "supply voltage variations" in the Norwegian power system have been  $\pm 10\%$  of the nominal voltage value in points of connections in the low voltage system. Both customers and network companies have adjusted to this level. Earlier this was not part of a public regulation, but part of national standards and standardized agreements between network companies and final customers (Ergeg, 2006).

### 2.3.6.3. Standards in Hungary

Supply voltage variations shall be within  $U_n \pm 7.5\%$  for 95 % of the time as a 10-minute average. Maximum voltage level is  $U_n + 15\%$  as a 1-minute average. All 10-minute averages must be within the  $+10\%$  and  $-15\%$  range of the nominal voltage. These limits apply for both Medium Voltage (MV) and Low Voltage (LV) network. For other voltage quality parameters EN 50160 limits apply.

Hungary regulated after the preparation of 3rd Council of European Energy Regulators (CEER) Benchmarking Report on Quality of Electricity Supply (December 2005) the number of short interruptions caused by fast and slow fault clearing (automatic reclosing) by maximum 70 cases in order to overcome the problems of the indicative levels for short interruption written in the EN 50160 (Between a few tens and several hundreds per year; in 70 % of the cases duration can be less than 1 second). This was done to protect the consumers (Ergeg, 2006).

#### 2.3.6.4. Standards in France

In France the voltage quality limits are set both in legal decrees and through contracts, where they can be negotiated between the customer and the distribution/transmission operator. Voltage quality regulation in France does not really exist. The regulator only surveys the contracts' models but does not set standards.

Requirements have been developed by agreements between networks' users, manufacturers and operators, for some of them before the regulator's existence.

For MV and High Voltage (HV) customers, contracts' models include limits required for voltage fluctuations, flicker, voltage unbalance, frequency fluctuations and voltage harmonics (only on the global rate). They also include the possibility for the customer to pay for an extra requirement related to the maximum number of voltage sags per year. This special service only takes into account voltage sags deeper than 30 % of  $U_n$  and longer than 600 ms. It is based on historical performances for the transmission network and on the local conditions for distribution networks.

A legal decree from the 29th May 1986 specifies that supply voltage variations on low voltage networks shall be within 358 V and 423 V for  $U_n = 400$  V and within 207 V and 244 V for  $U_n = 230$  V. In this case, EN50160 measuring conditions apply (Ergeg, 2006).

#### 2.3.6.5. Standards in Portugal

The first Quality of Service Code of Portugal, published in 2000, established the obligation of quality waveform monitoring. Considering the lack of expertise in this matter, and since EN 50160 is a European standard, this standard has been adopted. Since then, it has been already published two others quality of service codes, one in 2003 and the last one in 2006.

The transmission and distribution operators are responsible for the network voltage waveform quality. They have the duty to look out for the levels of each

characteristic. However, the other installations connected to the network are responsible for their installations disturbances emissions to the network.

#### **2.3.6.6. Standards in Spain**

In Spain maximum limits for supply voltage variations are  $\pm 7\%$  of the declared voltage measured as ten-minute average values and apply for 95 % of the time. For the remaining 5 % of the time and other voltage quality parameters the limits in EN 50160 apply (Ergeg, 2006).

#### **2.3.6.7. Standards in United States of America**

For the most part, power quality standards are not very stringent in the United States (US). For instance, most of the standards focus only on steady state conditions addressed either by IEEE/ANSI (Ansi, 2006). It recommends that equipment be designed to operate with acceptable performance under extreme steady state conditions of +6% and -13% of nominal 120/240 volt system voltage or local state regulatory requirements (New Jersey requires utilities to establish a standard frequency and to maintain voltages between  $\pm 4\%$  of a set nominal voltage for services supplied). There are no national or state reliability, voltage sag, flicker, transient disturbance or harmonic performance requirements. However, some states require reporting of reliability performance and submission of improvement plans for some of the worst performing circuits. Some utilities opt to adopt IEEE standards and recommended practices as they relate to specific power quality issues and phenomena, i.e., 519, 1159, 1250, 1346, 1433, etc. Utilities that adopt one or more of these IEEE standards/recommended practices usually do so within the context of assuring some reasonable level of compatibility between the utility system and the customer's end-use equipment and premise wiring systems. In rare situations, there have been performance contracts established between a customer and a serving utility but these have generally only been created where a significant economic

benefit exists for both parties, i.e., the Special Manufacturing Contracts (SMC) established between some Michigan utilities and large automobile manufacturers.

### **2.3.7. Standards Related to Power Quality in Turkey**

The importance of power quality will increase with the number of pieces of consumer equipment sensitive to power quality. Any disturbance in voltage, frequency or current may lead to serious damage to load equipment. Because of the cost of low power quality will be paid by the failure of consumer equipment, lost productivity and labor, poor power quality is the most important factors limiting growth in Turkey.

Until 1993, generation, transmission and distribution of electricity are delivered by Turkish Electric Authority (TEK). In September 1993, TEK was divided into two public companies: TEAŞ (generation and transmission) and TEDAŞ (distribution). The activities of both TEAŞ and TEDAŞ were excluded from the scope of public services. The share of TEAŞ generation in total fell to less than 80% in 1999 from more than 90% in 1995. Transmission and wholesale trade of electricity remained under TEAŞ control. TEAŞ was further divided into generation (EÜAŞ) and Turkey Transmission Co. Inc. (TEİAŞ), The Turkish Electricity Trading and Contracting Co. Inc. TETAŞ companies in 2001.

The TETAŞ will perform international interconnection activities in line with the decision provide transmission and connection services to all system. Turkey currently has electric transmission line connections with Georgia, Armenia, Azerbaijan, Bulgaria, Iran, Iraq and Syria. Projects are continuing to establish electric interconnection lines between Turkey-Greece, Turkey-Black Sea Countries, Egypt-Iraq-Jordan-Syria-Turkey and Turkey-Central Asian countries. The connection of 400 kV lines linking the Turkish and Greek networks is being tendered with the ultimate aim of integration with the West European Electrical System (UCTE) (Gul, 2007).

The generation, transmission, distribution, wholesale, retail sale and retailing services, import, export of electricity and the establishment of the Energy Market Regulatory Authority (EPDK) and rules and principles related to its operations, is the

subject of law. The power quality standards in distribution systems specified in the regulation of EPDK: “Elektrik Piyasasında Dağıtım Sisteminde Sunulan Elektrik Enerjisinin Tedarik Sürekliliği, Ticari ve Teknik Kalitesi Hakkında Yönetmelik”, Regulation on the Amendment of the Regulation Pertaining to the Continuing Supply of the Electricity Energy that is Provided in the Electricity Market Distribution System, and its Commercial and Technical Quality (Epdk, 2006). Below some standards are presented. Standards to be obeyed by the distribution companies and users are summarized in the Table 2.2.

Table 2.2. Power Quality Standards Turkey

| Responsible                   | Standards to be obeyed                                                                                                      |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| Utility (Distribution System) | <u>TS EN 50160:2001</u><br>Voltage magnitude variation<br>System frequency<br>Supply voltage unbalance<br>Voltage harmonics |
| End user (Customer)           | <u>IEEE Std.519-1992</u><br>Current Harmonics<br>Flicker<br>Power factor                                                    |

### i) Voltage Magnitude Variation

Voltage levels for the distribution level are 34.5 kV, 33 kV, 31.5 kV, 15.8 kV, 10.5 kV and 6.3 kV. TS EN 50160:2001 gives the main voltage parameters and their permissible deviation ranges at the customer’s point of common coupling in public LV and MV electricity distribution systems, under normal operating conditions (Epdk, 2006). In this context, LV means that the phase to phase nominal rms voltage does not exceed 1000 V and MV means that the phase-to-phase nominal rms value is between 1 kV and 35 kV. According to TS EN 50160:2001, voltage magnitude variations should be  $\pm 10\%$  for 95% of week, mean 10 minutes rms values for LV. For 5% of the time, the voltage magnitude variations should be  $(-15\%)-(+10\%)$  of nominal (Leonardo, 2009). For MV, during measurement period defined by IEC

61000-4-30, voltage magnitude variations should be  $\pm 10\%$  for 95% of week (uninterrupted one week measurement), mean 10 minutes rms values (Epdk, 2006).

## ii) System Frequency

The supply frequency in an AC power system is a main characteristic of the voltage at all locations, but the frequency varies over time as system conditions change. If frequency deviates too far from its nominal level of 50 Hz, the operation of customer can be impaired.

Table 2.3. Frequency ratings

| Frequency band    | Minimum time |
|-------------------|--------------|
| 50.5 Hz - 51.5 Hz | 1 hour       |
| 49 Hz - 50.5 Hz   | Normal band  |
| 48.5 Hz - 49 Hz   | 1 hour       |
| 48 Hz - 48.5 Hz   | 20 minutes   |
| 47.5 Hz - 48 Hz   | 10 minutes   |

In Turkey, the nominal system frequency is 50 Hz and be maintained around 49.8 Hz to 50.2 Hz by TETAŞ (Epdk, 2006). The devices of TETAŞ and the users' must be designed to operate under the same technical conditions as specified in Table 2.3. The frequency deviation should not be outside the band 47.5-51.5 Hz.

## iii) Unbalance for Supply Voltage

According to TS EN 50160:2001, the rms ratio of negative sequence components to positive sequence components can be maximum 2% for 95% of measurement period, mean 10 minutes rms values can take values up to 3% in some locations (Epdk, 2006).

#### iv) Harmonics

Table 2.4 shows the limits given in TS EN 50160 as requirements that must be guaranteed by the supplier.

Values in the Table 2.4 define individual harmonic voltages at the supply terminals for orders up to 25, given in percent of fundamental component. During each period of one week, 95% of the mean 10 minute rms values of each individual harmonic voltage shall be less or equal than proper values prescribed in Table 2.4. However, Total Harmonic Distortion (THD) value of voltage should be maximum 8% (including harmonic levels up to 40<sup>th</sup>) (Epdk, 2006).

Table 2.5 shows the current harmonic limits given in IEEE Std.519-1992 as requirements that must be guaranteed by the end user. For the current harmonic limits, Total Demand distortion (TDD) calculation is used. TDD shown in (2.1) shall be less or equal than proper values prescribed in Table 2.5.

Table 2.4. Voltage Characteristics of Public Distribution Systems

| Odd harmonics      |                         |                |                         | Even harmonics    |                         |
|--------------------|-------------------------|----------------|-------------------------|-------------------|-------------------------|
| Not multiples of 3 |                         | Multiples of 3 |                         |                   |                         |
| Order<br><i>h</i>  | Relative<br>voltage (%) | Order <i>h</i> | Relative<br>voltage (%) | Order<br><i>h</i> | Relative<br>voltage (%) |
| 5                  | 6                       | 3              | 5                       | 2                 | 2                       |
| 7                  | 5                       | 9              | 1.5                     | 4                 | 1                       |
| 11                 | 3.5                     | 15             | 0.5                     | 6-24              | 0.5                     |
| 13                 | 3                       | 21             | 0.5                     |                   |                         |
| 17                 | 2                       |                |                         |                   |                         |
| 19                 | 1.5                     |                |                         |                   |                         |
| 23                 | 1.5                     |                |                         |                   |                         |
| 25                 | 1.5                     |                |                         |                   |                         |

The term TDD is very much like the THD (2.2). The only difference is the dominator. The THD calculation compares the momentary measured harmonics with the momentary measured fundamental component. TDD calculation compares the momentary (but steady-state) measured harmonics with the maximum demand current, which is not a momentary number at all. Similarly, the individual harmonic current limits are not given in terms of percent of fundamental at a given point of

time. The difference between TDD and THD is important because it prevents a user from being unfairly penalized for harmonics during periods of light load (only the harmonic polluting loads are running). During periods of light load it can appear that harmonic levels have increased in terms of percent (THD calculation) even though the actual harmonic currents in amperes (TDD calculation) stayed the same (Blooming et al, 2007).

Table 2.5. Current distortion limits

| Maximum harmonic current distortion in percent of $I_L$                                                                                                                                                                                                                                                        |          |                  |                  |                  |             |      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------------------|------------------|------------------|-------------|------|
| Individual harmonic order (Odd harmonics)                                                                                                                                                                                                                                                                      |          |                  |                  |                  |             |      |
| $I_{sc}/I_L$                                                                                                                                                                                                                                                                                                   | $h < 11$ | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $35 \leq h$ | TDD  |
| $< 20^*$                                                                                                                                                                                                                                                                                                       | 4.0      | 2.0              | 1.5              | 0.6              | 0.3         | 5.0  |
| $20 < 50$                                                                                                                                                                                                                                                                                                      | 7.0      | 3.5              | 2.5              | 1.0              | 0.5         | 8.0  |
| $50 < 100$                                                                                                                                                                                                                                                                                                     | 10.0     | 4.5              | 4.0              | 1.5              | 0.7         | 12.0 |
| $100 < 1000$                                                                                                                                                                                                                                                                                                   | 12.0     | 5.5              | 5.0              | 2.0              | 1.0         | 15.0 |
| $> 1000$                                                                                                                                                                                                                                                                                                       | 15.0     | 7.0              | 6.0              | 2.5              | 1.4         | 20.0 |
| Even harmonics are limited to 25% of the odd harmonic limits above                                                                                                                                                                                                                                             |          |                  |                  |                  |             |      |
| * All power generation equipment is limited to these values of current distortions, regardless of actual $I_{sc}/I_L$ .                                                                                                                                                                                        |          |                  |                  |                  |             |      |
| Where,<br>$I_{sc}$ = Maximum short circuit current at point-of-common-coupling<br>$I_L$ = Maximum demand load current (fundamental frequency components) at point-of-common-coupling.<br>TDD = Total demand distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min demand). |          |                  |                  |                  |             |      |

$$TDD = \frac{RMS \text{ Harmonic Current}}{Max \text{ Demand Load Current (15 or 30 min)}} \quad (2.1)$$

$$THD_{Current} = \frac{RMS \text{ Harmonic Current}}{RMS \text{ Fundamental Current}} \quad (2.2)$$

#### v) Flicker

Utility companies satisfy the users to obey the limit values. Correct flicker perception level is measured using a flicker meter specified in TS EN 61000-4-15.

Flicker meter produces two important values namely  $P_{st}$  and  $P_{lt}$ .  $P_{st}$  and  $P_{lt}$  mean short term flicker severity and long term flicker severity, respectively.  $P_{st}$  must be less than 1.0 and  $P_{lt}$  must be less than 0.8.

#### vi) Power Factor

Progress in reactive energy penalty limits for the near future is recently imposed by the EPDK as summarized in Table 2.6

Table 2.6. Active/Reactive Power Limits

| Validity of the regulations | Energy Types (Demand / Month) |              |            |
|-----------------------------|-------------------------------|--------------|------------|
|                             | Active (%)                    | Reactive (%) |            |
|                             |                               | Inductive    | Capacitive |
| Date from year 2008         | 100                           | $\leq 20$    | $\leq 15$  |

Reactive energy penalty limits recently imposed by the EPDK of Turkey (Epdk, 2006). According to this regulation, the power factor must be minimum 0.98 in inductive side and must be 0.989 in capacitive side.

#### 2.4. Power Quality Levels in Turkey

The industry sector has been rapidly growing in Turkey. It is necessary for Turkish industry to identify its present level of power quality and to know about the cost effective power quality improvement devices for higher efficiency and profitability. To this aim, a wide literature survey related to power quality problems of South Industrial Districts of Turkey was performed in (Bayindir et al, 2007). Comprehensive questionnaire form concerned power quality knowledge, mitigation methods of power quality problems, real experienced problems and power quality related damages were directed to 24 industrial plants in south industrial districts of Turkey.

### 2.4.1. Profiles of the Industrial Plants in the Survey

The industrial plants joined to questionnaire can be divided into eight-business sector. Table 2.7 shows distribution of the sectors according to installed capacity.

Table 2.7. Distribution of the business sector

| Category       | Names    | Installed Capacity |
|----------------|----------|--------------------|
| Iron and Steel | I1-I5    | 55.5%              |
| Power Station  | PS1, PS2 | 23.6%              |
| Textile        | T1-T9    | 12.2%              |
| Chemical       | C1, C2   | 2.7%               |
| Food           | F1, F2   | 2.5%               |
| Plastics       | PL1, PL2 | 2.3%               |
| Automotive     | A1       | 1.0%               |
| Paper          | PR1      | 0.2%               |

### 2.4.2. Questions for the Power Quality Survey

24 Turkish industrial plants filled out a questionnaire form during 2006 manufacturing in Adana, Iskenderun, Gaziantep and Mersin organized industrial districts as shown in Table 2.8 (Bayindir et al, 2007).

Table 2.8. Questionnaire form and responses of the plants

| <b>POWER QUALITY SURVEY QUESTIONNAIRE</b>                                                                          | <b>Responses</b> |               |
|--------------------------------------------------------------------------------------------------------------------|------------------|---------------|
|                                                                                                                    | <b>Yes (%)</b>   | <b>No (%)</b> |
| <b>Stage 1: Power Quality Problems: Sag/Swell, Interruption and Harmonics</b>                                      |                  |               |
| 1. Have you ever done the instantaneous voltage drop measurement in your plant?                                    | 38               | 62            |
| 2. Do you have any voltage drop and interruption related problems in your plant at present?                        | 79               | 21            |
| 3. Have the voltage drop and outage related problems caused the lost of production and economical damage?          | 86               | 14            |
| 4. Have you ever had harmonic measurement and analysis in your plant?                                              | 84               | 16            |
| 5. Does your plant affected by harmonics?                                                                          | 24               | 76            |
| 6. Do the harmonics created by your plant affect the interconnected system or your plant?                          | 8                | 92            |
| 7. Does your plant have any harmonic polluting loads?                                                              | 70               | 30            |
| 8. Do you have any harmonic related problems in your plant at present?                                             | 4                | 96            |
| 9. Have the harmonic related problems ever caused the lost of production and economical damage?                    | 20               | 80            |
| <b>Stage 2: Power Quality: Mitigation methods and economical damages</b>                                           |                  |               |
| 10. Do you believe that you will increase your profitability using the harmonic eliminating devices?               | 79               | 21            |
| 11. Do you believe that you will increase your profitability using the voltage drop and outage mitigation devices? | 75               | 25            |

|                                                                                                                                         |     |    |
|-----------------------------------------------------------------------------------------------------------------------------------------|-----|----|
| 12. Does your company have any passive or active power filters?                                                                         | 54  | 46 |
| <b>Stage 3: Technical Questions</b>                                                                                                     |     |    |
| 13. Do you have any power meter at the incoming service entrance to measure and log V, I, S, P and Q?                                   | 71  | 29 |
| 14. Have you ever done any research related with electric power quality?                                                                | 58  | 42 |
| 15. Do you know reactive power limits established by Electricity Market Regulatory Authority?                                           | 75  | 25 |
| 16. There is need for new investments and system modernization due to new PF regulations. Have you started to effort for PF correction? | 46  | 54 |
| 17. Have you ever done the short circuit capability analysis and load analysis?                                                         | 50  | 50 |
| 18. Do you periodically make the relay maintenance and relay test?                                                                      | 50  | 50 |
| 19. Have you ever affected by the faults caused by the lack of relay coordination?                                                      | 12  | 88 |
| 20. Have you ever done the circuit breaker open-close tests?                                                                            | 54  | 46 |
| 21. Do you periodically make the grounding measurement of your plant?                                                                   | 100 | 0  |

### 2.4.3. Discussion of the Responses

Most of the respondents (86%) pointed out that the voltage sags and interruptions cause significant problems. For most respondents (76%), the harmonics do not cause any significant problems. Only about the 40% of the industrial plants have power-monitoring devices. The respondents also reported their willing to be aware of the new technological improvements. Most of the respondents wish to

install the power quality mitigation devices and they generally believe that their profitability will increase using the power quality mitigation devices.

The occurrence of probability of voltage sag and interruption is 78 times and 15 times in a year, respectively. These disturbances generally cause the lost products, restart procedures and high economical damage. The occurrence numbers of the problems generally increase in the summer time due to high temperature and humidity.

Some of the real plant problems caused high economical cost are as follows:

- The interruption caused the lost production of iron and the blast furnace unusable in I3 plant.
- T1 plant is fed by PS2 line. A short circuit fault caused the downtime of the two plants simultaneously. It took 17 hours start up time for T1 plant due to large loads to reach the pre-fault power level.
- F1 plant is one of the most damaged plants by voltage sags and interruptions causing at least 170000\$ in a year. The occurrence of probability of voltage sag and interruption is 12 times and 28 times in a year respectively in this plant.
- Voltage sag and transient problems cause the losing some controller cards of the T6 plant costing at least 10000 \$ in a year.
- The voltage swell caused the blow out of the circuit breakers and capacitor bank destruction in I3 plant.

However, almost half of the factories have not make any research about the short circuit test, relay maintenance and power factor correction. The iron and steel plants are very conscious about the harmonic measurements and usage of active/passive filters with the availability of 100%.

Harmonics are not a significant problem within the plants. Harmonics can generally cause the unwanted tripping of sensitive controls and capacitor fuse blowing.

### 3. CUSTOM POWER DEVICES: INNOVATIVE SOLUTIONS OF POWER QUALITY PROBLEMS

Power quality problems are evident in many commercial, industrial, residential and utility networks. As mentioned above, natural phenomena, such as lightning, are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, e.g. when capacitors are switched, also contributes substantially to power quality disturbances. The most significant and critical power quality problems are, however, voltage sags or complete interruptions of the energy supply (Douglas, 1996).

There are two general approaches to the mitigation of power quality problems. One, termed load conditioning, is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride through the disturbances. The other is to install a line conditioning device that suppresses or counteracts the disturbances (Rudnick et al, 2003). The mitigation device and point of connection is chosen according to its economic feasibility and the reliability that is required. Innovative solutions employing power electronics are often applied when rapid response is essential for suppressing or counteracting the disturbances, while conventional devices are well suited for steady-state or general regulation (Arora et al, 1998).

CP is the employment of power electronic or static controllers in medium and low voltage distribution systems for the purpose of supplying a level of reliability and/or power quality that is needed by electric power customers sensitive to power quality variations. In other words, CP is a concept based on the use of power electronic controllers in the distribution system to supply value-added, reliable and high quality power to its customers. CP devices, or controllers, include STSs, DVRs, Active Filters that have the ability to perform current and voltage regulation functions in a distribution system to improve reliability and/or power quality (Sabin et al, 2003).

For simple load applications, selection of the proper mitigation device is fairly straightforward. However, in large systems with many loads all aspects of the power system must be considered carefully. Also, when dealing with large systems it

is necessary to know the different sensitive load requirements. Consideration must also be given to the potential interaction between mitigation devices, connected loads and the power system (Arora et al, 1998).

### 3.1. Types of Custom Power Devices

The power electronic controllers that are used in the CP solution can be network reconfiguring type or compensating type as shown in Table 3.1 (Ghosh et al, 2002a).

Table 3.1. Types of CP devices

| <b>TYPES OF CUSTOM POWER DEVICES</b> |                                                                     |
|--------------------------------------|---------------------------------------------------------------------|
| <b>Network Reconfiguring Type</b>    |                                                                     |
| Static Current Limiter               | Limiting fault current                                              |
| Static Circuit Breaker               | Breaks a faulted circuit                                            |
| Static Transfer Switch               | Against interruption, voltage sag and swell                         |
| <b>Compensating Type</b>             |                                                                     |
| Distribution Static Compensator      | Harmonic filtering, power factor corrector, bus voltage regulation  |
| Dynamic Voltage Restorer             | Against voltage sag and swell                                       |
| Unified Power Quality Conditioner    | Reactive power compensation, harmonic filtering, voltage regulation |

#### 3.1.1. Network Reconfiguring Type Custom Power Devices

The network reconfiguring devices are usually called switchgear and they include current limiting, circuit breaking and current transferring devices.

##### 3.1.1.1. Static Current Limiter

Static Current Limiter (SCL) limits a fault current by quickly inserting a series inductance in the fault path. The basic diagram of a SCL is shown in Figure 3.1.

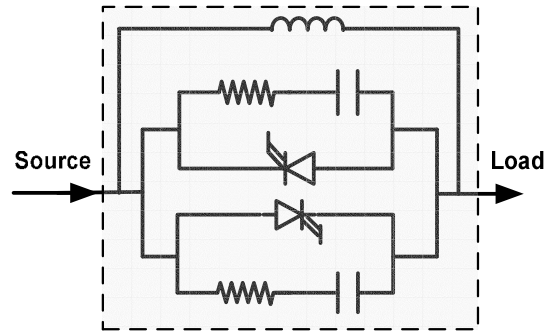


Figure 3.1. Basic diagram of a SCL

It consists of a pair anti parallel gate turn off thyristors switch with snubbers (RC circuit) and a current limiting inductor. The currents limiter is connected in series with a feeder such that it can restrict the current in case of a fault downstream. In the healthy state, the opposite poled switch remains closed. These switches are opened when a fault is detected such that the fault current now flows through the current limiting inductor (Ghosh et al, 2002a).

#### 3.1.1.2. Static Circuit Breaker

Static Circuit Breaker (SCB) breaks a faulted circuit much faster than a mechanical circuit breaker. The basic diagram of a SCB is shown in Figure 3.2.

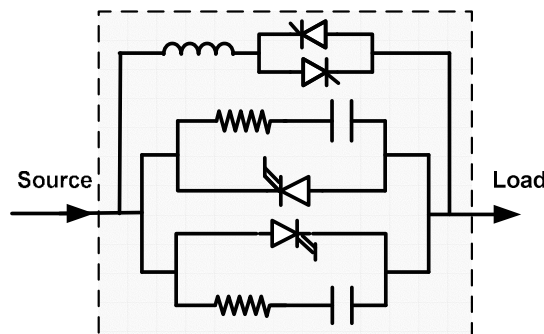


Figure 3.2. Basic diagram of a SCB

A SSB has almost the same topology as that of an SCL except that the limiting inductor is connected in series with an opposite poled thyristor pair. The

Gate Turn Off Thyristors (GTOs) are the normal current carrying elements. The thyristor pair is switched on simultaneously as the bidirectional switch GTO is switched off once a fault is detected. This will force the fault current to flow through the limiting inductor. The thyristor pair is blocked after a few cycles if the fault still persists. The current through the thyristor pair will cease to flow at the next available zero crossing of the current (Ghosh et al, 2002a).

### 3.1.1.3. Static Transfer Switch

STS is connected in the bus tie position when a sensitive load is supplied by two feeders. It protects the load from sag by quickly transferring it from the faulty feeder to the healthy feeder. The basic diagram of a STS is shown in Figure 3.3.

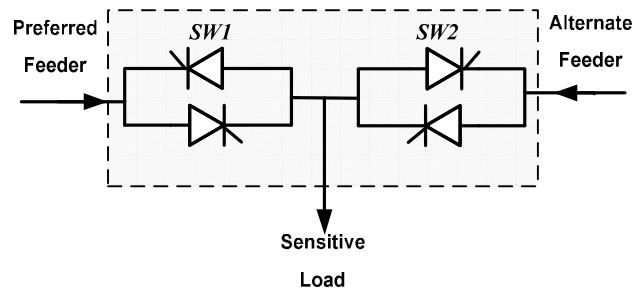


Figure 3.3. Basic diagram of a STS

Usually the load is supplied by the preferred feeder and the load current flows through the switch  $SW_1$ . When a deep voltage sag or interruption is detected in this feeder, the switch  $SW_1$  is turned off and  $SW_2$  is turned on.

### 3.1.2. Compensating Type Custom Power Devices

The compensating devices compensate a load, correct its power factor, unbalance or improve the quality of supplied voltage. They include Distribution Static Compensator (DSTATCOM) or Active Power Filter (APF), DVR and Unified Power Quality Conditioner (UPQC).

### 3.1.2.1. Distribution Static Compensator

The basic diagram of a DSTATCOM is shown in Figure 3.4.

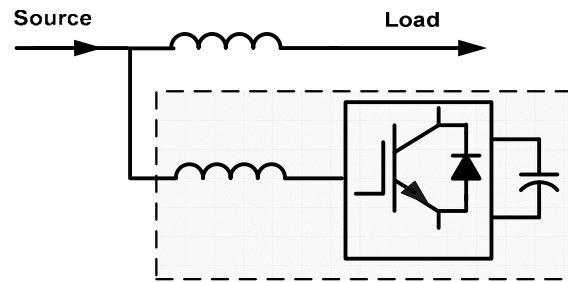


Figure 3.4. Basic diagram of a DSTATCOM

DSTATCOM is shunt connected device that can operate in current control or voltage control modes. In current control mode, DSTATCOM (also called Shunt Active Power Filter in this mode) acts as a harmonic filter and power factor corrector. These functions are called the load compensation. In voltage control mode, DSTATCOM can regulate a bus voltage against any distortion, sag/swell, unbalance, and even short duration interruptions.

### 3.1.2.2. Active Power Filter

The basic diagram of APF is shown in Figure 3.5.

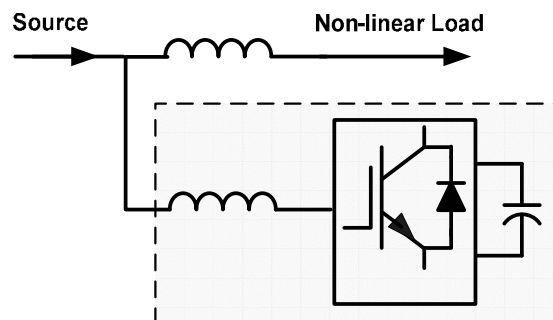


Figure 3.5. Basic diagram of a Shunt APF

APF is shunt connected device that can eliminate the non-linear load harmonics and can compensate load reactive current.

### 3.1.2.3. Dynamic Voltage Restorer

DVR is a series compensating device. The basic diagram of a DVR is shown in Figure 3.6.

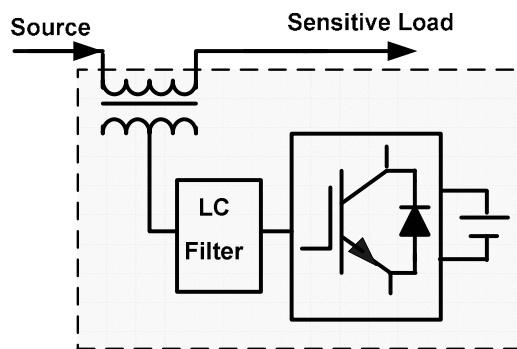


Figure 3.6. Basic diagram of a DVR

It is used for protecting a sensitive load that is connected downstream from sag/swell. It can also regulate the bus voltage at the load terminal.

### 3.1.2.4. Unified Power Quality Conditioner

Unified Power Quality Conditioner (UPQC) is consists of two voltage source inverters. It can simultaneously perform the tasks of DSTATCOM and DVR. The basic diagram of a UPQC is shown in Figure 3.7.

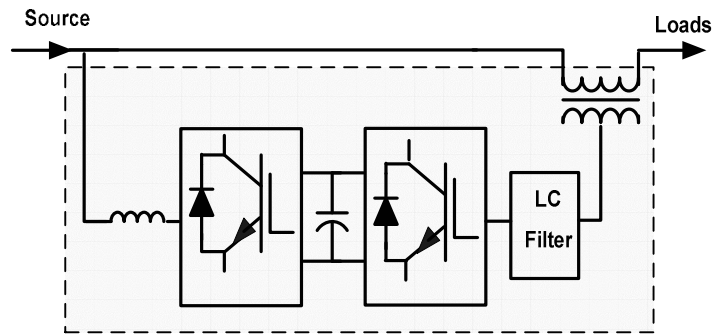


Figure 3.7. Basic diagram of a UPQC

UPQC protects the loads against voltage sag, swell, voltage unbalance, harmonics and poor power factor.

### 3.2. Comparisons for Application of Various Power Quality Devices

#### 3.2.1. Static Transfer Switch versus Mechanical Transfer Switch

A transfer system is designed to protect critical loads from distribution disturbances. This is accomplished by transferring the critical load from a preferred feeder to an alternate feeder when the preferred feeder is faulted but the alternate is not.

The Mechanical Transfer Switch (MTS) has often been used in applications requiring loads to be switched to a backup power source (e.g. alternate feeder, backup generator, etc.) when disturbances, such as sustained interruptions, occur on the preferred feeder. Typically a rather inexpensive device, the MTS has been used for many years. Unfortunately, due to the nature of the electromechanical switches used in the MTS, a “seamless” transfer is not obtainable. Typical transfer times can range from about 100 ms up to approximately ten seconds. For that reason, transfer systems using mechanical switches have been applied as an effective counter-measure against only long interruptions. Some work is currently in progress that involves incorporating vacuum switches in this type of application to obtain approximate transfer times between 1.5 and 2 cycles (Sabin et al, 2003).

With the availability of the fast, electronic-based STS; the transfer process can also be applied against short duration voltage disturbances, such as voltage sags and swells. STS essentially consists of a pair of back-to-back thyristor switches. It takes the place of the mechanical transfer switch and enables a seamless transfer of energy from the main (preferred) feeder to the back-up (alternate) feeder in order to avoid service interruption. As a result, this arrangement can provide reliable power to the customer well within the limits of the Computer and Business Equipment Manufacturers' Association (CBEMA) curves.

### **3.2.2. Dynamic Voltage Restorer versus Static Transfer Switch**

DVR is a compensating type CP device, however STS is a network reconfiguring type CP device.

DVR usually designed to mitigate voltage sags with magnitude lower than 50%. This is based on a Voltage Source Converter (VSC) that generates a compensation voltage, which is then injected in the distribution feeder by means of a series-injection transformer. Normally, an LC-filter between the VSC and the transformer is also present to remove high-order harmonic components from the converter output voltage. An energy storage device connected to the dc-link of the VSC provides the necessary active power for the compensation (Bangiorno et al, 2003).

The STS is able to limit the duration of interruptions and voltage sags to less than one half-cycle in most cases, by transferring the load from the affected line to a back-up feeder. This high speed of response is obtained by using two static switches, constituted each by two anti parallel thyristors, to perform the transfer of the load (Bangiorno et al, 2003).

The DVR is not suitable to compensate for interruptions of the supply voltage and the range of sags that it can mitigate depends on the size of the energy storage. On the other hand, the STS cannot mitigate sags that affect both feeders.

### 3.2.3. Dynamic Voltage Restorer versus Other Sag Mitigation Devices

DVR is a CP device and it is commonly used to mitigate voltage sag, voltage swell, voltage harmonic and voltage fluctuations. There are numerous reasons why the DVR is preferred over the others (Benachaiba et al, 2008). A few of these reasons are presented as follows.

DVR costs less compared to the UPS systems. UPSs have typically been designed for the correction of different types of voltage disturbances, which may not necessary, fall into the category of voltage sags. Taking the UPS as an example, this has two major implications (Ramachandaramurthy et al, 2004). First, the energy that a UPS is required to store is based upon the long duration of a typical voltage outage or blackout, not relatively short duration voltage sag. Secondly, UPS systems are typically designed for small loads, such as a computer mainframe or low power safety critical systems. It is widely accepted that voltage sags are most troublesome on the distribution network, where loads can range from a few tens of kilowatts to a few mega watts. At these power levels the cost of a UPS system could be prohibitive as the UPS would need to be able to withstand not only the load current, but also the full load voltage.

DVR is smaller in size and costs less compared to the DSTATCOM. In terms of minimum apparent power injection or size of the coupling transformer, the performance of a DVR is found to be superior to a DSTATCOM. The amount of apparent power injection required by a DSTATCOM to correct a given voltage sag is much higher than that of a DVR. The main reason of that is a DVR corrects the voltage sag only on the downstream side (Haque et al, 2001).

Another solution may be using a tap-changing transformer where it only takes care of a limited range of voltage sag. The tap-changing transformer is: slow in response, exhibits contact erosion, needs routine maintenance of its parts, has an uneconomical size and requires frequent replacement of transformer oil. Moreover, due to its inability to eliminate harmonics, the tap-changing transformer employed for voltage sags needs a separate harmonics compensation scheme for nonlinear loads to mitigate voltage harmonics at the PCC (Singh et al, 2004).

Based on these reasons, it is no surprise that the DVR is widely considered as an effective CP device in mitigating voltage sags. In addition to voltage sags and swells compensation, DVR can also added other features such as harmonics and Power Factor correction. Compared to the other devices, the DVR is clearly considered to be one of the best economic solutions for its size and capabilities (Benachaiba et al, 2008).

#### **3.2.4. Active Power Filter versus Other Harmonic Mitigation-Power Factor correction Methods**

Mitigation methods fall broadly into three groups; passive filters, isolation and harmonic reduction transformers and active solutions (Chapman, 2001b).

Passive filters are used to provide a low impedance path for harmonic currents so that they flow in the filter and not the supply. The filter may be designed for a single harmonic or for a broad band depending on requirements. Triple-N currents circulate in the delta windings of transformers. Although this is a problem for transformer manufacturers and specifiers -the extra load has to be taken into account- it is beneficial to systems designers because it isolates triple-N harmonics from the supply.

The solutions mentioned above have been suited only to particular harmonics, the isolating transformer being useful only for triple-N harmonics and passive filters only for their designed harmonic frequency. In some installations the harmonic content is less predictable. In many IT installations, for example, the equipment mix and location is constantly changing so that the harmonic culture is also constantly changing. A convenient solution is the active filter or active conditioner.

Power Factor Correction (PFC) techniques include both passive and active solutions for eliminating harmonic distortion and improving power factor. The passive approach uses inductors, transformers, capacitors and other passive components to reduce harmonics and phase shift. The passive approach is heavier and less compact than the active approach, which is finding greater favor due to new technical developments in circuitry, superior performance and reduced component

costs. Specially corrected transformers are effective only for certain harmonic frequencies and most passive filters, once installed and tuned, are difficult to upgrade and may generate harmful system resonance. As for active PFC techniques, they must be applied to each individual power supply or load in the system, which complicates architecture and results in high system cost. Unlike traditional PFC techniques, APF supplies only the harmonic and reactive power required to cancel the reactive currents generated by nonlinear loads. In this case, only a small portion of the energy is processed, resulting in greater overall energy efficiency and increased power processing capability (Brooks, 2004).

APF utilizes harmonic or current injection to achieve PFC. Unlike designs that process all the power presented to the converter - due to the fact that they are in series or cascade with the AC line - APF can be accomplished parallel to the line. The APF device determines the harmonic distortion on the line and injects specific currents to cancel the reactive loads. This technique has been used for years in high-power, three-phase systems, but high costs and complicated high-speed circuitry made it impractical for low-level power systems. However, new techniques that utilize simpler circuitry are making active power filtering more attractive and advantageous for low power, single-phase systems. The APF is connected in parallel to the front end or AC input of the system and corrects all loads directly from the AC line.

### **3.3. Custom Power Park Concept**

As a new CP concept of improving power quality, attention has been paid to CPP, which is able to offer customers high quality of power (Hingorani, 1998), (Ghosh et al, 2004), (Ghosh, 2005). The concept requires integration within the park of multiple CP devices which have previously been deployed independently. These devices compensate for power quality disturbances to protect sensitive process loads as well as improve service reliability.

In a CPP all customers of the park should benefit from high quality power supply. Even the basic form of this supply is superior to normal power supply from a

utility. Electrical power to the park is supplied through two feeders from two independent feeders as shown in Figure 3.8. Both these feeders are joined together via a STS. The incoming feeders to the park can be designed with improved grounding, insulation, arresters and reclosing (Ghosh et al, 2002a). The STS transfers the loads of the park to alternate feeder which has nominal voltage in case of voltage sag or interruption.

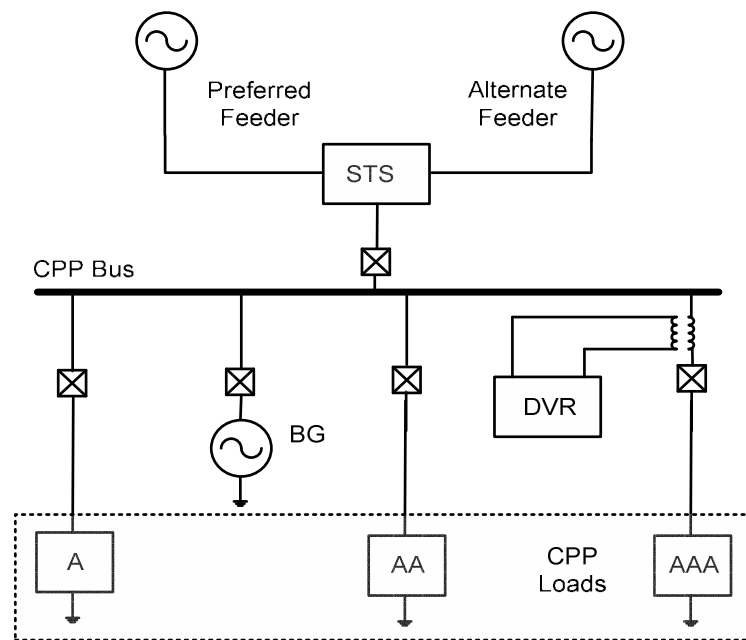


Figure 3.8. Basic diagram of a CPP

There are different grades of power that can be supplied to the park's customers (Ghosh, 2005). These are:

**Grade A:** This is the basic quality power. Since the STS protects the incoming feeders, the quality of the power is usually superior to the normal utility supply.

**Grade AA:** This includes all features of Grade A. In addition, it receives the benefit of a Backup Generator (BG). The generator can be brought into service in about 5-10 seconds in case of a serious emergency such as power interruption in both feeders.

**Grade AAA:** This includes all features of Grade AAA. In addition, it has the benefit of receiving sag free voltage due to DVR in case of voltage sag in two incoming feeders.

Through the CPP it is possible to supply power to different types of sensitive loads ranging from shopping malls and hospitals to semiconductor manufacturing. For example, a semiconductor manufacturing plant needs Grade AAA supply since a sudden voltage sag can cause the loss of a few hours of production. A hospital on the other hand, requires both AA and AAA grade supplies. Most shops in a shopping center or offices in an office building require grade A power. The grade of power quality of a customer depends on the nature of its load and price he is ready to pay (Ghosh et al, 2002a).

### **3.4. Various Economic Evaluations of Custom Power Devices**

The evaluation of power quality improvement alternatives is an exercise in economics. Facility managers and utility engineers must evaluate the economic impacts of the power quality variations against the costs of improving performance for the different alternatives. The best choice of alternatives will depend on the costs of the problem and the total operating costs of the various solutions. Note that the solutions should include options for improving performance on the utility supply system. Improving facility performance during power quality variations can result in significant savings and can be a competitive advantage. Therefore, it is important for customers and suppliers to work together in identifying the best alternative for achieving the required level of performance (McGranaghan et al, 2002). Below, some comparative economic analyses are given for various power quality devices.

#### **3.4.1. Economic Analysis of Power Quality Solutions with Benefit/Cost Assessment Method**

In the benefit/cost assessment, firstly, the total costs of all events are calculated. Then, the benefit of a power quality improvement technology can be

estimated as the expected reduction in costs associated with voltage sags and interruptions at the facility (Arora et al, 1998). In reference (Arora et al, 1998), different sag mitigation alternatives are compared according to benefit/cost assessment. Table 3.2 shows this comparison for STS, DVR, UPS, Super Conducting Magnetic Energy Storage (SMES).

Table 3.2. Economic comparison of voltage sags mitigation alternatives

| Device | Total Solution Cost (USD) | Annual operating costs (% of total costs) | Total Annual Cost (USD) | Benefit/Cost Ratio |
|--------|---------------------------|-------------------------------------------|-------------------------|--------------------|
| STS    | 240,000                   | 5%                                        | 74,400                  | 2.96               |
| DVR    | 1,200,000                 | 5%                                        | 372,000                 | 1.10               |
| UPS    | 2,400,000                 | 25%                                       | 1,224,000               | 0.44               |
| SMES   | 2,400,000                 | 15%                                       | 984,000                 | 0.52               |

STS alternative assumes the availability of a secondary independent feeder. If this is not available, the cost of a new feeder must then be added and as such the DVR alternative will in most cases be the more cost-effective solution.

### 3.4.2. Economic Analysis of Power Quality Solutions with Annual Costs Method

The process of comparing the different alternatives for improving performance involves determining the total annual cost for each alternative, including both the costs associated with the power quality variations and the annualized costs of implementing the solution. The objective is to minimize these annual costs (PQ costs + solution costs). Comparing the different power quality solution alternatives in terms of their total annual costs (annual power quality costs + annual power quality solution costs) identifies those solutions with lower costs that warrant more detailed investigations. The “do nothing” solution is generally included in the comparative analysis and is typically identified as the base case. The “do nothing” solution has a zero annual power quality solution cost but has the highest

annual power quality costs (McGranaghan et al, 2002). Figure 3.9 gives an example of this type of analysis.

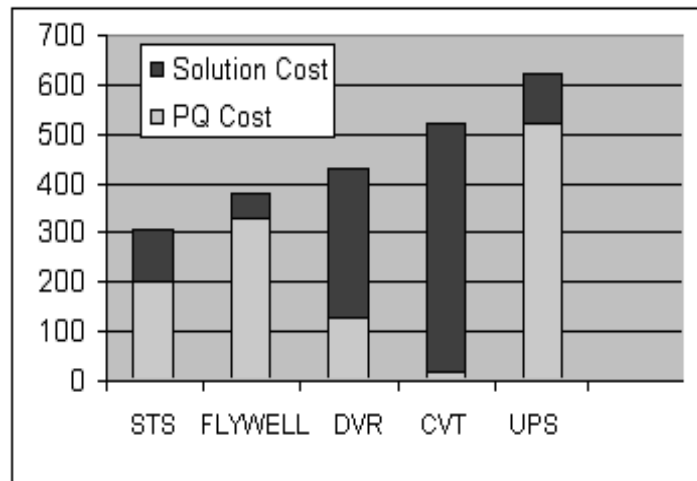


Figure 3.9. Example of comparing solution alternatives according to total annualized costs

The best solution in this case involves applying STS on the utility side if an alternate feeder would be available. However, this has a major assumption that there would be no charge from the utility for providing a connection to this backup feeder except the equipment and operating costs. If the solution is implemented in the facility, DVR or Flywheel-based standby power supply might make sense for protecting the some of sensitive loads. In this case, protecting just the controls with Constant Voltage Transformer (CVT) does not provide the best solution because the machines themselves are sensitive to voltage sags.

#### **3.4.3. Economic Evaluation of DVR, STS and Hybrid Compensator (STS+DVR) with Payback Method.**

In reference (Bongiorno et al, 2003), economic evaluation of DVR (Static Series Compensator), STS and Hybrid Compensator (STS+DVR) is made:

- The DVR designed to mitigate voltage sags lower than 50%.
- The STS is able to limit the duration of interruptions and voltage sags to less than one half-cycle. These devices present some limitations: the DVR is not suitable to compensate for interruptions of the supply voltage and the range of sags that it can mitigate depends on the size of the energy storage. On the other hand, the STS cannot mitigate sags that affect both feeders.
- The hybrid compensator is obtained by a combination of an STS in series with a DVR. In this way, total protection can be obtained against both interruptions and voltage sags.

Assume that the cost of the STS for 10 MVA load is 600 000 USD, including losses and maintenance calculated on the expected lifetime of the equipment. The cost of the DVR, according to, is 300 USD/kVA, when it is sized for 50% voltage injection and 500 ms sag duration. For the whole facility rated 10 MVA, the total cost of the second solution would thus amount to 3.000.000 USD (again including losses and maintenance calculated on the expected lifetime of the equipment).

### i) Example 1

Assume that the STS can save the plant from shutdown in 60 % of the total power quality events during one year (Bongiorno et al, 2003). If the cost of the STS is  $C_{STS}$ , the cost of a production interruption is  $C_{int}$  and their number  $n_{int}$ , and the pay-back time for the investment is denoted as  $T_{payback}$ ,

$$0.6 \times C_{int} \times n_{int} \times T_{payback} = C_{STS} \quad (3.1)$$

With  $C_{STS}=600\,000$  USD and  $C_{int}=100\,000$  \$

$$n_{int} \times T_{payback} = \frac{600000}{0.6 \times 100000} = 10 \quad (3.2)$$

i.e. with 10 interruptions a year the investment would pay back within one year or, which is the same, if a payback time of e.g. two years is accepted, the balance is reached for 5 interruptions a year in average (Bongiorno et al, 2003).

## ii) Example 2

Assume the DVR to be able to compensate for 75 % of the power quality events causing process disruption during one year (Bongiorno et al, 2003). It is in fact reasonable to assume that a DVR with 50 % voltage injection capability would be able to compensate not only for the transmission-related sags, but also for part of the distribution-related ones. If the cost of the DVR is  $C_{DVR}$ , then

$$0.75 \times C_{int} \times n \times T_{int} = C_{payback} \quad (3.3)$$

Assuming  $C_{DVR}=3.000.000$  USD,  $C_{int}=100.000$  \$ yields,

$$n_{int} \times T_{payback} = \frac{3000000}{0.75 \times 100000} = 40 \quad (3.4)$$

i.e. with 40 interruptions a year the investment would pay back within one year. On the other hand, if a payback time of e.g. two years is accepted, the balance is reached for 20 interruptions a year in average. With 10 interruptions a year, the payback time is 1 year for the STS and 4 for the DVR (Bongiorno et al, 2003).

## iii) Example 3

Assume that by reducing the voltage injection of the DVR down to 30 % and by combining it with the STS (Hybrid Compensator). 100 % coverage of the critical power quality events for the plant is reached (Bongiorno et al, 2003). Moreover, assume that the cost of the DVR varies proportionally with the voltage injection: this is reasonable because when reducing the maximum injected voltage we reduce the

size of both the converter and the injection transformer. With the same symbols used before:

$$C_{\text{int}} \times n_{\text{int}} \times T_{\text{payback}} = C_{\text{STS}} + \left(\frac{30}{50}\right) \times C_{\text{DVR}} \quad (3.5)$$

And with the same values used before we have:

$$n_{\text{int}} \times T_{\text{payback}} = \frac{600000 + 1800000}{100000} = 24 \quad (3.6)$$

Moreover, if the DVR compensates for short sags, the size of the storage can also be reduced. Assume that the duration is reduced down to 100 ms and that the cost also reduces proportionally, i.e.

$$C_{\text{int}} \times n_{\text{int}} \times T_{\text{payback}} = C_{\text{STS}} + \left(\frac{30}{50}\right) \times \left(\frac{100}{500}\right) \times C_{\text{DVR}} \quad (3.7)$$

With the same values as before:

$$n_{\text{int}} \times T_{\text{payback}} = \frac{600000 + 360000}{100000} = 9.6 \quad (3.8)$$

Which now becomes the most economical solution? However, one has to keep in mind that the most economical solution must be found on a case-by-case base, depending on the cost of the process disruption and the statistical distribution of events that the load can be subjected to.

## 4. DYNAMIC VOLTAGE RESTORER

### 4.1. Literature Review

DVR is a Custom Power Device used to eliminate supply side voltage disturbances. DVR (also known as Static Series Compensator (Lee et al, 2004)) maintains the load voltage at a desired magnitude and phase by compensating the voltage sags/swells and voltage unbalances presented at the point of common coupling (Mahesh et al, 2008).

In order to mitigate voltage quality problems, DVR injects voltages of suitable magnitude and phase in series with the line. During standby operation, DVR neither absorbs nor delivers real power. However, when voltage sag/swell occurs in the system, DVR delivers/absorbs real power transiently to/from dc link. Many loads facilitated in industrial plants such as adjustable speed drives and process control equipments are able to detect voltage faults as minimal as a few milliseconds. Due to the sensitivity of the loads, the DVR is required to response in a very high speed (Chan et al, 2006).

The alternative solution to DVR can be Uninterruptible Power Supply, Dynamic Uninterruptible Power Supply (Raithmayr et al, 1998), switched autotransformer (Lee, 2004) or D-STATCOM (Banaei et al, 2006). DVR provides relatively better voltage regulation than its alternative solutions and it has fast response and fewer transients (Ravi et al, 2007). Furthermore, the DVR is smaller in size and costs less compared to the DSTATCOM (McHattie, 1998).

DVR system can be divided into two sections: The control system and the power circuit. In the following sections, the available studies related with the control system and the power circuits of the DVR are summarized using the findings of the comprehensive literature survey. Field applications of DVR are also presented.

In this thesis, the following studies are performed:

- Literature survey of the DVR
- Design of the DVR

- Modeling of the DVR; a new sag detection method and a new reference voltage generation method are proposed for control of the DVR.
- Experimental implementation and verification of the proposed DVR.

#### 4.1.1. Studies Related to Power Circuit of DVR

DVR can be used for medium voltage and low voltage applications (Praveen et al, 2004). The power circuit of DVR generally consists of energy storage unit, DC/AC converter, LC filter and injection transformer. DVR is generally designed as 3-phase 3-wire (Saleh et al, 2008) but there are also 1-phase (Perera et al, 2006) and 3-phase 4-wire (Wang et al, 2004) studies for DVR. H bridge (Jimichi et al, 2008), multilevel (Loh et al, 2004), four-leg DVR (Naidu et al, 2007), transformerless DVR (Li et al, 2002), cyclo-converter based DVRs (Sree et al, 2000) are the examined topologies of DVR.

##### i) Energy Storage Unit

For most DVR applications, the energy source can be an electrolytic capacitor bank. The selection of the optimum topology and DVR ratings is related with the distribution of the remaining voltage, the outage cost and investment cost. There are two types of storage system (Nielsen et al, 2001):

“Storage systems with auxiliary supply” topology is applied to increase the performance when the grid of DVR is weak. In this type, variable DC link voltage or constant DC link voltage topologies are applied.

With the “storage systems with grid itself” topology, the remaining voltage on supply side (Saleh et al, 2008) or load side (Jimichi et al, 2008) is used to supply necessary power to the system if the DVR is connected to the strong grid.

**ii) DC/AC Converter**

The inverters circuits convert DC power to AC power. The types of inverter are voltage source inverter and current source inverter (Dixon et al, 1997; Nielsen et al, 2003):

It is easy to limit over current conditions but the value of output voltage varies widely with changes in load with the “current source inverter” topology. The values of output voltage variations are relatively low due to capacitor but it is difficult to limit current because of capacitor with the “voltage source inverter” topology.

**iii) LC Filter**

The effect of harmonics generated by the inverter can be minimized using the inverter side and line side filtering (Choi et al, 2000):

With the “inverter side filtering scheme”; it has the advantage of being closer to the harmonic source thus high order harmonic currents are prevented to penetrate into the series injection transformer but this scheme has the disadvantages of causing voltage drop and phase angle shift in the fundamental component of the inverter output.

With the “line side filtering scheme”; harmonic currents penetrate into the series injection transformer but the voltage drops and phase shift problems do not disturb the system (Acar, 2002).

**iv) Injection Transformer**

DVR is in standby mode for most of the time and conduction losses will account for the bulk of converter losses during the operation (Daehler et al, 2000). In this mode, the injection transformer works like a secondary shorted current transformer using bypass switches delivering utility power directly to the load. Alternatively, during standby operation of DVR, two lower Insulated Gate Bipolar

Transistors (IGBTs) in each phase of the inverter remain turned on while the two upper IGBTs remain turned off. A short circuit across the secondary (inverter side) windings of the series transformer through  $L_F$  is obtained eliminating the use of bypass switches (Jimichi et al, 2008).

#### 4.1.2. Studies Related to Control System of DVR

The control system is the most important part of the DVR system. The main considerations for the control system of a DVR include: sag detection, voltage reference generation for transient/steady state control, voltage injection strategies and methods for generating of gating signals.

##### i) Sag Detection

Voltage sag must be detected fast and mitigated with a minimum of false operations for 3 phase systems. In the Synchronous Reference Frame (SRF), Monitoring of  $\sqrt{V_d^2 + V_q^2}$  or  $V_d$  in a vector controller is the simplest and the most common type of sag detection, which will return the state of supply at any instant in time and hence, detect whether or not sag has occurred (Fitzer et al, 2004). To separate the positive and negative sequence components, low pass filters (LPFs) are used after the d-q transformation in the literature.

Further information about conventional sag detection method is presented in (Mokhtari et al, 2000). The other sag detection methods used in the literature are rms detection (Lee, 2004), peak detection (Lee, 2004), wavelet transform (Lee, 2004), kalman filtering (Dash et al, 2004), artificial neural network (Santoso et al, 1996) and vector controller (Fitzer et al, 2004). There are also single phase sag detection methods used in DVR. Soft Phase Locked Loop (Yue et al, 2008), Mathematical Morphology theory based low-pass filter (Zhou et al, 2008), Instantaneous Value Comparison Method (Bae et al, 2007) are the commonly used methods for single phase sag detection.

## ii) Reference Signal Generation and Injection Strategies

The most common voltage reference generation methods are d-q-0 (Jung et al, 2002), (Niese et al, 2004), (Yin et al, 2005), (Bongiorno et al, 2003) transform and p-q-r (Lee et al, 2004) transform. However, the other methods are software PLL (Liu et al, 2007), space vector control (Awad et al, 2007), p-i control (Lee, 2004) and artificial neural network (Jurado, 2004).

Most of the DVR controllers are using open-loop feed forward control in order to meet the fast compensation requirement. However, the presence of the switching harmonic LC filter would introduce voltage oscillations in transients. These oscillations increase the damping response time of the system as mentioned in (Otaoui et al, 2002).

Other factors that affect the performance of a DVR in open-loop control are the saturation of the series connected transformer and the voltage drop across the inductor in steady-state operation (Choi et al, 2002). The load voltage may not be compensated to the desired value in open-loop feed forward control. The problems stated above shown that closed-loop control can reduce the damping oscillations caused by the switching harmonic LC filter, and the load voltage can track closer to the reference load voltage under varied load condition. Some closed-loop control strategies of DVR are proposed, such as multi-loop control and closed-loop state variable control (Vilathgamuwa et al, 2002),(Joos et al, 2004). The performance of these control strategies are investigated with its dynamic and damping performance. These control schemes can reduce the damping oscillations, but not catching up with the fast dynamic response. Other control strategy is boundary controller (Chant et al, 2006).

DVR should ensure the unchanged load voltage with minimum energy dissipation for injection. The characteristic of load determines the required control strategy to inject compensation voltage. The methods for injection of missing voltage can be divided into four groups (Chung et al, 2003), (Won et al, 2003).

- Pre-sag compensation method
- In-phase voltage injection method

- Phase advance method
- Voltage tolerance method with minimum energy injection

In pre-sag compensation, the supply voltage is continuously tracked and the load voltage is compensated. On the other hand, for in-phase compensation, the DVR voltage is always in phase with the measured supply voltage regardless of the load current and pre-sag voltage. In phase advance method, decreasing the power angle between the remaining voltage and the load current minimizes real power spent by DVR. In voltage tolerance method with minimum energy injection method, the phase angle and magnitude of corrected load voltage within the area of load voltage tolerance are changed. The small voltage drop and phase angle jump on load can be tolerated by load itself and the size of the energy storage is minimized.

The control of the DVR can be implemented using Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA) or combination of them with passive circuits.

### **iii) Generating of Gating Signals**

The outputs of controller process are the control signals that are used in generation of switching signals of the inverter. The main modulation methods used in DVR are Pulse Width Modulation (PWM) (Takushi et al, 2005), Hysteresis (Takushi et al, 2005), deadbeat control (Ghosh et al, 2004b) and space vector PWM modulation (Duane et al, 1999). Pulse width modulation has a great impact on its transient performance and higher operating frequency capability. Thus, PWM method is widely used for gate signal generation in custom power applications.

#### **4.1.3. DVR Applications**

DVR have been installed in the Semiconductor, Plastic Extrusion, Food Processing and Paper Mill factories. DVR applications are (Buxton, 1998);

**i) Orian Rum Company**

The first DVR to enter service was installed by Westinghouse at the Orian Rugs Co. Plant in the USA. This is a highly automated facility with two main processes. The plant is served by a single 12.47 kV feeder from a 20 MVA substation transformer four miles away. A 2MVA DVR was installed to this plant.

**ii) Florida Power Corporation**

The 2MVA DVR was installed as part of Florida Power Corporation's new Power Quality Program.

**iii) Bonlac Foods**

The Bonlac load is approximately 5.25 MVA and the facility is served by a 22 kV feeder from Powercor's Kyabram substation 11 miles away. A 2MVA DVR was installed to this plant.

**iv) Caledonian Paper**

Scottish Power serves Caledonian Paper via a 132kV transmission line which is stepped and the total plant load is 47MVA. 4MVA DVR, with 800 kW of energy storage was installed to this plant.

**4.2. Design of Proposed DVR**

The major components of DVR system are composed of power circuit and control system as shown in Figure 4.1. The main components of power circuit are energy storage unit, inverter circuit, LC filter and series injection transformer. The control system of a DVR includes voltage measurements, sag detection and reference voltage generation.

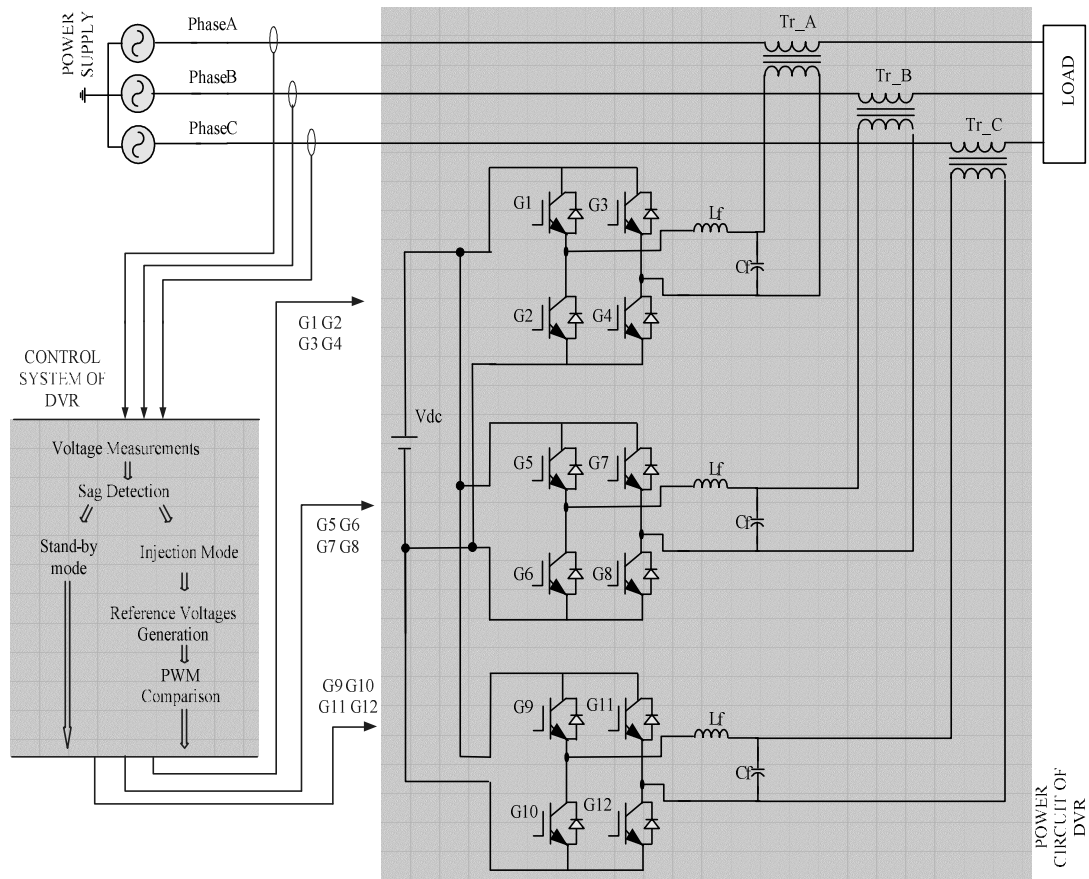


Figure 4.1. Power circuit and control system of DVR

The source voltages are measured by transducers. The control system senses the sag and generates the required PWM signals for disturbance mitigation using the PLL algorithm. The generated signals for each phase trigger PWM inverters and the missing voltage is injected to the load in series using injection transformers.

#### 4.2.1. Configuration of Power Circuit

The main components of DVR power circuit are shown in Figure 4.2. The components are described in more detail in the following sections.

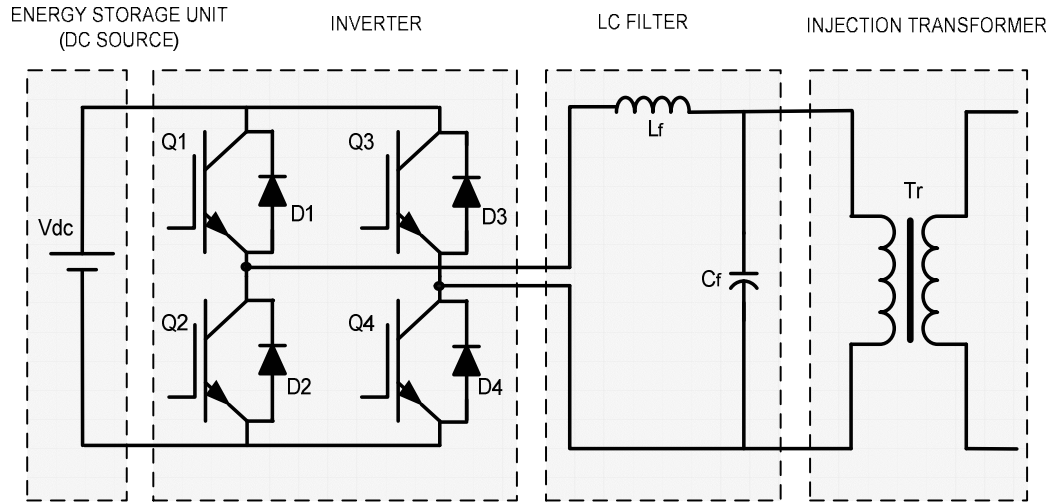


Figure 4.2. Main components of single phase of the DVR system

#### 4.2.1.1. Energy Storage Unit

The energy storage unit (DC Source) supplies required power for compensation of load voltage during voltage sag. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any ac passive reactive components, e.g. reactors or capacitors. Real power exchanged at the DVR ac terminals must be provided at the DC terminal of DVR by an auxiliary energy storage system (Woodley et al, 1999). Storage Systems with Auxiliary Supply is applied to DVR. Thus, the DC link voltage is almost kept constant with this topology during voltage sag.

#### 4.2.1.2. Inverter Circuit

The inverter circuit converts DC power to AC power. Solid-state semiconductor devices with turn-off capability (IGBTs) are used in the inverter circuits. A voltage source inverter is energized by a stiff DC voltage supply of low impedance at the input. The output voltage is independent of load current. The inverters are then connected in series to the distribution line through single-phase injection transformers as shown in Figure 4.3.

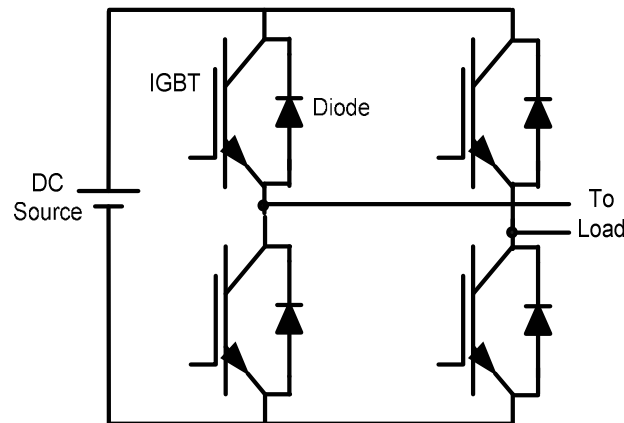


Figure 4.3. Circuit diagram of a single-phase h-bridge inverter

IGBT technology has undergone rapid advances which have drastically improved the performance of the device. Today's IGBTs have high latch-up immunity, low on-state voltage drop, and switching frequencies up to, and even more than, 20 kHz. IGBT is a unidirectional conducting device and hence in most of the applications an anti-parallel diode has to be used (Pendharkar et al, 1997). When IGBTs are used as switching components in an inverter or converter, freewheeling diodes are needed to sustain the current from the inductive load such as a motor or transformer.

The three single-phase Pulse Width Modulation (PWM) voltage source inverters will be used in this study. PWM switched inverters provide better performance to control asymmetries and especially over currents during unbalanced faults. The voltage control is achieved by modulating the output voltage waveform within the inverter. The rating of PWM voltage source inverter is low in voltage and high in current because of using the step up injection transformer.

The main advantage of PWM inverter is including fast switching speed of the power switches. PWM technique offers simplicity and good response. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses (Lara et al, 2002).

#### 4.2.1.3. LC Filter

The filter unit eliminates the dominant harmonics produced by inverter circuit. In this study, the inverter side filtering is preferred for harmonic elimination. The inverter side filter is closer to the harmonic source and low voltage side thus it prevents the harmonic currents to penetrate into the series injection transformers (Choi et al, 2002).

The equivalent circuit of inverter side filter is shown in Figure 4.4.

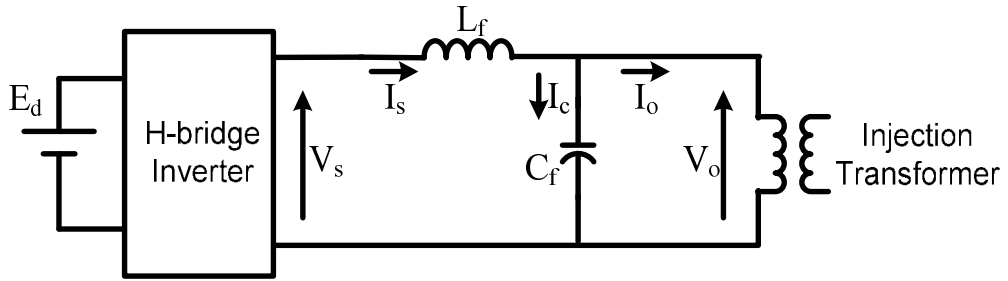


Figure 4.4. Equivalent circuit for inverter side filter

$E_d$  is the nominal DC source voltage,  $V_s$  is the output voltage of the PWM inverter,  $I_s$  is the source current,  $L_f$  is the filter inductance,  $I_c$  is the capacitor current,  $C_f$  is the filter capacitance,  $I_o$  is the load current,  $V_o$  is the load voltage (Dahono et al, 1995).

Based on Figure 4.4, the output voltage equation of the inverter can be written as:

$$V_s = V_o + L_f \frac{dI_s}{dt} \quad (4.1)$$

The design procedure of the LC filter can be divided into three steps by considering the assumptions of (Dahono et al, 1995). The following equations are obtained through comprehensive analysis of derived formulas.

Based on the dc source voltage  $E_d$  and nominal load voltage  $V_o$ , the modulation index  $k$  is calculated.

$$k = \sqrt{2} \frac{V_o}{E_d} \quad (4.2)$$

The result is used to calculate the filter factor  $K$  by using Equation (4.3).

$$K = \left[ \frac{k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6}{1440} \right]^{1/2} \quad (4.3)$$

Equation (4.4) calculates the optimum value of the filter inductance.

$$L_f = \frac{V_o}{I_o f_s} \left\{ K \frac{E_d}{V_{o,av}} \left[ 1 + 4\pi^2 \left( \frac{f_r}{f_s} \right)^2 K \frac{E_d}{V_{oav}} \right] \right\}^{1/2} \quad (4.4)$$

Where  $f_s$  is the switching frequency;  $V_{oav}$  is the total harmonic of the load voltage;  $f_r$  is the fundamental output frequency.

Equation (4.5) calculates the optimum value of the filter capacitance:

$$C_f = K \frac{E_d}{L_f f_s^2 V_{o,av}} \quad (4.5)$$

$L$  and  $C$  values are calculated following the design procedure of (Dahono et al, 1995) in this study. The values of filter design parameters shown in Table 4.1.

The nominal modulation index is calculated using (4.2).

$$k = \sqrt{2} \frac{V_o}{E_d} \rightarrow k = 1$$

Table 4.1. The values of filter design parameters

| $V_o$                | $E_d$               | $I_o$                 | $f_r$ | $f_s$  | $V_{oav}$ |
|----------------------|---------------------|-----------------------|-------|--------|-----------|
| 110 V <sub>rms</sub> | 155 V <sub>dc</sub> | 4.54 A <sub>rms</sub> | 50 Hz | 10 kHz | 0.1%      |

The result is then used to calculate the factor  $K$  by using (4.3).

$$K = \left[ \frac{k^2 \frac{15}{4} k^4 + \frac{64}{5\pi} k^5 \frac{5}{4} k^6}{1440} \right]^{1/2} \rightarrow K = 0.00716$$

The optimum values of the inductance and capacitance of the filter can be calculated by using (4.4) and (4.5).

$$L_f = \frac{V_o}{I_o f_s} \left\{ K \frac{E_d}{V_{o,av}} \left[ 1 + 4\pi^2 \left( \frac{f_r}{f_s} \right)^2 K \frac{E_d}{V_{o,av}} \right] \right\}^{1/2} \rightarrow L_f = 7.8 \text{ mH}$$

$$C_f = K \frac{E_d}{L_f f_s^2 V_{o,av}} \rightarrow C_f = 13 \text{ } \mu\text{F}$$

From the view of costs and weight, the capacitor is the much cheaper device than the inductor. To improve the filter performance considering the filter market, the capacitor is selected as 18  $\mu\text{F}$  and the filter inductor is selected as 10 mH in the study.

#### 4.2.1.4. Series Injection Transformer

The transformers not only reduce the voltage requirement of the inverters, but also provide isolation between the inverters. This can prevent the dc storage capacitor from being shorted through switches in different inverters (Ghosh et al, 2002b).

The electrical parameters of series injection transformer should be selected correctly to ensure the maximum reliability and effectiveness. IGBT switches are commonly used in series connected circuits. In normal bypass mode, full load currents pass through these semiconductor switches. In addition to this, the flowing current will increase during sags because of injected power for compensation so the switches and protection devices should handle the total current.

#### 4.2.2. Configuration of Control System

In this study, simple and effective control algorithms are proposed for both sag detection and reference voltage generation. The algorithms are based on the nonlinear adaptive filter presented in (Karimi et al, 2002). This filter can be used as a phase locked loop. The filter has also the abilities of peak detection and signal decomposition.

##### 4.2.2.1. Phase Locked Loop

The phase locked loop (PLL) used in this study is comprised of a phase detector, a loop filter and a voltage controlled oscillator. In Figure 4.5, the block diagram of the PLL is given. The PLL tracks a specific component of the input signal and simultaneously extracts its amplitude and phase. The error signal represents the deviation of the input signal from the output signal.

$u(t)$  is the input signal to the PLL that will be tracked while  $y(t)$  is the output of the PLL.  $Mag(t)$  is the amplitude and  $\theta(t)$  is the phase angle of the tracked signal.  $e(t)$  is used to represent the error signal which represents the difference between input signal and output signal. The  $w_0$  determines the frequency of the output signal.

The generated output signal  $y(t)$  is both in phase and amplitude with the input signal  $u(t)$ .

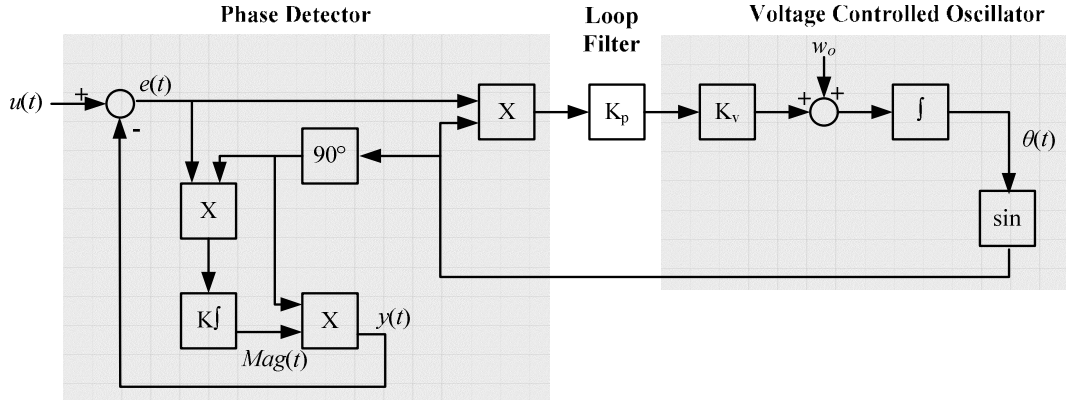


Figure 4.5. Block diagram of the phase locked loop used in DVR control

The speed of the response is determined by parameters  $K$ ,  $K_p$  and  $K_v$ . These parameters control transient as well as steady state behavior of the filter. There exists a compromise between speed and accuracy. For large  $K$  and  $K_p K_v$ , the convergence of the estimated values to actual values is faster but the steady state misadjustment is higher. This is an inherent characteristic of an adaptive algorithm. Parameters ought to be selected appropriately according to the application. Increasing the value of  $K$  increases the speed. However, it creates oscillations in the peak detection response. There is a trade-off between speed and accuracy (or smoothness). Decreasing  $K$  and  $K_p K_v$  yields an estimation of the peak which is insensitive / robust to the undesirable variations and noise in the input signal (Karimi et al, 2002).

The presented PLL provides the following advantages (Karimi et al, 2002): Online estimation of the amplitude, phase and their corresponding time derivatives of the pre-selected component of the input signal are provided.

#### 4.2.2.2. Sag Detection Method

To show the superiority of the proposed sag detection method, it is compared with the  $dq$  transformation based conventional sag detection. In the  $dq$  method, the

phase-to-neutral voltages  $V_a$ ,  $V_b$  and  $V_c$  are subjected to transformation given in Eq. (4.6). With the use of Eq. (4.7), the voltage phasor is obtained.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4.6)$$

$$V_p = \sqrt{V_d^2 + V_q^2} \quad (4.7)$$

It is note that, in the literature, there are various equations related to  $abc$ - $dq$  transformation. Some of them give  $d$  component as “1” and  $q$  component as “0” during unfaulted conditions. However, some transformation equations give  $q$  component as “1” and  $d$  component as “0”. In this study, the transformation gives  $d$  component as “1” during unfaulted conditions. In Figure 4.6, the block diagram of the  $abc$ - $dq$  transformation based sag detection method is shown. After the three phase set of voltages are transformed into  $d$  and  $q$  components, the square root of the sum of squares of these components is obtained. The obtained value is filtered with a 50 Hz low pass filter and subtracted from the reference value of 1. The obtained output is subjected to the hysteresis comparator and the output of this comparator is the sag detection signal. The signal is high when the sag occurs, low otherwise.

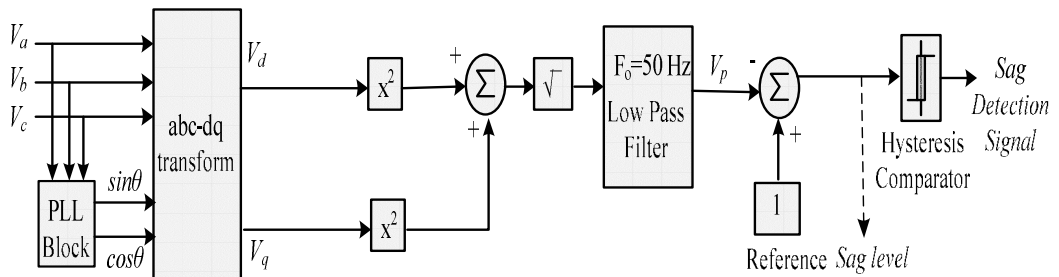


Figure 4.6. Block diagram of the  $dq$  sag detection method for DVR

This method is able to detect the three phase balanced voltage sags with an acceptable performance. However, the most important disadvantage of this method is

that it uses three phase voltage measurements for the sag detection. The method is unable to detect the voltage sags lower than a definite level. As an instance, a single phase to ground fault resulting in 15% of voltage sag cannot be determined by this method because the method used the average of the three phase voltages and sees the single phase voltage sag as an average value of 5% (15/3) if the voltage sag detection limit is selected to be 10% of nominal. Besides another restriction of this method is the use of low pass filter tuned at 50 Hz. This filter reduces the response speed of the detection scheme.

To overcome the disadvantages of the  $dq$  sag detection method, the PLL explained in the previous section is used in this study. With the proposed method, the controller is able to detect balanced, unbalanced and single phase voltage sags without an error. In this method, three PLLs are used to track each of the three phases.

The signal  $Mag$  shown in Fig. 4.5 gives the amplitude of the tracked signal  $u(t)$ . For example, if the amplitude of the measured signal is 220 V<sub>rms</sub>, the  $Mag$  signal is obtained as continuous 1 pu. If the amplitude falls to the 176 V<sub>rms</sub>, the amplitude of the  $Mag$  signal falls to 0.85 pu. Figure 4.7 summarizes the voltage sag detection using PLL.

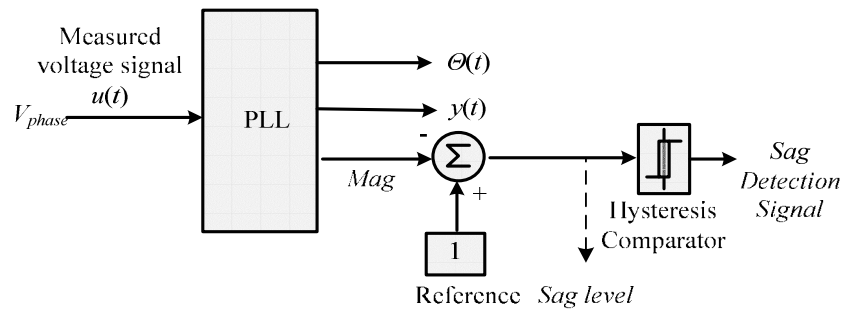


Figure 4.7. Block diagram of proposed PLL based sag detection method for DVR

By subtracting the  $Mag$  signal from the ideal voltage level (1 pu), the voltage sag level could be detected. The comparison of this value with the limit value of 10% (0.1 pu) points to a voltage sag.

#### 4.2.2.3. Reference Voltage Generation Method

Most of the methods in literature have drawbacks to generate reference voltage signals and compensation signals experimentally when the supply voltage contains distortions. With the reference voltage generation method used in this thesis, “distortions in the supply line are perfectly filtered” and a pure sinusoidal reference voltage is obtained.

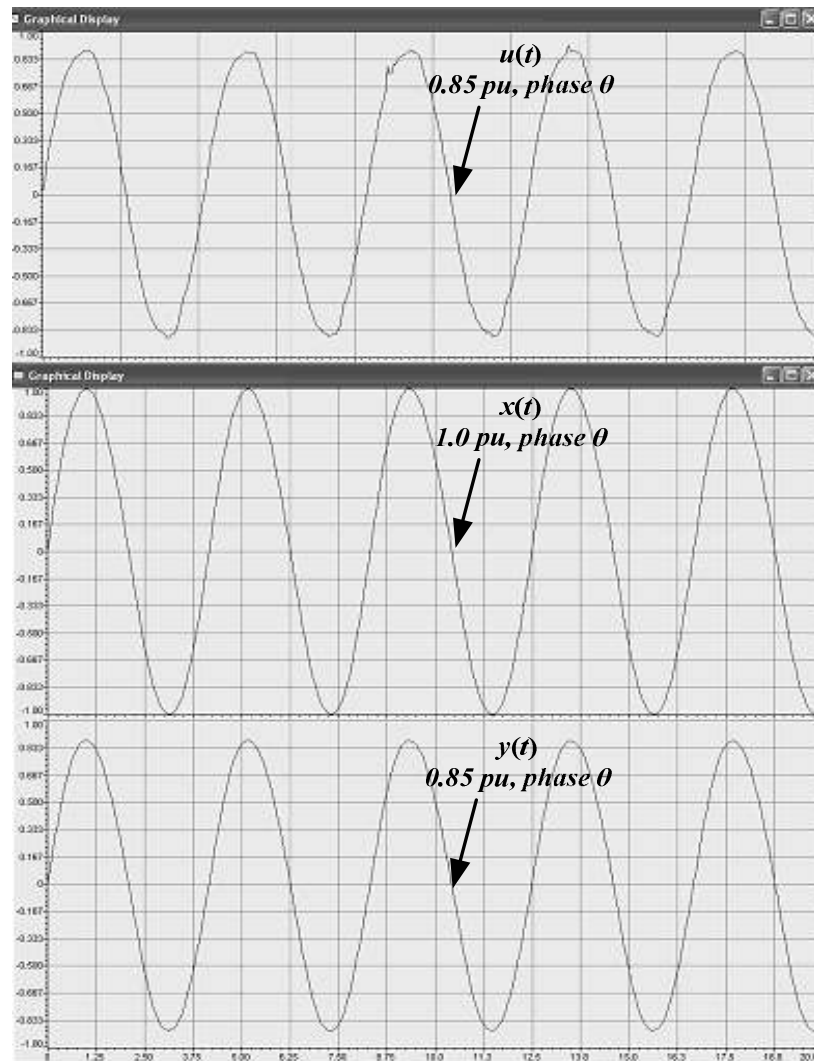


Figure 4.8. Measured supply voltage  $u(t)$ , reference signal  $x(t)$  and extracted  $y(t)$

For the reference voltage generation, another property of the PLL is used. As it was, the output  $y(t)$  shown in Figure 4.8 is an extracted signal from the input  $u(t)$  having the amplitude  $Mag$  and phase  $\theta(t)$  of the input  $u(t)$ . In this way, “distortions in the supply line are perfectly filtered”.

$$V_{dif} = u(t) - y(t) \quad (4.8)$$

In the proposed method, a reference sinusoidal signal  $x(t)$  having 1 pu magnitude and having phase angle  $\theta(t)$  is used. Reference voltage signal is generated (7) from the difference of  $y(t)$  and  $x(t)$ .

$$x(t) = 1.\sin(\theta(t)) \quad (4.9)$$

$$y(t) = Mag(t).\sin(\theta(t)) \quad (4.10)$$

$$V_{error} = x(t) - y(t) \quad (4.11)$$

$V_{dif}$  is the real difference voltage value for the PLL and  $V_{error}$  is the ideal error signal. If  $V_{dif}$  is used for reference voltage generation, this reference voltage will contain distortions and negatively effect the control signals during experimental study. The ideal reference voltage signal  $V_{error}$  is compared with a fixed frequency carrier wave to generate the firing pulses (or gating signals) as PWM signals. In this way, the voltage in the same phase with supply side generated by the DVR voltage source inverter is injected to the load side.

As shown in Figure 4.9, the voltage compensation signal  $V_{error}$  is compared with a fixed frequency carrier wave to generate the firing pulses as PWM signals. In this way, the voltage in the same phase with supply side generated by the DVR voltage source inverter is injected to the load side. Thus load is not affected by the sag.

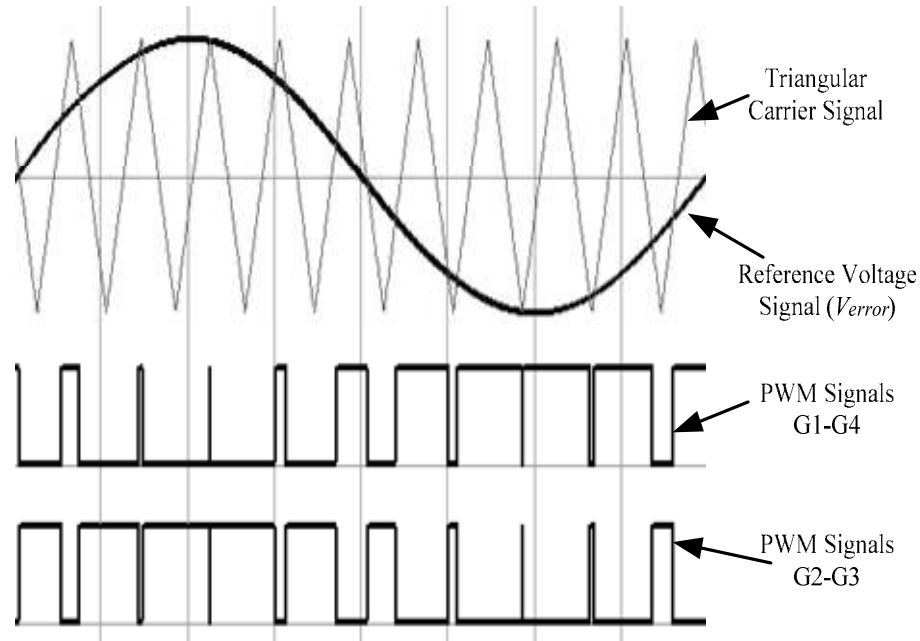


Figure 4.9. Generation of PWM signals

#### 4.2.2.4. Minimum Energy Injection and Stand by Operation

The DVR models presented in the literature before including H-bridge inverters control all the H-bridges at the same time. That is, the H-bridge inverters are dependent on each other. However, sometimes when a single phase fault occurs, it is not necessary to operate all of the inverters. But conventionally, all the H-bridges are operated at the same time resulting in increased losses. In this study, by using an independent sag detection method for each phase, each H-bridge inverter is controlled independently. With this method, minimum energy is injected and switching losses are reduced.

During standby operation of DVR, two lower IGBTs of each phase H-bridge inverter remain turned on while the two upper IGBTs remain turned off, thus forming a short circuit across the secondary (inverter side) windings of the series transformer through  $L_F$  (Jimichi et al, 2005). Thus, there is no need to use of bypass switches.

### 4.3. Simulation Study of Proposed DVR

#### 4.3.1. Simulation Model of Proposed DVR

The designed DVR is modeled and simulated by using PSCAD/EMTDC program. The simulation model of DVR Power Circuit is shown in Figure 4.10. As seen from the power circuit; the load is fed by a disturbance generator which generates sag. The DVR (composed by transformers, filters, inverters and DC source) power circuit is connected between source and load. In the simulation model, source voltages are modeled with voltage harmonics in order to obtain more realistic results such as experimental results of laboratory.

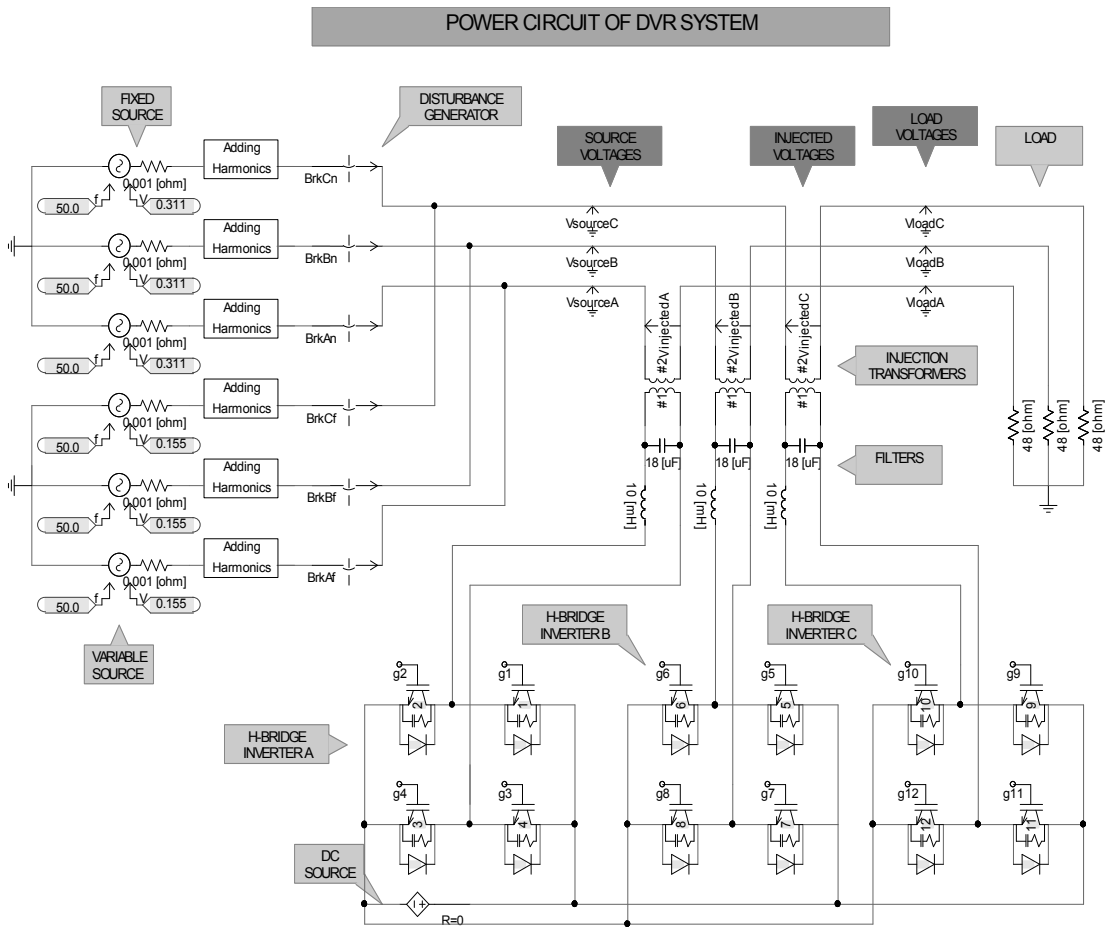


Figure 4.10. Simulation model of DVR power circuit

Table 4.2. Parameters of simulated DVR system

| Description                    | Value / profile                                                                                                                                                                                                                           |
|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Fixed Source                   | Phase to neutral 220 V <sub>rms</sub>                                                                                                                                                                                                     |
| Variable Source                | Phase to neutral 0-220 V <sub>rms</sub>                                                                                                                                                                                                   |
| Harmonic Voltage Sources       | 3th harmonic: 0.9% of fundamental, 5rd harmonic: 1.5% of fundamental, 7th harmonic: 0.9% of fundamental, 9th harmonic: 0.75% of fundamental, 11th harmonic: 0.45% of fundamental, Source Voltage THD is 2.15%, Load Voltage THD is 1.69%. |
| Load impedance / per phase     | 48 $\Omega$                                                                                                                                                                                                                               |
| Injection transformer          | Single phase, 1:1, 1 kVA                                                                                                                                                                                                                  |
| Filter capacitor and inductor  | 18 $\mu$ F and 10 mH                                                                                                                                                                                                                      |
| Voltage source inverter of DVR | Three single phase H-bridge inverter                                                                                                                                                                                                      |
| DC source of DVR               | 150 V                                                                                                                                                                                                                                     |
| Sample time for simulation     | 25 $\mu$ s                                                                                                                                                                                                                                |
| Hysteresis Comparator          | Upper Limit 0.1, Lower Limit 0.04                                                                                                                                                                                                         |

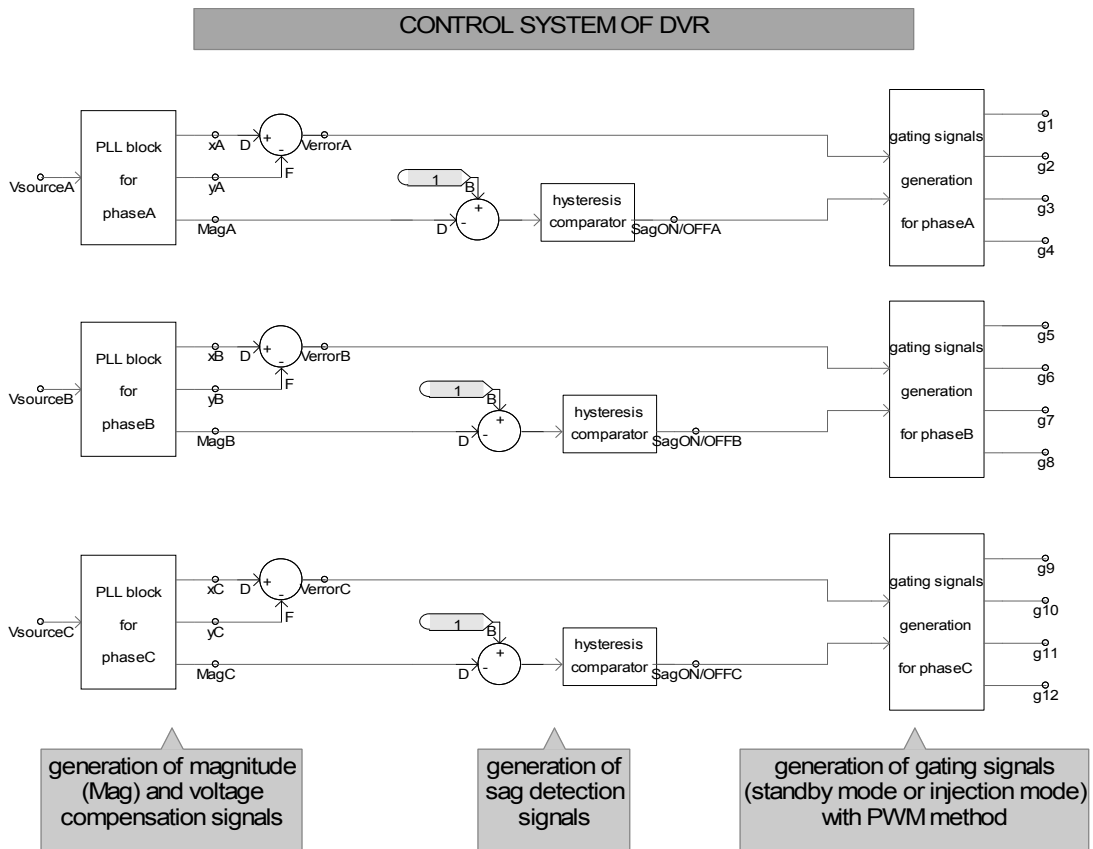


Figure 4.11. Simulation model of proposed DVR control system

### 4.3.2. Simulation Results for Proposed DVR

#### 4.3.2.1. Unbalanced Fault: %15 Single Phase Voltage Sag

In this case, an unbalanced fault occurs on phase A resulting in 15% decrease from nominal value (15% voltage sag) between the period 120 ms and 220 ms.

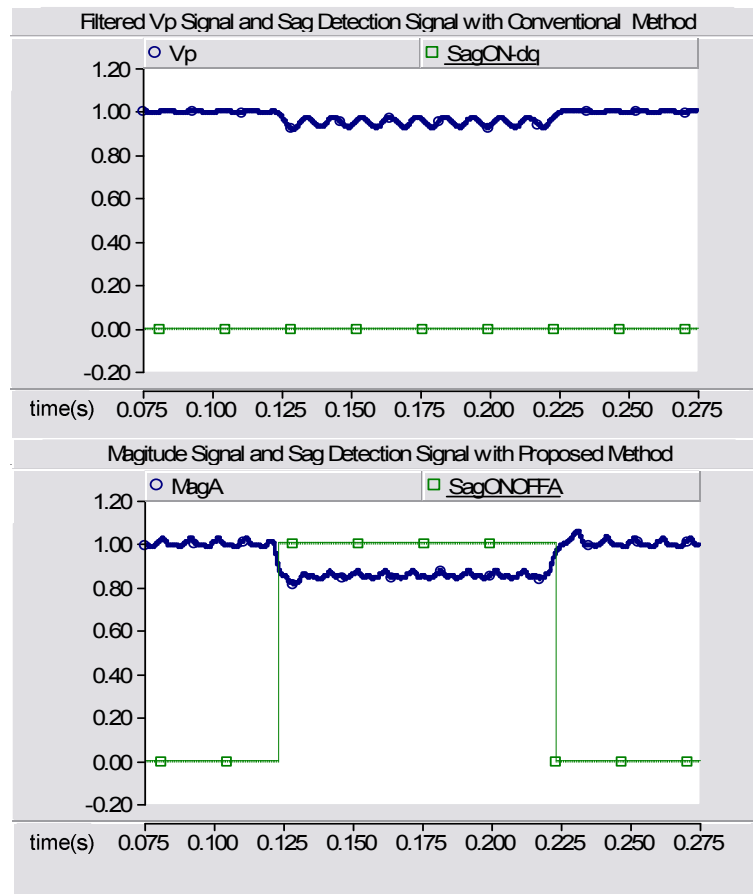


Figure 4.12. Sag detection signals for conventional and proposed sag detection methods

Figure 4.12 shows the  $Mag$  signal and sag detection signal with proposed method for phase A. The filtered  $V_p$  and sag detection signals with conventional methods are also shown in Figure 4.12. Normally, the value of the sag detection signal is equal to 0. When a fault occurs in the phase voltage and magnitude signal less than 0.9 value, the output of the hysteresis comparator becomes 1, and thus, the

injection mode starts. As seen from Figure 4.12, conventional method can not detect the sag. Because, the level of voltage sag is detected as 5% by conventional method. Sag detection time of proposed method is total 3.05 ms for this case (The horizontal axes in all simulation graphics represent the time as seconds). However, the ripples of magnitude signal are caused by the harmonic voltage components of source.

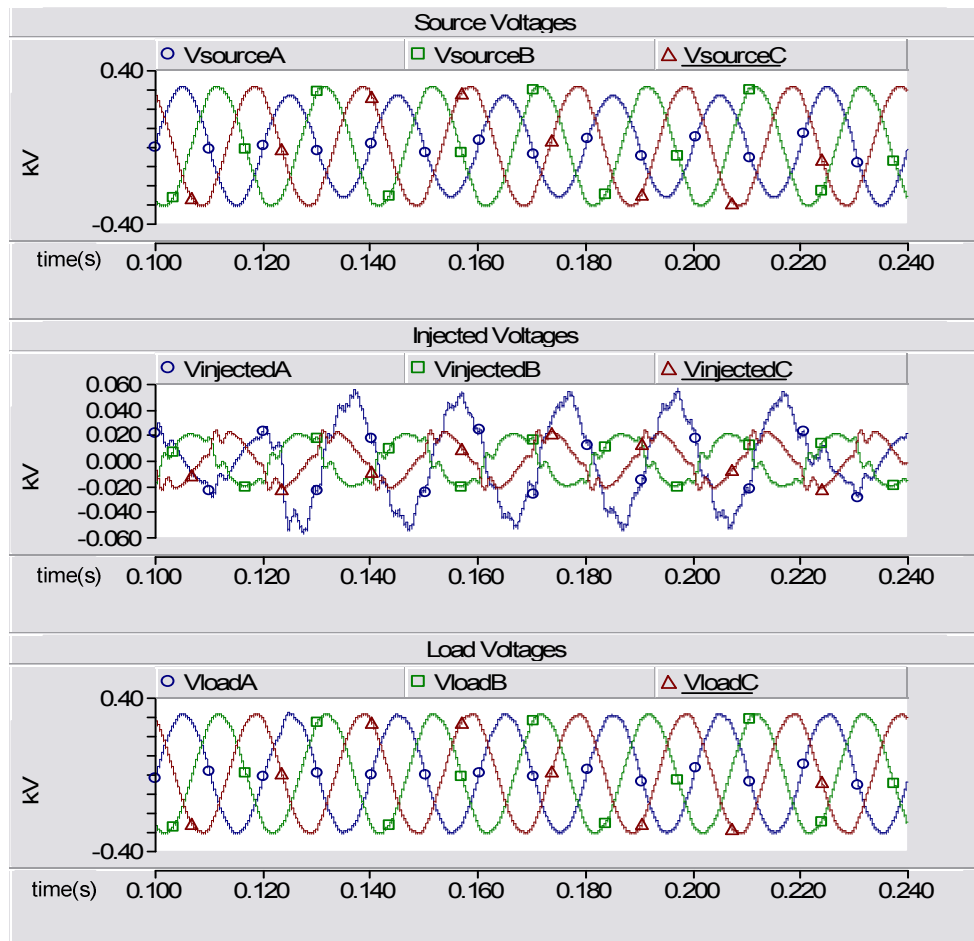


Figure 4.13. Source voltages, injected voltages and load voltages during the unbalanced fault period for proposed methods

Figure 4.13 shows the source voltages, injected voltages and load voltages during the unbalanced fault period for proposed sag detection and proposed voltage compensation methods. The injected voltage has disturbances because the reference compensation signal is too small for triangular carrier signal. However, all the phase

voltages of load are maintained at nominal values. The THD value of source voltage is 2.15%, and the THD value of load voltage is 2.01% during 15% voltage sag.

It is observed that the injected voltages are not equal to zero during the standby mode because the full load current passes through the LC filter and lower switches of IGBT inverter even if the system is in the standby mode. The voltage drop is caused by the reactance of the inductor.

#### 4.3.2.2. Balanced Fault: %40 Three Phase Voltage Sag

A balanced fault occurs on source side resulting in 40% three phase voltage sag between the period 245 ms and 345 ms, in this case.

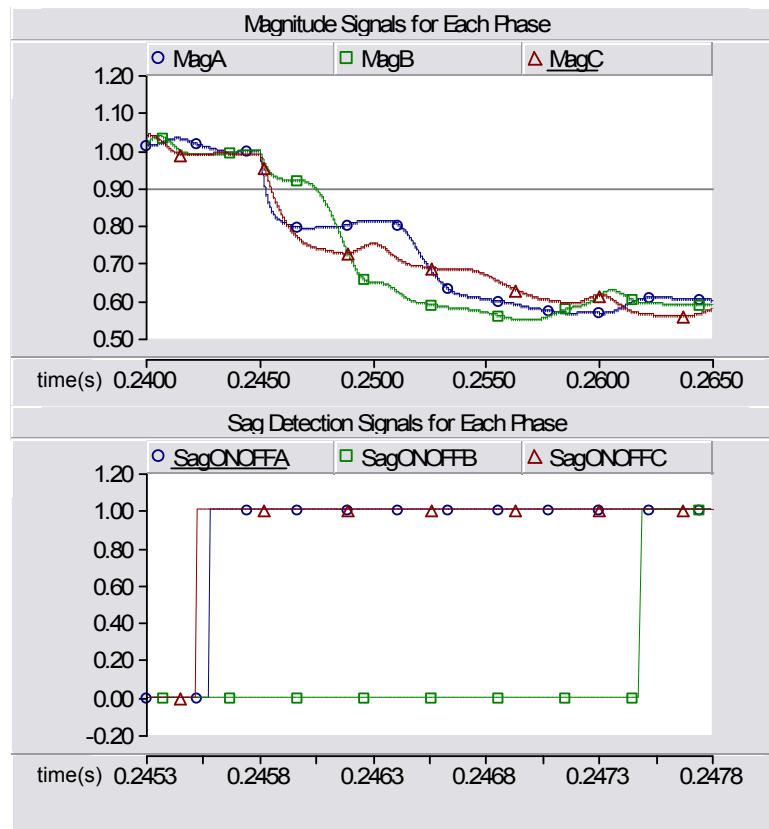


Figure 4.14. Magnitude signals and sag detection signals for each phase with proposed method

Figure 4.14 shows the magnitude signals and sag detection signals for each phase. The magnitude signals are decrease to 0.6 of nominal. The sag starting time is worst case for phase B. Total sag detection times are 0.46, 2.4 and 0.52 ms for phase A, phase B and phase C, respectively.

Figure 4.15 shows the source voltages, injected voltages and load voltages during the balanced fault period. The injected voltages are much similar to ideal sinusoidal signal, than injected voltage for the case of 15% voltage sag. However, all the phase voltages of load are maintained at nominal values.

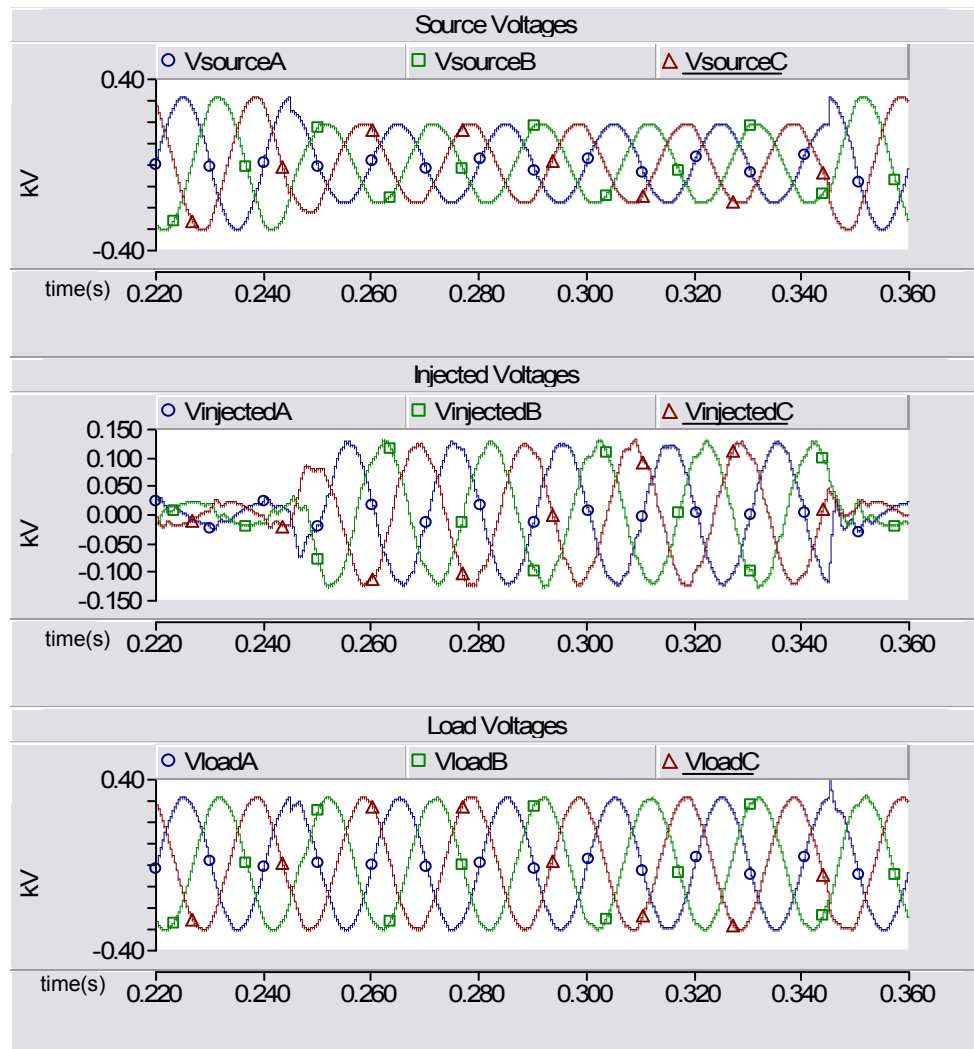


Figure 4.15. Source voltages, injected voltages and load voltages during the balanced fault period

The THD value of source voltage is 2.15%, and the THD value of load voltage is 2.33% during 40% voltage sag.

#### 4.3.2.3. Discussions for Various Case Studies

The DVR simulation results for various fault scenarios occurring at times interval 0.245-0.345 ms are given in Table 4.3 as numerical values.

Table 4.3. The DVR simulation results for various fault scenarios

| Case Study                                   | Sag Detection Times (ms) |      |      | Injected Voltages (pu) |       |       | Load Voltages THD (%) |
|----------------------------------------------|--------------------------|------|------|------------------------|-------|-------|-----------------------|
|                                              | PhA                      | PhB  | PhC  | PhA                    | PhB   | PhC   |                       |
| Non-Faulted Condition                        | -                        | -    | -    | 0.068                  | 0.068 | 0.068 | 1.69                  |
| 0.15 pu sag on Phase A Voltage               | 6.40                     | -    | -    | 0.158                  | 0.068 | 0.068 | 2.02                  |
| 0.25 pu sag on Phase A Voltage               | 0.76                     | -    | -    | 0.247                  | 0.068 | 0.068 | 2.29                  |
| 0.40 pu sag on Phase A Voltage               | 0.52                     | -    | -    | 0.385                  | 0.068 | 0.068 | 2.34                  |
| 0.15 pu sag on Phases A and Phase B Voltages | 6.40                     | 3.62 | -    | 0.158                  | 0.156 | 0.068 | 2.06                  |
| 0.30 pu sag on Phases A and Phase B Voltages | 0.64                     | 2.82 | -    | 0.301                  | 0.300 | 0.068 | 2.10                  |
| 0.15 pu sag on Phase A Voltage               | 6.40                     | 3.62 | 2.02 | 0.158                  | 0.156 | 0.157 | 2.04                  |
| 0.25 pu sag on three phase voltages          | 0.76                     | 3.05 | 0.85 | 0.247                  | 0.242 | 0.243 | 2.28                  |
| 0.50 pu sag on three phase voltages          | 0.46                     | 2.01 | 0.39 | 0.482                  | 0.480 | 0.481 | 2.40                  |

As seen from the results, each phase has own sag detection algorithm. For example, for single phase 15% sag, or double phase 15% sag, or three phase 15% sag, phase A, has same sag detection times, voltage sags of other phases don't affect this phase.

The sag level and the starting time is important. For example, the 15% sag and 0.25% sag occurring at same time on phase A, have different sag detection times. One of them is very short, the other is very long. The cause of this situation is that the changing of  $Mag$  signal shape according to sag level (as shown before in Figure 4.12 and Figure 4.14).

As seen from the Table 4.3, the source voltage sag levels and injected voltage levels are almost same. Thus, the load voltage is kept at nominal values (1 pu). As mentioned before, it is observed that the injected voltages are not equal to zero (0.068 pu) during the non-faulted conditions. But this voltage isn't injected by DVR, it is measured voltage drop caused by the reactance of the inductor in the stand-by mode.

As seen from the THD results, the voltage THD value of load is 1.69% in case of non-faulted condition. At the worst case (50% voltage sag), the load voltage has 2.40% voltage THD and kept below IEEE voltage THD limits (IEEE519, 1992).

#### 4.4. Experimental Setup of Proposed DVR

The block diagram of the DSP controlled experimental hardware of three-phase DVR is shown in Figure 4.16.

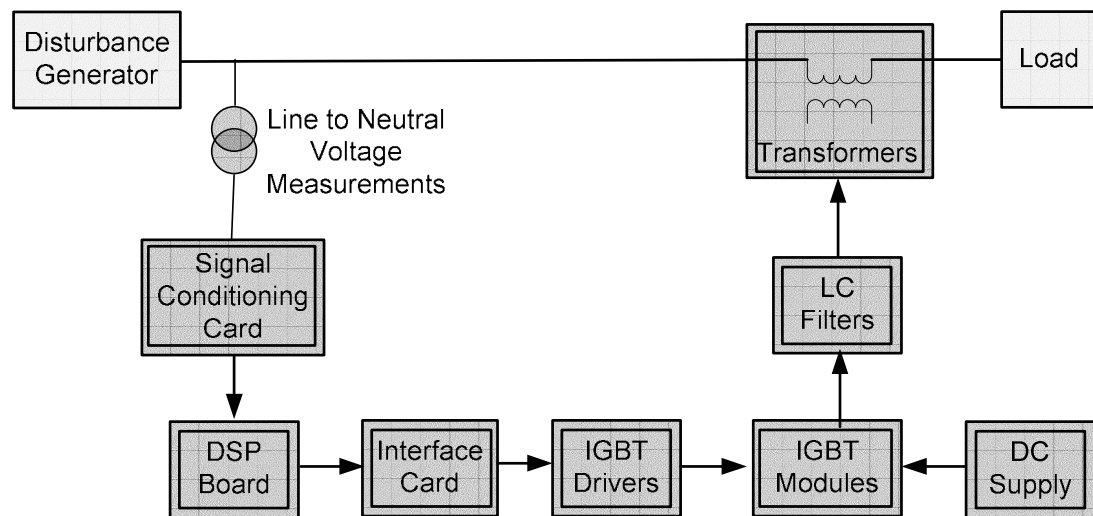


Figure 4.16. The block diagram of DSP controlled experimental hardware DVR

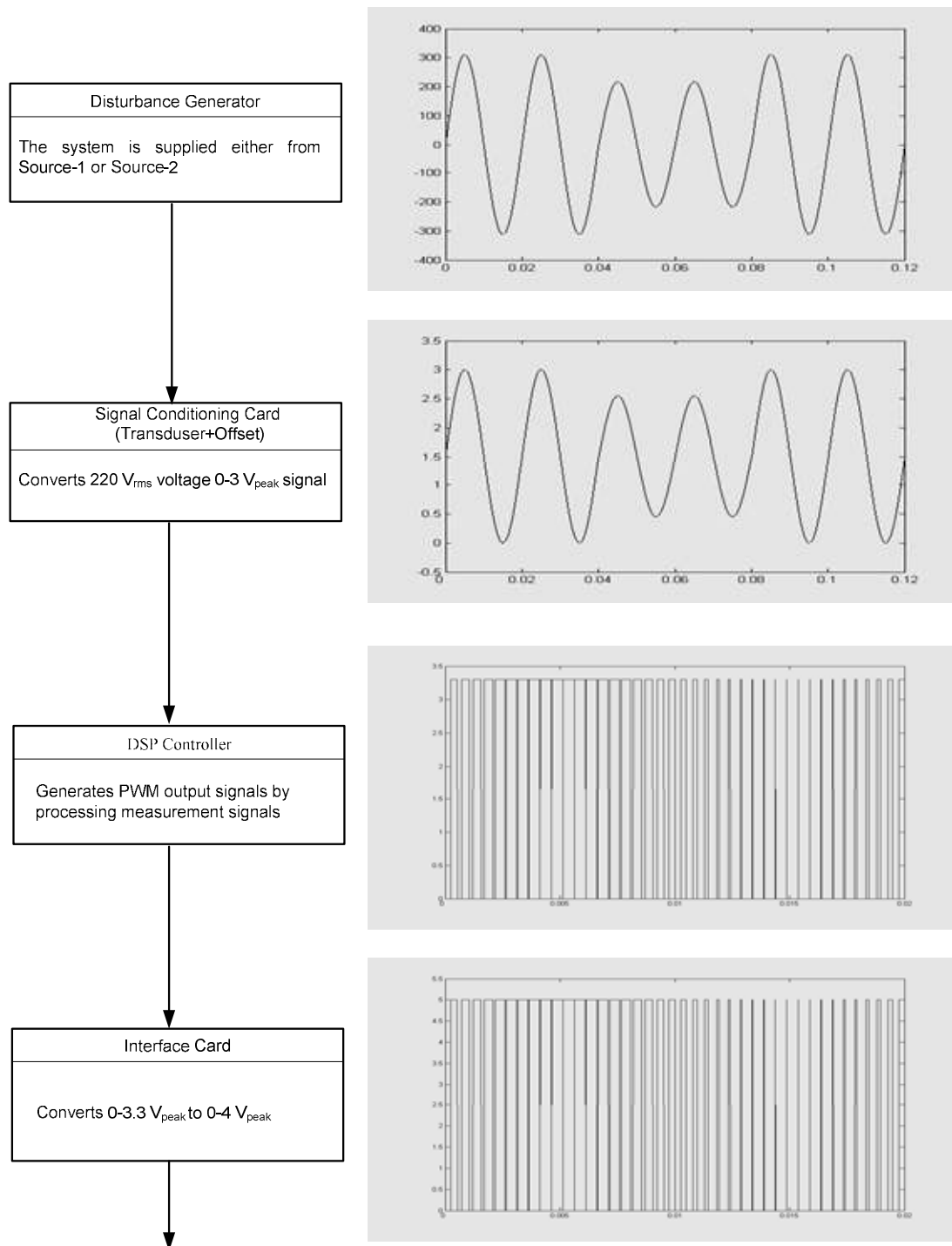


Figure 4.17. (a) Equipments used in DSP based DVR and their typical output waveforms: Part 1

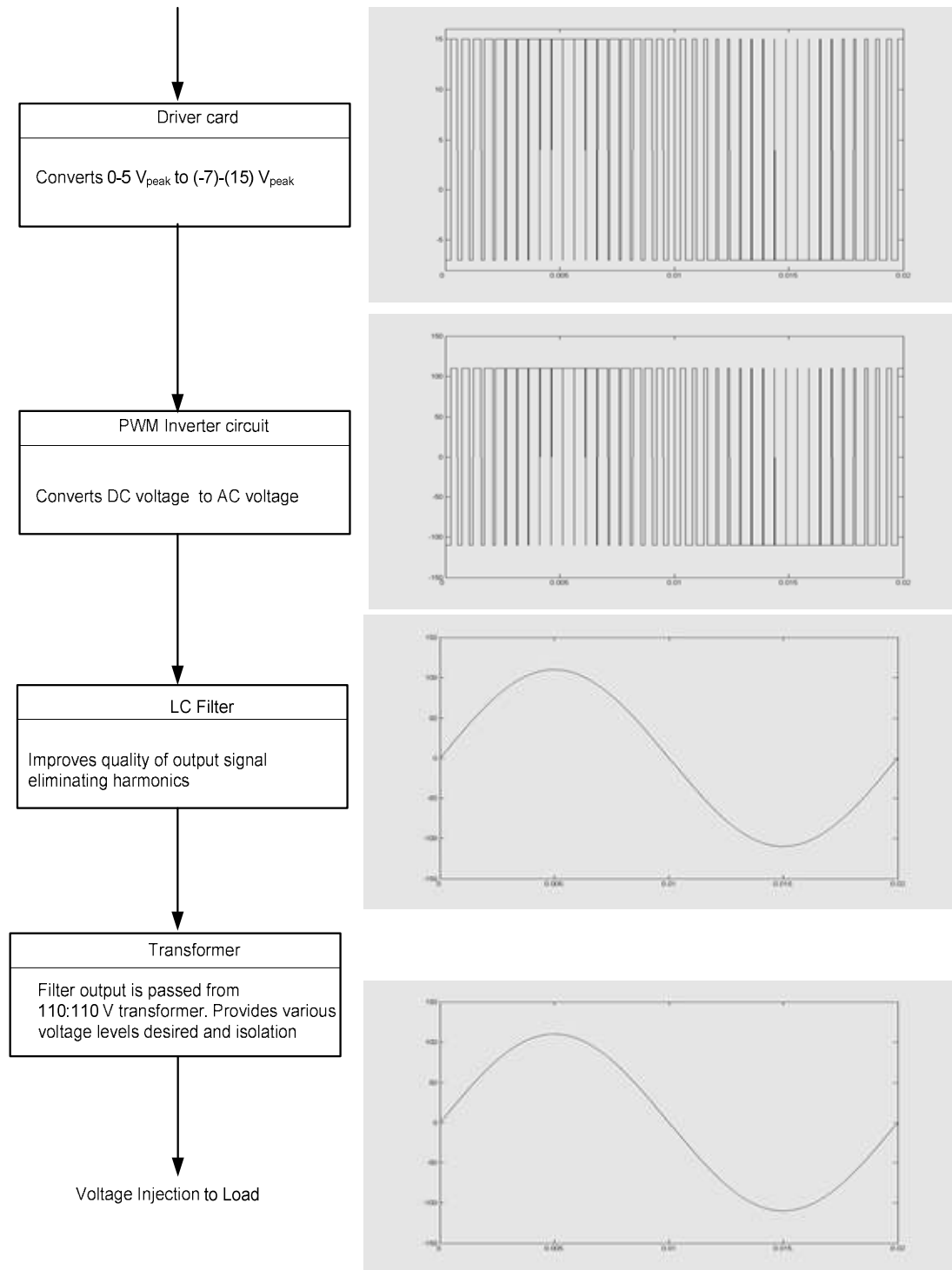


Figure 4.17. (b) Equipments used in DSP based DVR system and their typical output waveforms: Part 2

The proposed system consists of an eZdsp F2812 DSP board, H-bridge IGBT inverter, LC filter circuit, DC source, injection transformer and measurement devices.

The hardware components of DSP controlled three phase DVR and typical output waveforms are given in Figure 4.17. The components used are comprehensively described respectively in the following sections. DSP generates three phase reference signals and then produces sinusoidal PWM output signals. The produced signals have  $0-3.3 V_{\text{peak}}$  value. These signals are amplified to 0-5 V and connected to IGBT driver circuit. The driver circuit changes the amplitudes of the signals to  $(-7 V_{\text{peak}})-(15 V_{\text{peak}})$ . The amplified signals are given to Gate-Emitter of each IGBT which is now suitable to trigger an IGBT. Four IGBTs (two legs) are required to obtain an H bridge inverter. Two IGBTs are used for each leg and one driver circuit is required for each leg. The procedure is the same for other two phases.

#### 4.4.1. Disturbance Generator

For testing custom power devices and custom power park proposed in this study, a disturbance generator is designed and implemented in this study. The designed disturbance generator system consists of variable voltage sources, thyristors pairs, thyristors drivers, protection devices and time relays.

Table 4.4. The ratings of components on disturbance generator

| Component         | Ratings                                                     |
|-------------------|-------------------------------------------------------------|
| Voltage Sources   | 18.75 kVA, 25 A, 3x380 V input, 3x(0-380) V variable output |
| Thyristor Modules | Semikron 1200 V, 40 A                                       |
| Thyristor Drivers | Semikron 12 V                                               |
| Timer Relays      | 220 V, single phase AC time relays                          |

During normal operating conditions, the load is supplied from Source-1. This source is fixed at  $220 V_{\text{ph}}$ . When a disturbance is desired, the system is supplied from Source-2 arranged as desired voltage level ( $0-220 V_{\text{ph}}$ ) and time interval. The

parameters of disturbance generator system are given in Table 4.4.

#### 4.4.2. Signal Conditioning Card

The voltage measurement is achieved using transducers circuit and offset boards. The source voltages are measured using voltage transducers. The transducers convert  $220\text{ V}_{\text{rms}}$  value to  $1.5\text{ V}_{\text{peak}}$  sinusoidal signals. The circuit diagram of signal conditioning for single voltage measurement is shown in Figure 4.18.

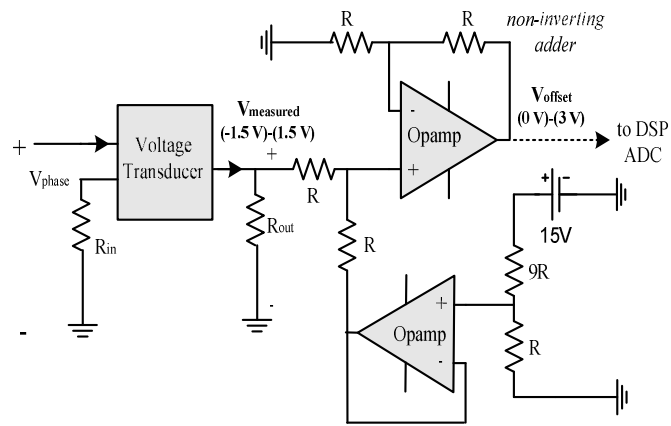


Figure 4.18. The circuit diagram of signal conditioning for voltage measurement

Figure 4.19 shows the transducer circuit boards (LV 25-400), and waveform of transducer output.

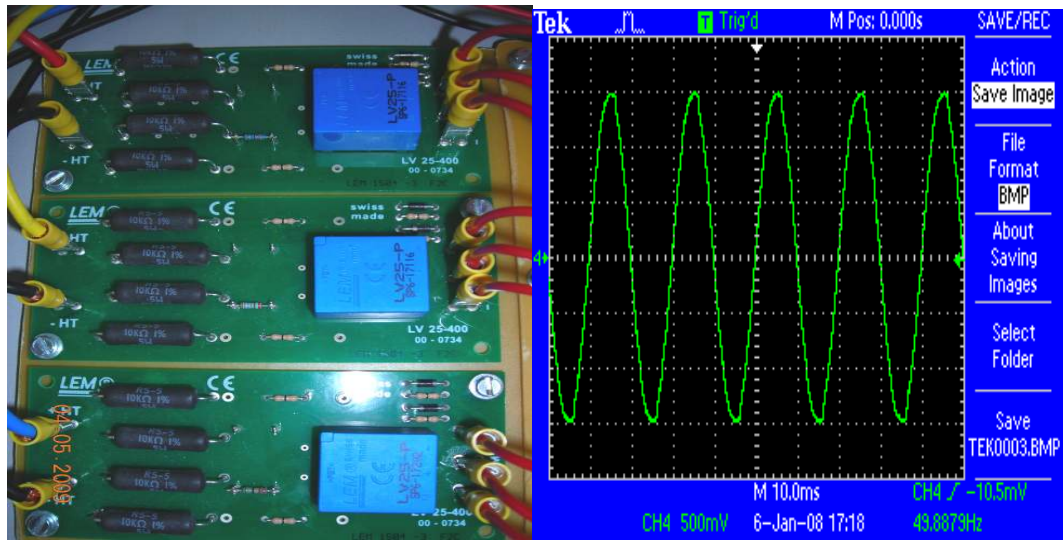


Figure 4.19. Three phase transducer circuit board and output waveform of the transducer

The offset card shown in Figure 4.20 adds  $1.5 V_{dc}$  offset to  $1.5 V_{peak}$  ac signal to convert the signal  $0-3 V_{peak}$  value that is necessary for DSP/ADC input. The circuit includes LM324 and other passive circuit components.

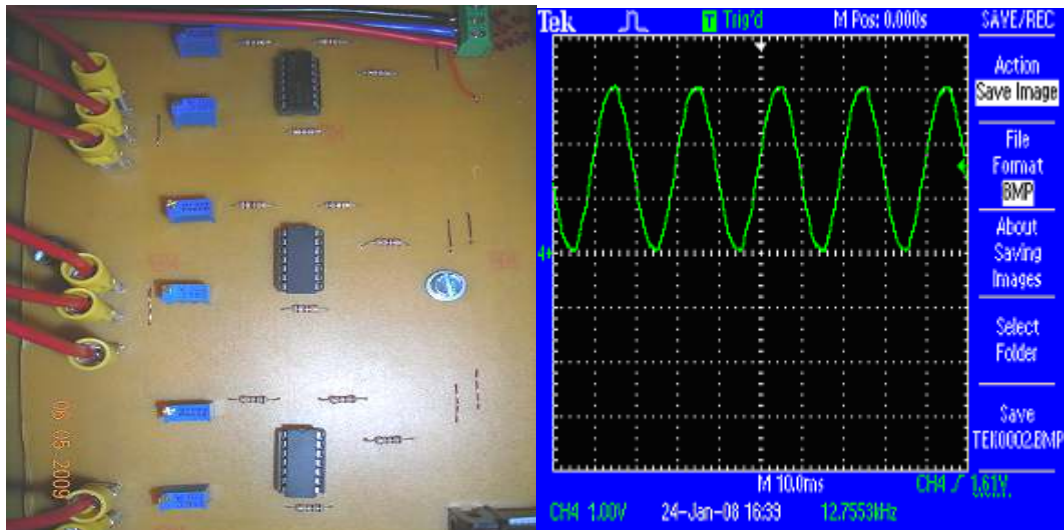


Figure 4.20. Three phase offset circuit board and output waveform of the offset circuit for phase A

#### 4.4.3. DSP Controller

TMS320F2812 ezDSP is used in the experimental study as shown in Figure 4.21. DSP takes the inputs, processes them using the internal algorithm and produces square wave output signals having 0-3.3 V amplitudes.

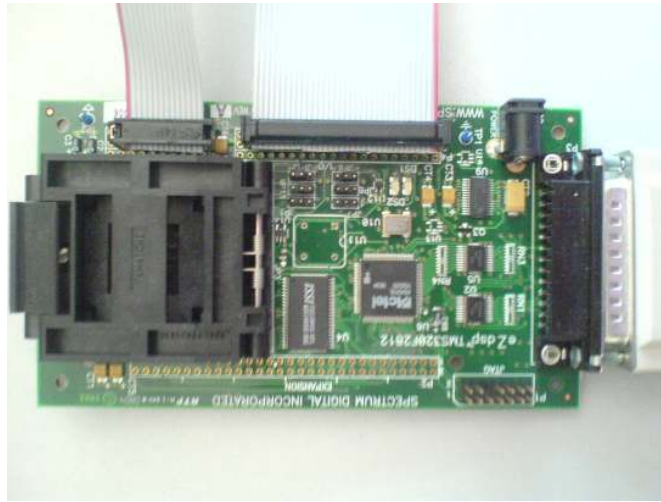


Figure 4.21. TMS320F2812 ezDSP for the DVR

The control strategy in DSP is based on generation of necessary PWM patterns by processing the error signal. Sinusoidal PWM technique is used to generate the required gate drive signals to the inverter. TMS320F2812 eZdsp offers real time control and adds user interface and produces gate pulses by using a triangular carrier wave at 10 kHz. The gate signal is positive when the carrier wave is larger than the reference wave and the gate signal zero when the condition is reverse. The error wave amplitude adjusts the amplitude of the generated AC voltage and the error wave frequency determines the frequency of the generated AC voltage.

#### 4.4.4. Interface Card

DSP outputs must be amplified from 0-3.3 V to 0-5 V low and high levels which are required value for the input of IGBT driver. However, 0.7 V logic low and

4 V logic high level is sufficient for the used driver. Diodes and resistors are used in the circuit. The circuit diagram for a single digital signal is shown in Figure 4.22. The interface card is shown in Figure 4.23.

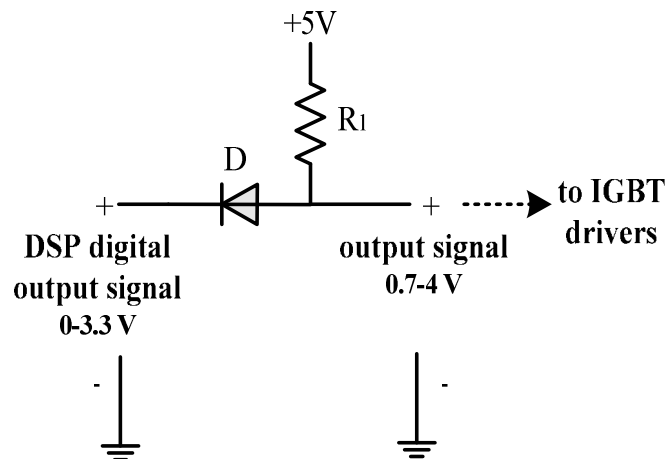


Figure 4.22. The circuit diagram of interface card for a single digital signal



Figure 4.23. Interface card

#### 4.4.5. IGBT Driver Circuit

The driver circuit (SKHI 22-2) amplifies the amplitudes of buffer card at 0-5 V to (-7 V)-(15V). Figure 4.24 shows IGBT driver cards for one of h-bridge inverters.



Figure 4.24. IGBT driver cards for one of h-bridge inverters

#### 4.4.6. IGBT Modules and DC Source

Figure 4.25 shows a basic Voltage Source Inverter circuit (VSI) and IGBT based DVR setup experimentally. Semikron SKM75GB123D IGBT modules are used in the experimentally setup of the inverters. The inverter is fed from 150 V<sub>dc</sub> supply and gives 110 V<sub>rms</sub> output voltage. This output voltage will be used to compensate 50% voltage sag for the DVR.

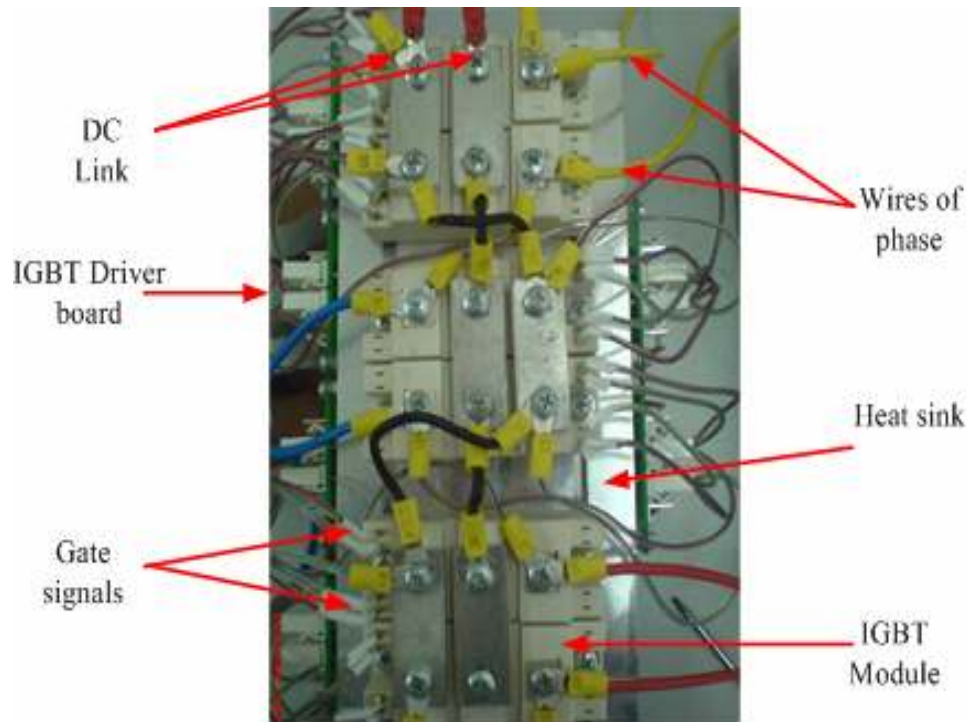


Figure 4.25. Three base VSI with IGBT modules and IGBT driver boards.

#### 4.4.7. LC Filter

The method used for LC filter design in (Dahono et al) gives optimum results especially for H bridge IGBT inverter. The design procedure is given in Section. By taking into consideration of capacitor values in the electric markets;

$L_f = 5 \text{ mH}$  and  $C_f = 18 \text{ } \mu\text{F}$  are chosen. The nominal values of inductor and capacitor are 11A/350 V and 6A/400V, respectively. Figure 4.26 shows the designed LC filter.

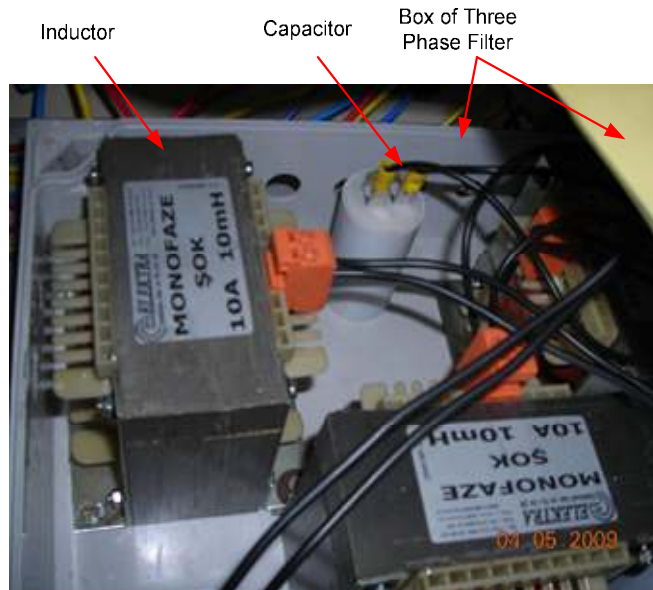


Figure 4.26. LC filters for three phases of DVR

#### 4.4.8. Transformer

The output of the LC filter is given to the load using a transformer rated at 110:110 V<sub>rms</sub>. A 2 kVA single phase transformer is shown in Figure 4.27.



Figure 4.27. Single phase injection transformer

#### 4.4.9. Load

DVR protects the load against voltage sags. The three phase load used for the experiment is shown in Figure 4.28. The load has  $48 \Omega/2185 \text{ W}$  resistors for each phase.



Figure 4.28. Three phase 3 kVA load

#### 4.5. Experimental Results of Proposed DVR

In this section, firstly, the stand-by operation and the minimum energy injection capability of proposed DVR is presented, experimentally. The sag detection and voltage compensation abilities of proposed DVR are also presented in case of various faults. The presented experimental results are listed below:

- Stand-by mode of proposed DVR; given as oscilloscope graphs
- Voltage injection mode of proposed DVR; given as oscilloscope graphs
- Minimum energy injection with proposed DVR; given as oscilloscope graphs
- Voltage Compensation with proposed DVR; given as power quality analyzer graphs

The data of experimental setup parameters are summarized in Table 4.5.

Table 4.5. Data for the DVR experimental system

|                                         |                             |                                                                                      |
|-----------------------------------------|-----------------------------|--------------------------------------------------------------------------------------|
| <b>SYSTEM</b>                           | Voltage                     | 220 V <sub>rms</sub> /phase                                                          |
|                                         | Frequency                   | 50 Hz                                                                                |
| <b>DYNAMIC<br/>VOLTAGE<br/>RESTORER</b> | Controller                  | ezDSP TMS320F2812 DSP,<br>sample time 25 $\mu$ s                                     |
|                                         | IGBT Inverter               | Semikron<br>SKM 75GB123D, 1200 V, 50 A                                               |
|                                         | Switching<br>Frequency      | 10 KHz                                                                               |
|                                         | IGBT Driver                 | Semikron<br>SKHI 22BH4 R, Supply voltage                                             |
|                                         | Inverter filter             | Capacitance: 18 $\mu$ F, 400 V<br>Inductance: 10 mH, 10 A                            |
|                                         | Transformer                 | Primary/Secondary: 110/110<br>V <sub>rms</sub> , 2 kVA                               |
|                                         | DC Source                   | 150 V <sub>dc</sub>                                                                  |
|                                         | Voltage<br>Measurement      | LEM LV25-P voltage transducer,<br>LV25-400 transducer board                          |
|                                         |                             |                                                                                      |
| <b>LOAD</b>                             | Resistive Load Bank         | 48 $\Omega$ /phase                                                                   |
| <b>DISTURBANCE<br/>GENERATOR</b>        | Variable Voltage<br>Sources | 18.75 kVA, 25 A, 3x380 V input,<br>3x(0-380) V variable output                       |
|                                         | Thyristor Module            | 1200 V, 40 A Semikron SKKT<br>42/12E                                                 |
|                                         | Thyristor Driver            | Semikron APTT-841M                                                                   |
|                                         | Timer Relay                 | 220 V, single phase AC time<br>relay, 1 NO and 1 NC contacts,<br>minimum 50 ms range |
| <b>WAVEFORM<br/>MEASUREMENTS</b>        | PQ Analyzer                 | HIOKI 3196                                                                           |
|                                         | Oscilloscope                | Tektronix TDS 2014B                                                                  |

#### 4.5.1. Experimental Results for Stand by Mode and Minimum Energy Injection

##### 4.5.1.1. Stand by Mode and Voltage Injection Mode

During standby operation of DVR, two lower IGBTs of each phase H-bridge inverter remain turned on while the two upper IGBTs remain turned off. Figure 4.29

shows the gating signals of phase-A H-bridge inverter. Signals 1 and 3 are for the upper IGBTs (Q2 and Q4) and Signals 2 and 4 are for the lower IGBTs (Q1 and Q3). For the results shown in Figure 4.29, shown values must be multiply by 10, due to measurement range of oscilloscope probes. As seen from Figure 4.29, the Signal 1 and 3 are -7 V (logic low), and the Signal 2 and 4 are +15 V (logic high). In other words, the upper IGBTs are turned off and the lower IGBTs are turned on.

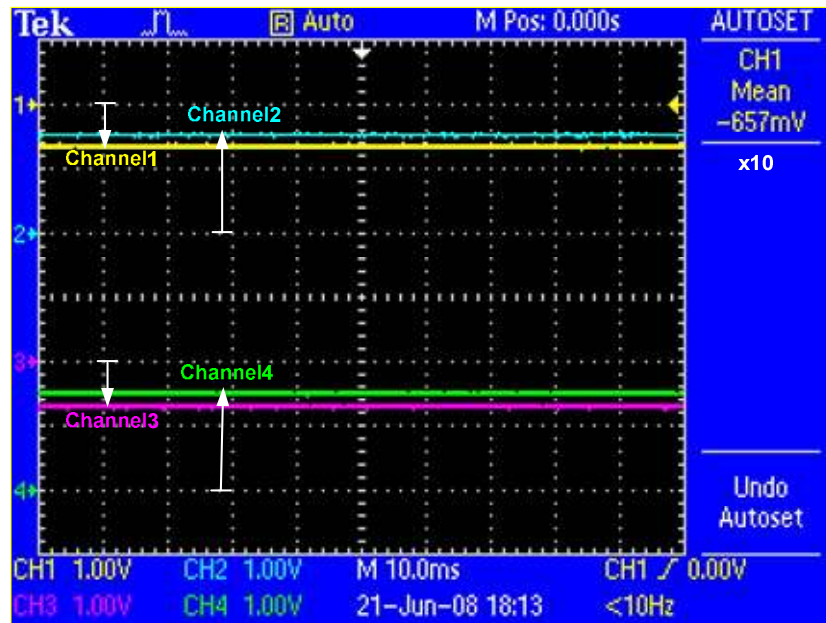


Figure 4.29. The gating signals of phase-A H-bridge inverter in case of stand-by operation

PWM signals in case of injection mode of inverter are shown in Figure 4.30. Signal 1, 2, 3 and 4 are upper IGBT of left leg (Q1), lower IGBT of left leg (Q2), upper IGBT of right leg (Q3) and lower IGBT of right leg (Q4), respectively.

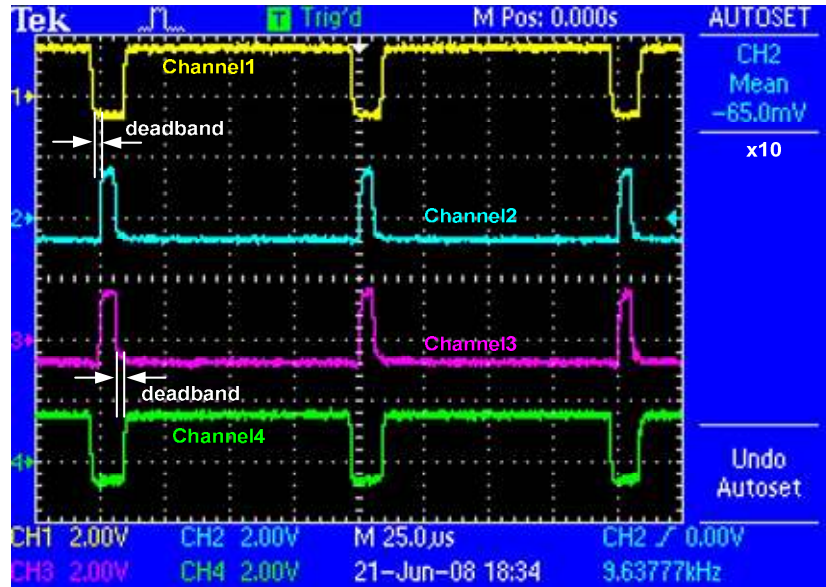


Figure 4.30. The PWM signals of phase-A H-bridge inverter in case of voltage injection mode

As seen from Figure 4.30, two diagonal IGBTs namely Q1-Q4 in the H-bridge are simultaneously switched on. After a period of time, determined by the duty cycle of the PWM waveform, Q1-Q4 are turned off and Q2-Q3 of the H-bridge are turned on. Q2-Q3 remain on for a period of time, again determined by the duty cycle of the PWM waveform. After this period of time, the second pair of Q2-Q3 is turned off, and the Q1-Q4 transistors pair is turned on. However, a time called dead-band is used which is the time difference between turn-on time of upper IGBT and turn-off time of lower IGBT to avoid the short circuit problem.

#### 4.5.1.2. Minimum Energy Injection

In this study, by using an independent sag detection method for each phase, each H-bridge inverter is controlled independently, as mentioned Section 4.2.2.4. With this method, minimum energy is injected and switching losses are reduced. Figure 4.31 shows the gating signals of phase-A and phase-B H-bridge inverters. In this case, sag is occurred in phase-A voltage of source, but phase-B voltage is in nominal value. Signals 1 and 2 are for the left leg IGBTs of phase-A and Signals 3 and 4 for the left leg IGBTs of phase-B.

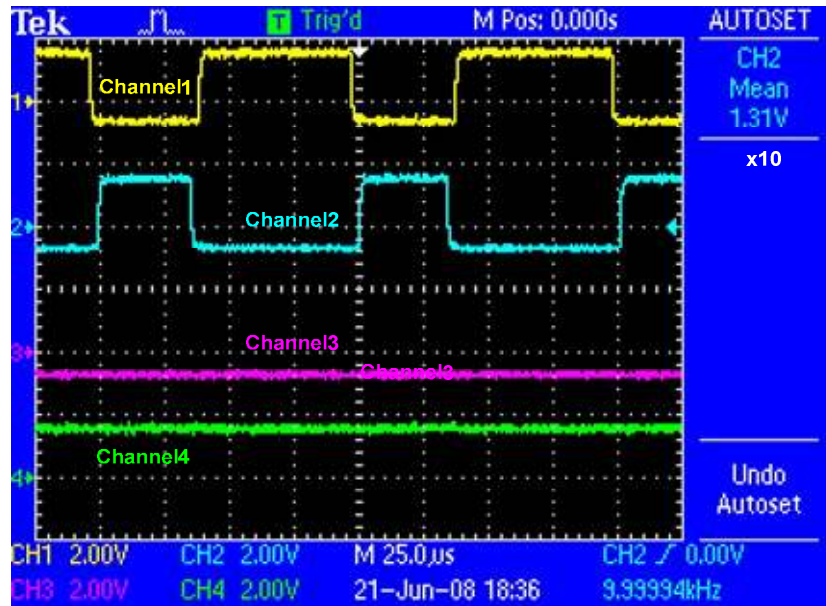


Figure 4.31. The PWM signals for H-bridge inverters of phase-A and phase-B

As seen from Figure 4.31, the inverter of phase-A is operating mode, but the inverter of phase-B is in stand-by mode.

#### 4.5.2. Experimental Results for Voltage Compensation with Proposed DVR

In this section, the results of power quality analyzer are presented to show the performance capability of DVR for sag mitigation. Two cases are comprehensively analyzed: i) 15% single phase voltage sag and ii) 40% three phase voltage sag.

The first case shows that the proposed method detects the voltage sags lower than 30% correctly which can not be detected using conventional 3 sag detection method (also see Section 2.2.2). The second case presents the performance of DVR to compensate 3 phase voltage sags at 40% level, effectively (the maximum sag mitigation capability of DVR is 50% of the nominal voltage).

At stand-by operation (non-faulted condition), Source voltage THD is 2.15% and load voltage THD is 1.53%. These values are close to values used in simulation studies.

#### 4.5.2.1. Performance of Proposed DVR in case of %15 Single Phase Voltage Sags

Figure 4.32 shows the waveform results for 15% sag on phase A supply voltage with 200 ms duration. The voltage waveforms of Ch1, Ch2 and Ch3 indicate the phase A, phase B and phase C supply voltages, respectively. Similarly, the current waveforms of Ch1, Ch2 and Ch3 indicate the phase A, phase B and phase C load currents, respectively.

The each division is 100 V for voltage waveforms and 5 A for current waveforms. The load voltage waveform is identical with load current waveforms because the load is pure resistive. Figure 4.32 shows that the proposed DVR system can perfectly detect the 15% single phase voltage sag lasting 8 cycles. As shown in Figure 4.32, the phase A load current so its load voltage does not affected by voltage sag. Only at the starting and ending times of sag, the load voltage is affected due to instantaneous reduction of the voltage reference and delay originated from sag detection time. Then, the DVR is started to voltage injection.

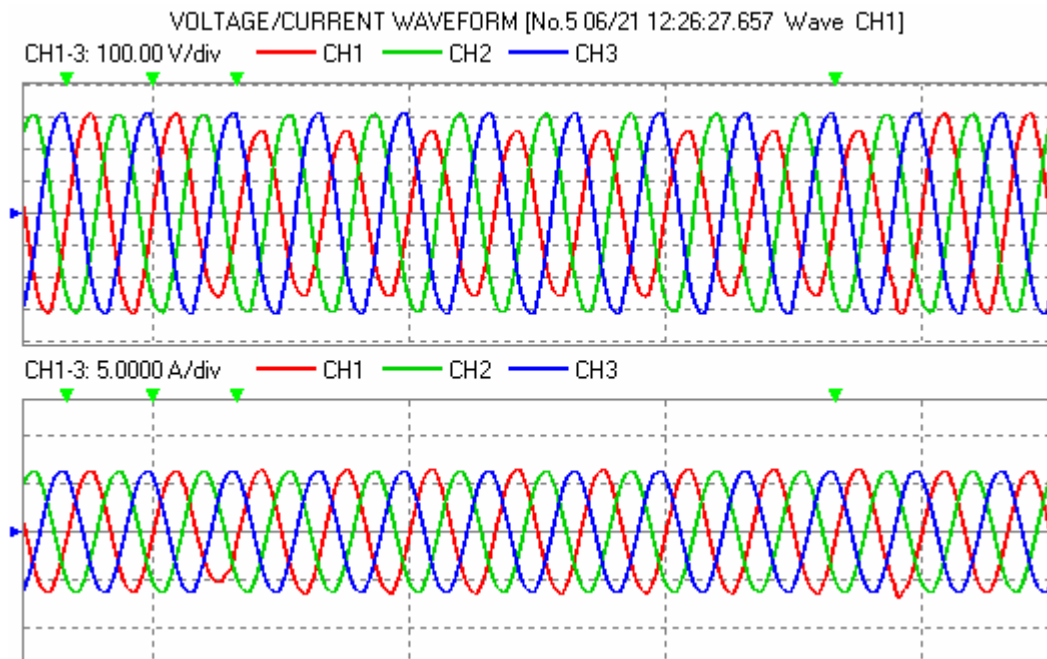


Figure 4.32. Voltage/Current waveforms for a single phase 15% sag

Figure 4.33 shows the standby operation of DVR. The waveforms of Ch1, Ch2 and Ch3 indicate the phase A source voltage, phase A load voltage and injected voltage at load side, respectively. As shown in Figure 4.33, the load voltage is identical to source voltage. The voltage drop for injected voltage seen from Figure 4.33 is caused by the reactance of the inductor in the standby mode.

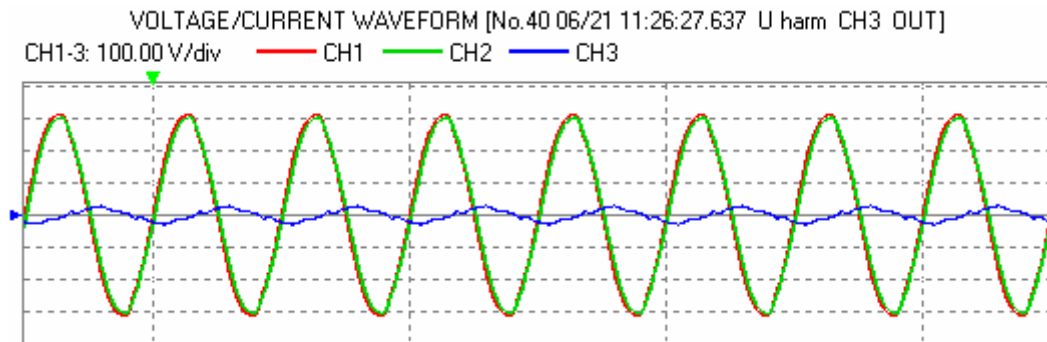


Figure 4.33. Voltage waveforms for normal operating condition

The voltage and current waveforms at starting of another single phase 15% voltage sag are shown in Figure 4.34. The voltage waveforms of Ch1, Ch2 and Ch3 indicate the phase A source voltage, phase A load voltage and injected voltage at load side, respectively. The current waveforms of Ch1, Ch2 and Ch3 indicate the phase A, phase B and phase C load currents, respectively. As seen from Figure 4.34, when the sag occurs, only the related H-bridge inverter of DVR starts to operate. As also shown from the current waveforms, the sag occurs only on phase A and the phase A load current so its voltage do not affected by sag.

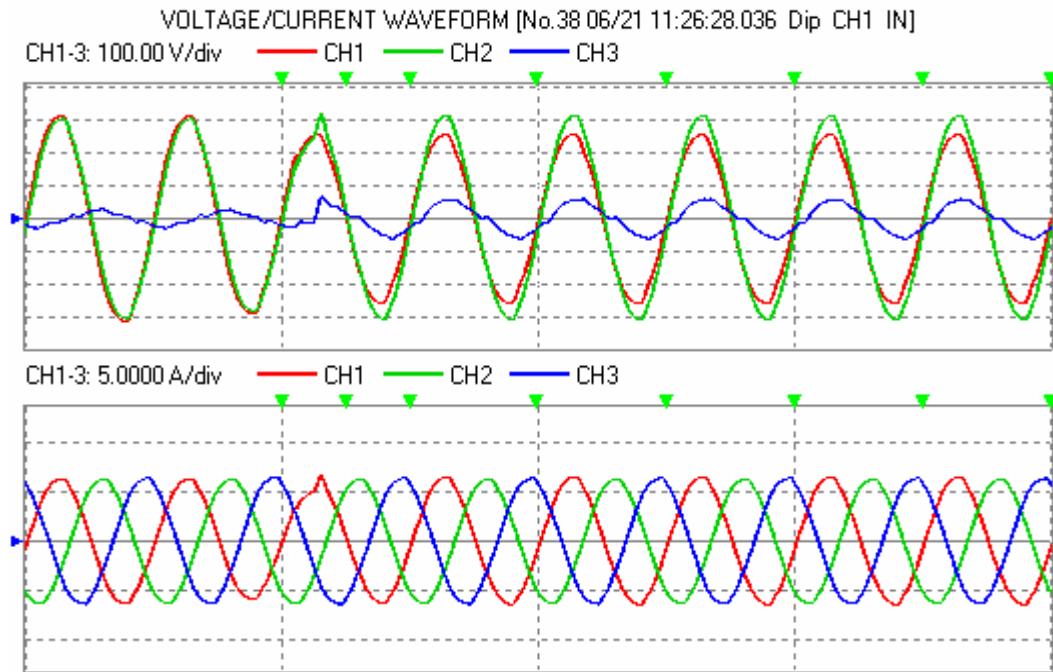


Figure 4.34. Voltage/Current waveforms for starting of a single phase 15% sag

The voltage and current waveforms at ending of single phase 15% voltage sag are shown in Figure 4.35. The sag is lasting 600 ms. As shown in Figure 4.35, DVR comes into standby operation whenever the sag ends. For Figures 4.34 and 4.35, the THD values of source voltage and load voltage are measured as 2.26% and 2.92%, respectively. The difference between source voltage THD and load voltage THD is based on the injected voltage. However, THD of the load voltages is always kept below the IEEE voltage harmonic limits (IEEE519, 1992).

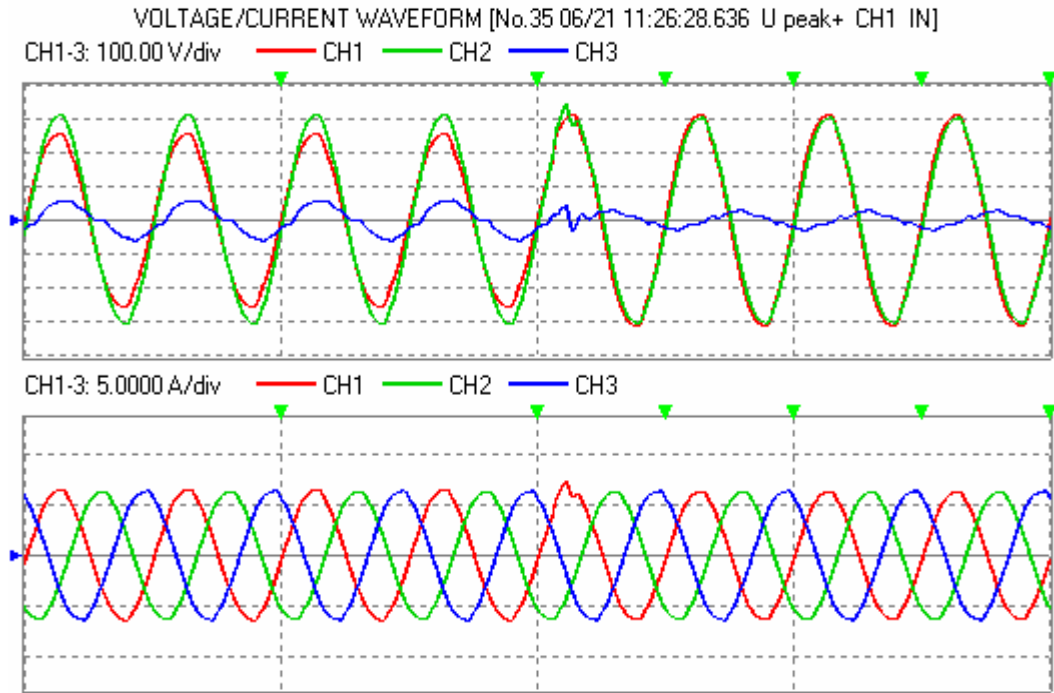


Figure 4.35. Voltage/Current waveforms for ending of a single phase 15% sag

Figure 4.36 shows the rms results of source voltage for 15% voltage sag occurring at different time instants. Ch1, Ch2 and Ch3 indicate the rms values of source phase A voltage, load phase A voltage and injected voltage at load side, respectively. As seen from the results, DVR rapidly responses to sags occurring at different times and keeps the load voltages almost constant.

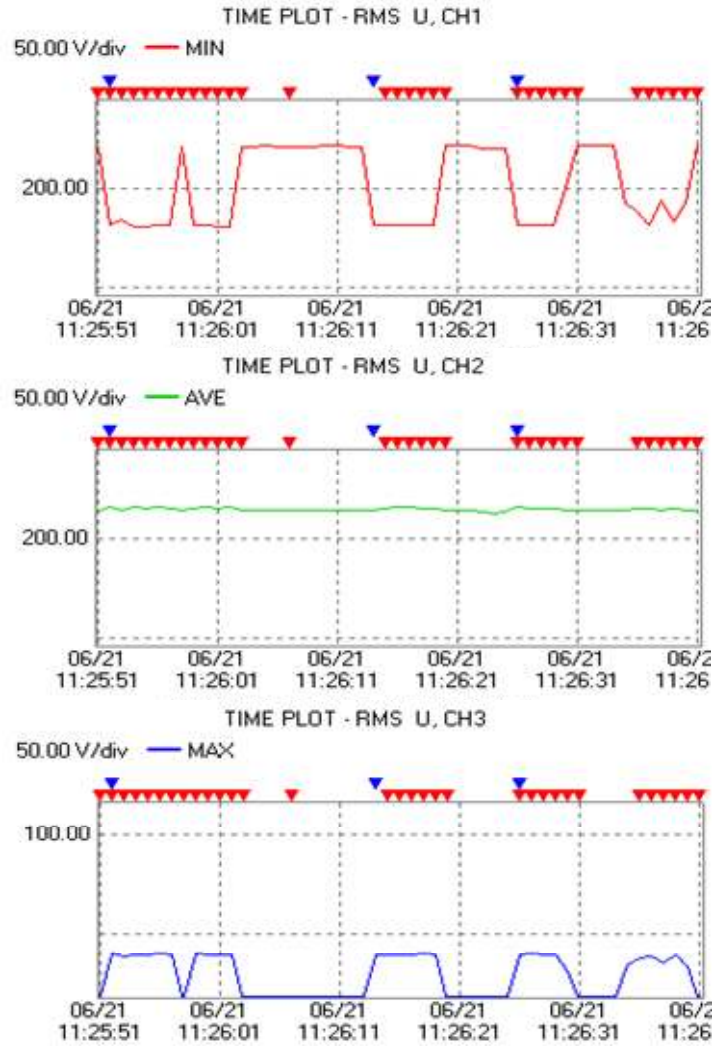


Figure 4.36. RMS voltage trends for single phase 15% sags

#### 4.5.2.2. Performance of Proposed DVR in case of %40 Three Phase Voltage Sags

Figure 4.37 shows the waveform results for 40% sag on three phases of source voltage. The voltage waveforms of Ch1, Ch2 and Ch3 indicate the phase A, phase B and phase C of source voltages, respectively. Similarly, the current waveforms of Ch1, Ch2 and Ch3 indicate the phase A, phase B and phase C of load currents, respectively. The load voltage waveforms are identical with load current waveforms because the load is pure resistive.

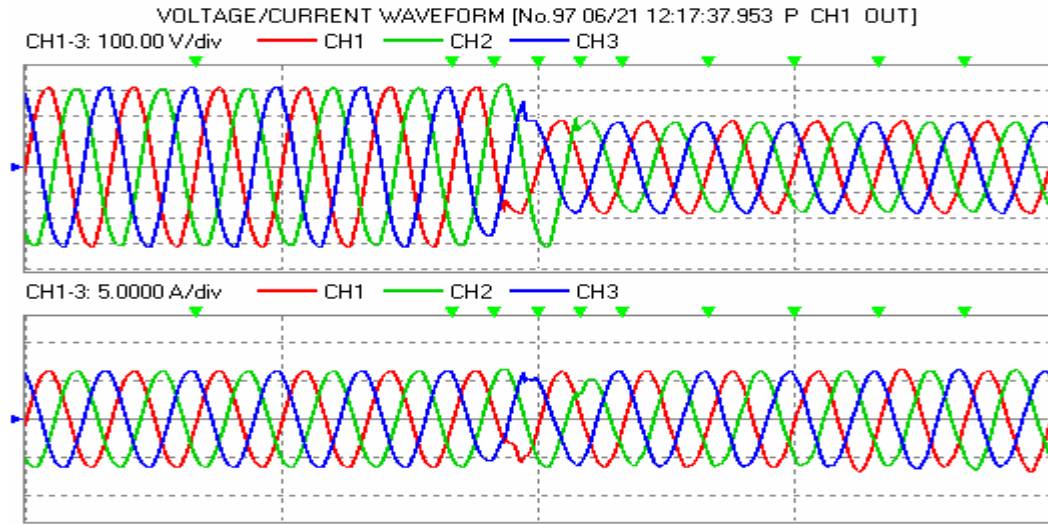


Figure 4.37. Voltage/Current waveforms for starting of a three phase 40% sag

As seen from Figure 4.37, the load current so the load voltage does not affected by voltage sag. Only at the starting and ending times of sag, the load voltage is affected due to instantaneous reduction of the voltage reference and delay originated from sag detection time. THD values of source voltage and load voltage are measured as 2.17% and 3.01%, respectively.

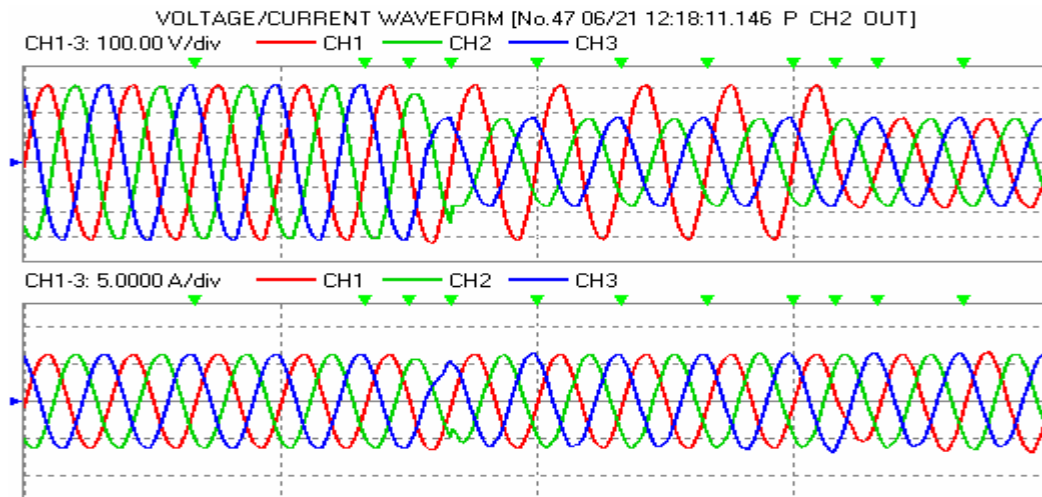


Figure 4.38. Voltage/Current waveforms for starting of a asynchronous three phase 40% sag

As shown in Figure 4.38, firstly, the double phase voltage sag occurs. After a short time, the three phase balanced sag occurs. Because each phase of the DVR is

controlled independently, phase A of the inverter does not operate during double phase sag and starts to operate whenever a three phase sag occurs.

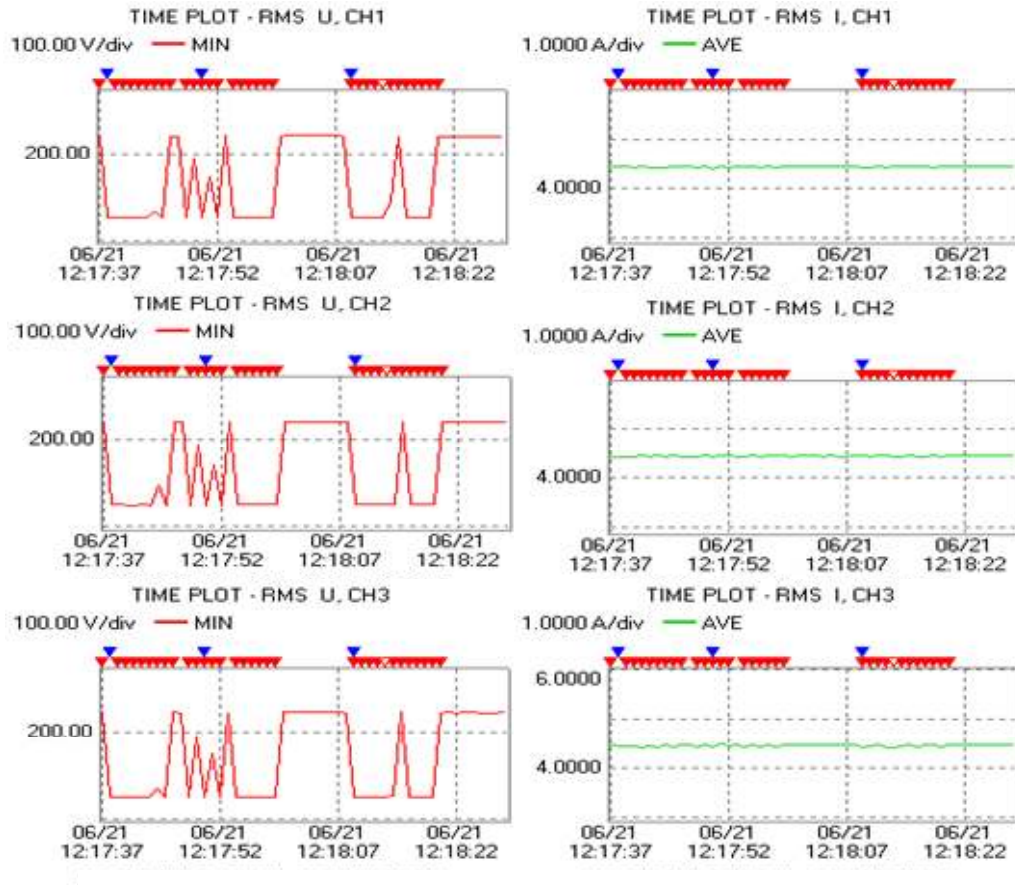


Figure 4.39. RMS voltage/current trends for three phase 40% sags

RMS results of source voltage for 40% voltage sag occurring at different time instants lasting 50 ms are shown in Figure 4.39. The Ch1, Ch2 and Ch3 voltage measurements indicate the rms values of phase A, phase B and phase C source voltages, respectively. The Ch1, Ch2 and Ch3 current measurements indicate the rms values of phase A, phase B and phase C load currents, respectively. As seen from the results, DVR rapidly responses to sags occurring at different times and the load currents (so load voltages) do not affect by sags.

## 5. STATIC TRANSFER SWITCH

### 5.1. Literature Review

Many customers have become dependent on electricity that must be as free as possible from outages and voltage fluctuations. Absolute reliability, continuity and quality of the utilities' voltage can not be guaranteed and various disturbances are expected. To protect customers against voltage sags or interruptions, critical loads are supplied by two sources of power. If one source fails, the loads will be transferred to the other one. The transfer process must be fast enough so that a critical load can ride through the interruption. The duration of power discontinuity is the key factor in predicting the survival of critical loads in case of an interruption (Mokhtari, 2002).

The STS has been widely used in low-voltage applications. Availability of reliable semiconductor switches and stringent voltage quality requirements of sensitive loads have led to medium voltage applications of STS during the last few years (Iravani, 2001). In high-power applications, Electromechanical Transfer Switches (EMTS) has been used to switch critical loads between two medium-voltage feeders (Hornak et al, 1995). EMTS is slow in switching operations and can cause power interruptions of several cycles. There has been recent interest in replacing medium-voltage EMTS with STS to achieve fast load switching between two distribution feeders (Schwartzenberg et al, 1995).

Fast transfer switches that use vacuum breaker technology can transfer in about two electrical cycles, which may be fast enough to protect many sensitive loads (Ecm, 2009a) Mechanical transfer switches use circuit breakers or switches to perform their transfer function. The operation of these switches depends on an open transition to the source and load. The mechanical switches do not provide a continuous source of power to the loads (Eeonline, 2009). Multi-tap transformers are configured with electronic switches at each tap and can be used to provide a degree of regulation in voltage output for varying input voltages. These devices on the market currently react in a minimum of one-half cycle. Neither as such provides limited protection against deep sags nor do they correct shifts in voltage phase.

Additionally, the device presents only limited sag mitigation capability due to the limited tap range (Degeneff, 2000).

Design and performance evaluation of a STS system require detailed analysis of the supply system, STS power circuit, STS control circuit and sensitive load. The basic structure of a STS system includes (Iravani, 2001);

- a load which is sensitive to variations of utility supply voltage,
- two independent sources one of which is the preferred one and the other is the alternate one,
- two thyristor blocks which connect the load to the power sources,
- a control logic to monitor voltage quality of both sources, detect voltage sag and interruption, compare the two sources and perform a load transfer from preferred source to the alternate source if needed.

The findings of the comprehensive literature survey summarize the available studies related with the control unit and the power circuit of the STS. Field applications of STS are also presented in the survey.

In this thesis, the following studies are performed:

- Literature survey of the STS,
- Design of the STS,
- Modeling of the STS; a new and effective sag detection method is proposed for control of the STS,
- Experimental implementation and verification of the proposed STS.

#### **5.1.1. Studies Related to Power Circuit of STS**

The main power circuit configuration of a Static Transfer Switch can generally be divided into two categories as Dual Service Topology and Bus Tie Topology (Pavlyuk, 1997).

The STS is a solid-state switch based on the thyristor device. The basic ON-state and OFF-state properties of a thyristor are used to form an intelligent switch which can choose between two upstream power sources and provide the best available power to the electrical load downstream (Bhanoo et al, 1998). Usually

Silicon Controlled Rectifiers (SCRs) or sometimes GTOs are used as semiconductor devices in STS applications. Since a SCR is turned off at zero crossing of the current, its turns off time can be as long as half period of the power source. On the other band, a GTO breaks current within about 20 microseconds, since it has self turn off capability. Although the GTO has superior turns off time characteristics, it has some disadvantages as compared with the thyristor, such that the GTO itself is still expensive, steady-state dissipation is large and gating and snubber circuits are large (Pavlyuk, 1997).

The Static Transfer Switch is composed of two thyristor blocks (for a main feeder and for a backup feeder) and connects the load to the power sources. Each thyristor block is composed of three thyristor modules corresponding to the three phases of the system. In each thyristor module, two sets of thyristor switches are connected in opposite directions (Mokhtari, 2002).

There is also a hybrid STS structure that consists of a thyristor switch, a parallel switch and a surge arrestor protecting the thyristors against overvoltage (Takeda, 2003).

### **5.1.2. Studies Related to Control System of STS**

The control unit is the most important part of the STS system. The main considerations for the control system of a STS include: i) sag detection, and ii) transfer and gating strategy.

#### **5.1.2.1. Sag Detection**

The principal contribution to thyristor application technology in the STS are the algorithms that make firing control possible without delays at current zero crossings, and the near instantaneous detection of fault direction to inhibit transfer of downstream faults (caused to sag or interruption) (Rauch et al, 1999).

If a system is balanced and it supplies power for a balanced load, the “abc to dq” transformation can be applied to obtain ripple free DC quantities (Pavlyuk,

1997), (Sannino, 2001), (Mokhtari et al, 2002a).  $dq$  transformation requires very accurate synchronization with the three phase system. Therefore, it is difficult to implement in a practical setup. As an alternative to the  $dq$  transformation, the  $\alpha\beta$  transformation can be used (Pavlyuk, 1997). Wavelet based voltage detection scheme for power quality applications is examined in (Mokhtari et al, 2001b), (Ghartemani et al, 2002). In (Moschakis, 2003), a fast method using rms method and second order transfer functions is proposed.

#### 5.1.2.2. Transfer and Gating Strategy

During normal operation only one pair of thyristors is turned on in each phase correspondingly. Preferred and alternate feeder voltages are continuously monitored by control logic. When the preferred source has a proper voltage, control logic turns on thyristors on the preferred feeder side. If a deviation of the preferred source voltage from the pre-specified limits is detected, transfer to the alternate feeder is initiated by removing gating pulses from the thyristors of the preferred feeder switch and firing thyristors on the alternate feeder side (Pavlyuk, 1997).

The gating system generates suitable gating patterns for the thyristor switches before, during and after a load transfer based on the direction of line current. Conventionally, two different transfer schemes can be employed; zero-current strategy and commutation strategy (Mokhtari, 2002), (Bertuzzi et al, 2007). By applying zero-current gating scheme, a “break-before-make” (BBM) transfer can be achieved. However, the disadvantage of this system is the long transfer time. In the worst case condition, a transfer time can take as long as half a cycle.

To achieve a faster load transfer, commutation gating strategy (Moschakis, 2003) can be employed. In this method of gating, the control system does not wait for the current zero-crossings and starts the transfer as soon as the disturbance is detected. However, to avoid source paralleling and cross current, the transfer process is preceded according to the direction of line currents (selective gating) (Eonline, 2009). This type of transfer is normally referred to as “make-before-break” transfer (MBB) (Mokhtari, 2002), (Bertuzzi et al, 2007). However, BBM method is a more

reliable method, because the zero-crossings of feeder currents are waited for transferring in this transfer strategy.

The effect of fault type and fault severity, the effect of regenerative loads and the maximum transfer time have also been discussed in References (Mahmood et al, 2007), (Mokhtari et al, 2001c), (Mokhtari et al, 2002), (Moschakis, 2003).

### **5.1.3. STS Applications**

STS have been installed in the Semiconductor, Plastic Extrusion, Food Processing and Paper Mill factories. STS applications are (Mokhtari et al, 2002);

i) American Electric Power (AEP): AEP is in the process of installing an indoor 15kV, 600A static transfer switch at an industrial park in Columbus, Ohio.

ii) Baltimore Gas and Electric (BGE): BGE has demonstrated an indoor 15kV, 600A static transfer switch at an office building in downtown Baltimore.

iii) Chubu Electric Corporation: Chubu Electric Corporation of Japan installed three 7.2 kV, 300 A static transfer switches in a loop line configuration. The devices are reported to have a high reliability rate since installation and require a maintenance check every year.

iv) Commonwealth Edison Company (ComEd): ComEd installed a static transfer switch rated at 12.47kV, 600 A at a plastic film manufacturer.

v) Detroit Edison Company: Detroit Edison installed a static transfer switch at the Ford Motor Company Sheldon Road Plant. Sheldon Road is a components plant that provides parts to all of Ford's North American assembly plants on a just in time basis. This plant is fed from a 40kV sub transmission system and has a load has a load of 9MVA. The switch is installed on the 13.8kV side of the transformers.

vi) Kyushu Electric Corporation: Kyushu Electric of Japan has installed eleven static transfer switches between 1990 and 1997 for the purpose of high-speed line transfer. They are each rated at 7.2kV, and for 200A to 300A. The devices use a hybrid switching device made up mainly of a thyristor switch and a high-speed parallel switch.

vii) PG&E Energy Services: PG&E Energy Services installed two static transfer switches rated at 25kV, 300A and are in commercial operation.

viii) Texas Utilities: Texas Utilities has demonstrated an outdoor 15kV, 600A static transfer switch at an electric operations building in Fort Worth, Texas.

ix) Toyo Oil Industry Company: The Toyo Oil Industry Company of Japan installed a static transfer switch for a generating unit transfer application.

x) Various low voltage applications

## 5.2. Design of Proposed STS

The major components of STS system include the power circuit and control system as shown in Figure 5.1.

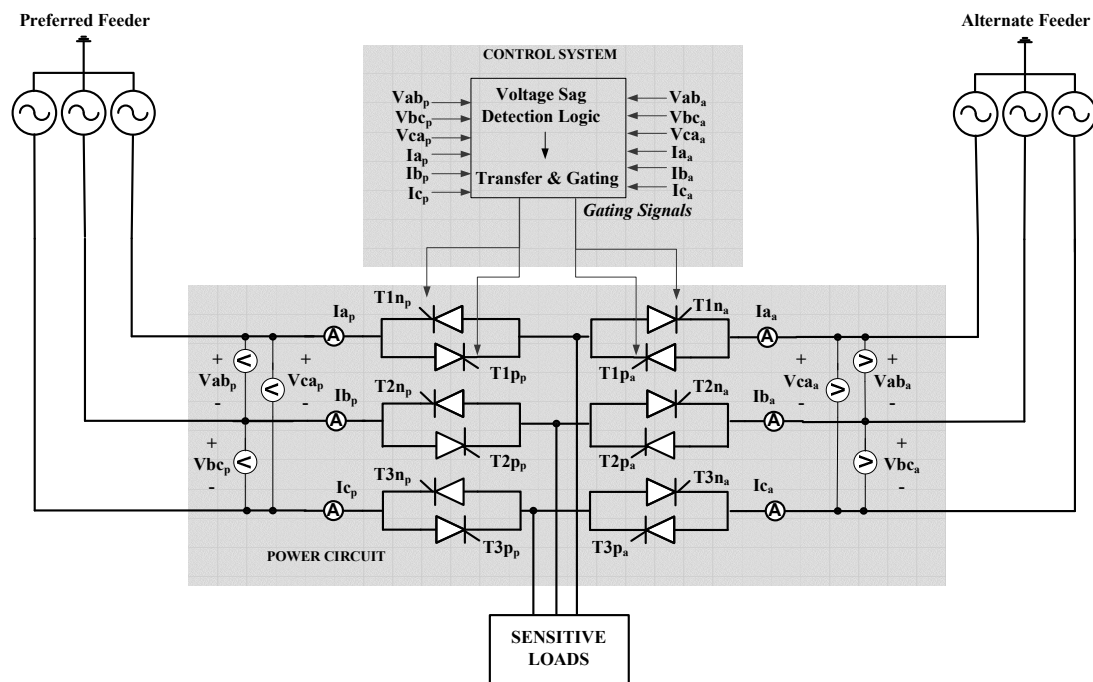


Figure 5.1. Power circuit and control system of STS

The main components of power circuit are pairs of back-to-back thyristor switches and snubber circuits. The control system of a STS performs a load transfer

from one feeder to the other one if needed and includes voltage/current measurements, fault detection and gating signal generation.

Line to line voltages and line currents are the required input signals to the control unit and the outputs are the gating patterns for the preferred feeder and the alternate feeder thyristor switches. Under normal operating conditions, the control unit triggers only thyristors of the preferred feeder ( $T_{pP}$  and  $T_{nP}$ ).

### 5.2.1. Configuration of STS Power Circuit

The main components of STS power circuit are shown in Figure 5.2. The components are described in more detail in the following subsections.

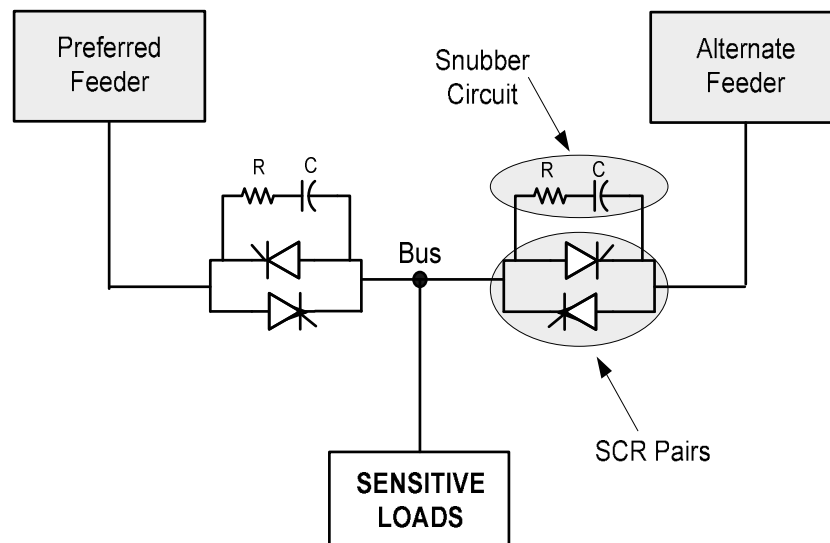


Figure 5.2. Main components of single phase of the STS system

#### 5.2.1.1. Silicon Controlled Rectifier (SCR)

SCRs belong to the thyristor family. They are capable of switching the current in one direction once they have been triggered (on-state) while blocking forward and reverse voltage when they are not triggered (off-state). Therefore, two pairs of SCRs connected inverse parallel provide the solution required for a STS. Most of the static transfer switches commercially available are based on SCRs (Aguinaga, 2008).

### 5.2.1.2. Snubber Circuit

The sudden interruption of current flow would lead to a sharp increase in voltage across the device. The sharp increase might lead to a transient or permanent failure of the controlling device. The combination of the resistor ( $R_s$ ) and capacitor ( $C_s$ ) in series will suppress the rapid rise in voltage across the thyristor, preventing the turn-on of the SCR device (Olawale et al, 2007).

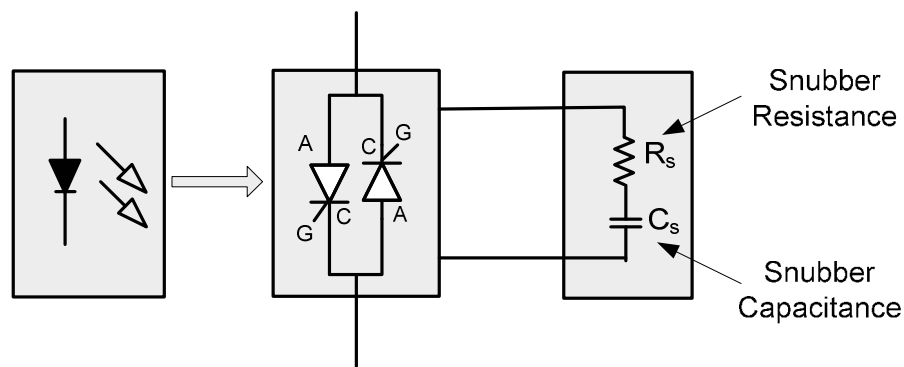


Figure 5.3. Snubber circuit connected to the SCR pairs

The snubber (RC) circuit shown in Figure 5.3 limits the drift of the voltage through the capacitor. The resistance of the snubber circuit limits the discharging current of the capacitor.

### 5.2.2. Configuration of STS Control System

In this study, a new sag detection method mentioned previously in Chapter 4 is used for sag detection. As transfer and gating strategy, BBM transfer strategy is used.

#### 5.2.2.1. Sag Detection Method

The PLL used in this study is comprised of a phase detector, a loop filter and a voltage controlled oscillator. In Figure 5.4, the block diagram of the PLL is given.

The PLL tracks a specific component of the input signal and simultaneously extracts its amplitude and phase. The error signal represents the deviation of the input signal from the output signal. In Figure 5.4,  $u(t)$  is the line to line voltage as input signal, is the output signal and  $Mag(t)$  is the amplitude which is used for sag and/or momentary interruption detection.

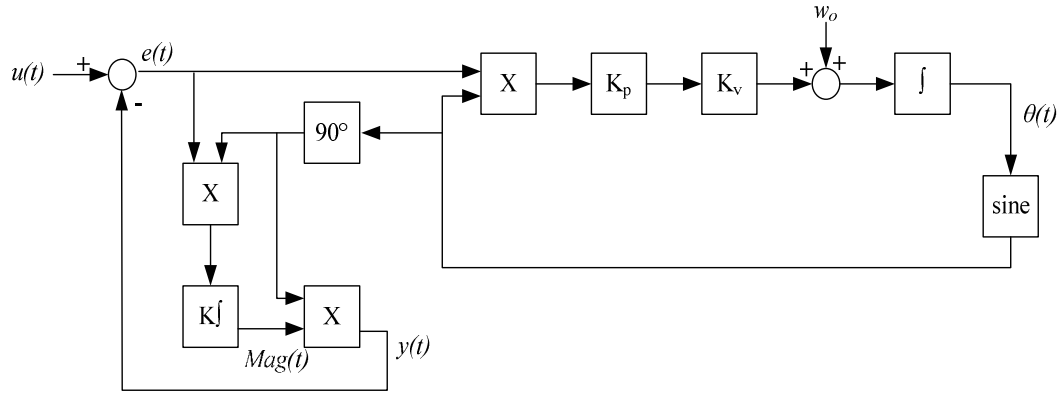


Figure 5.4. Block diagram of the phase locked loop used in STS control

To show the superiority of the proposed sag detection method, it is compared with the  $dq$  transformation based conventional sag detection. In the  $dq$  method, the line to line voltages  $V_{ab}$ ,  $V_{bc}$  and  $V_{ca}$  are subjected to transformation given in Eq. (5.1). With the use of Eq. (5.2), the voltage phasor is obtained.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad (5.1)$$

$$V_p = \sqrt{V_d^2 + V_q^2} \quad (5.2)$$

In Figure 5.5, the block diagram of the  $dq$  transformation based sag detection method is shown. After the three phase set of voltages are transformed into  $d$  and  $q$  components, the square root of the sum of squares of these components is obtained.

The obtained value is filtered with a 50 Hz low pass filter and subtracted from the reference value of 1. The obtained output is subjected to the hysteresis comparator and the output of this comparator is the sag detection signal. The sag detection signal is low during normal operating conditions, and is high under faulty conditions.

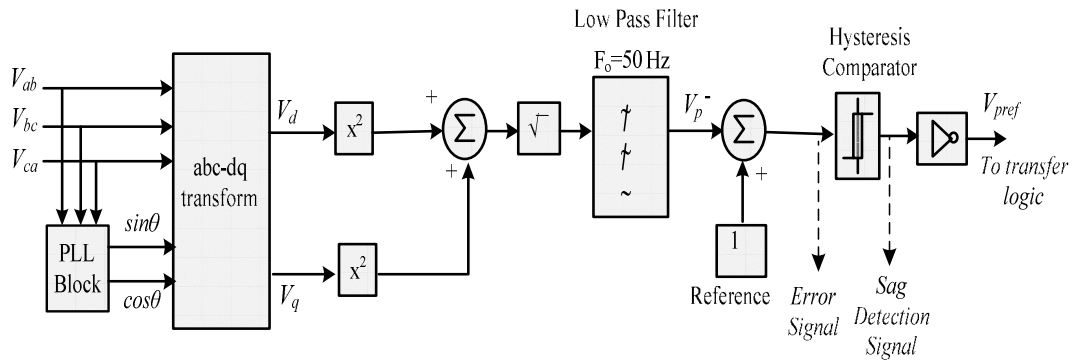


Figure 5.5. Block diagram of the  $dq$  sag detection method for STS

This method is able to detect the three phase balanced voltage sags with an acceptable performance. However, the most important disadvantage of this method is that it uses three line to line voltage measurements for the sag detection. The method is unable to detect the voltage sags lower than a definite level. As an instance, a single phase to ground fault resulting in 15% of voltage sag can not be determined by this method because the method used the average of the three phase voltages and sees the single phase voltage sag as an average value of 5% ( $15/3$ ) if the voltage sag detection limit is selected to be 10% of nominal. Besides another restriction of this method is the use of low pass filter tuned at 50 Hz. This filter reduces the response speed of the detection scheme.

To overcome the disadvantages of the  $dq$  sag detection method, proposed method is used. With the proposed method, the controller is able to detect balanced, unbalanced and single phase voltage sags without an error. In the method, three PLLs based on adaptive filter are used to track each of the three phases.

Block diagram of proposed sag detection method is shown in Figure 5.6. The obtained sag detection signal is inverted to show the condition of measured line to line voltage. Logic high (1) signal shows that the feeder voltages are at nominal

values. An AND block is used to take into consideration three of voltages. If there is a sag at any of measured voltage,  $V_{pref}$  is logic low. Two identical sag detection methods have been used for both feeder voltages.

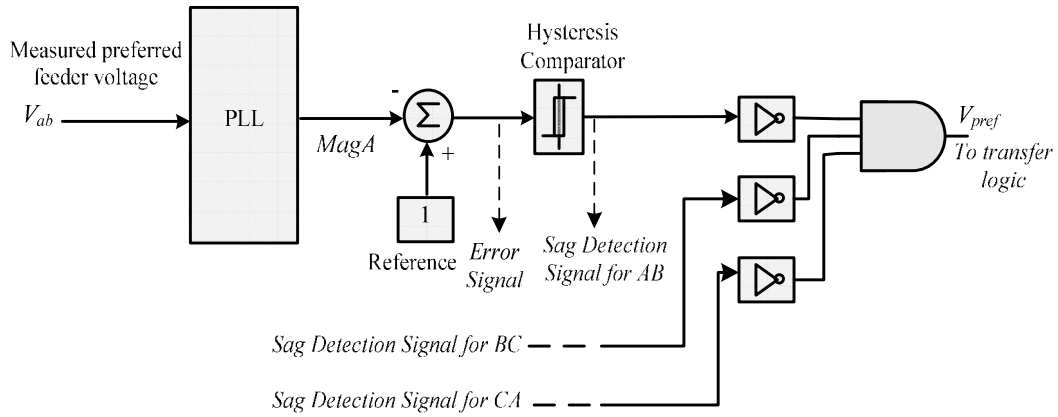


Figure 5.6. Block diagram of proposed PLL based sag detection method for STS

#### 5.2.2.2. Transfer and Gating Strategy

The gating system generates suitable gating patterns for the thyristor switches, before, during and after a load transfer based on the direction of the line current. Two different transfer schemes can be employed. These are zero-current strategy (BBM) and commutation strategy (MBB) (Mokhtari, 2002). Experimentally the implementation of MBB strategy is much harder than the implementation of BBM strategy. In MBB strategy, the zero current detection and polarity detection must be achieved carefully to prevent source paralleling. Moreover, each thyristor of anti parallel switch block must be controlled independently.

In the zero-current strategy used in this study, load transfer to the alternate feeder is not performed until the preferred side thyristors are turned off. When a disturbance is detected in the preferred feeder (main feeder), the gating signals are removed from the preferred side thyristors. The gating logic will then wait for the preferred side thyristors to be turned off which occurs after a current zero crossing is reached. In practice, since real zero current can not be measured, a zero-current threshold limit (ZC), e.g. 2-5% of the rated current, is used as a reference for the zero

current. To compensate for the resulting error, a turn-off delay may be considered before gating the other set of thyristors which connect the load to the alternate feeder.

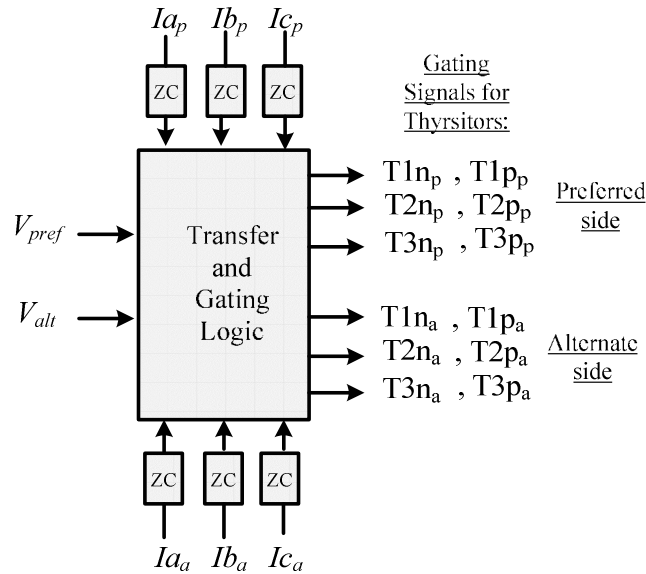


Figure 5.7. Block diagram of transfer and gating logic used in proposed STS

After the sag detection process, transfer and gating logic unit shown in Figure 5.7 is used in the control of STS. This unit is responsible for gating signals of thyristors. The following steps summarize the principles of operation of the gating logic during the normal operating and load-transfer processes:

- The thyristors connected to preferred feeder are turned on under normal operating conditions. The back to back thyristors of each phase (such as  $T1n_p$  and  $T1p_p$ ) have same gating signals.
- When a fault caused to sag or momentary interruption in the preferred feeder is detected, the gating signals are removed from both  $Tp_p$  and  $Tn_p$  thyristors switches for all phases.
- The preferred feeder currents are measured and zero current transition of each phase current is waited. When the zero current transition is detected (for example in preferred feeder phase A), the alternate feeder thyristors are gated (for example  $T1n_a$  and  $T1p_a$  are turned on.). The same process is performed for each phase according to zero current transitions.

- If the fault is cleared and preferred feeder voltages have nominal values, the loads are transferred to preferred feeder. The same process is performed for back transition.
- If faults are occurred in both the preferred and alternate feeders, the loads are fed by preferred feeder.

The flowchart of the transfer and gating strategy (BBM) is shown in Figure 5.8.

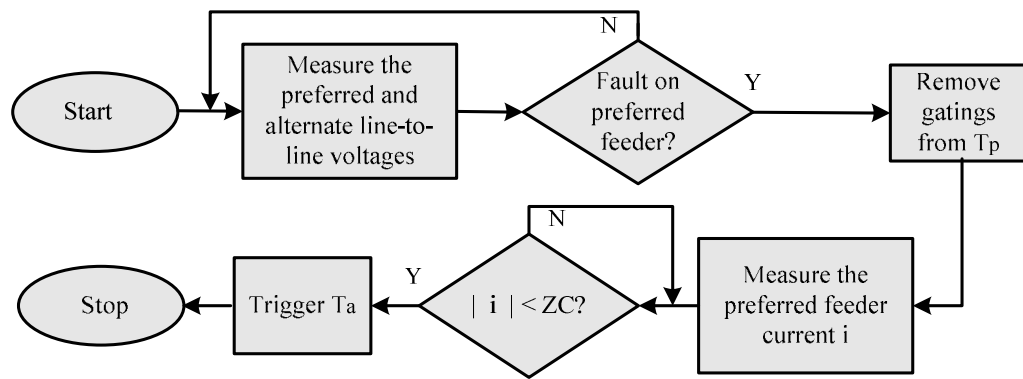


Figure 5.8. The flowchart of the transfer and gating strategy used for STS

### 5.3. Simulation Study of Proposed STS

#### 5.3.1. Simulation Model of Proposed STS

The designed STS is modeled and simulated by using PSCAD/EMTDC program. The simulation model of STS Power Circuit is shown in Figure 5.9. The loads are fed by preferred feeder during normal operating conditions. The STS (composed by two block of three phases thyristor based AC controller) power circuit is connected between preferred-alternate feeders and load bus.

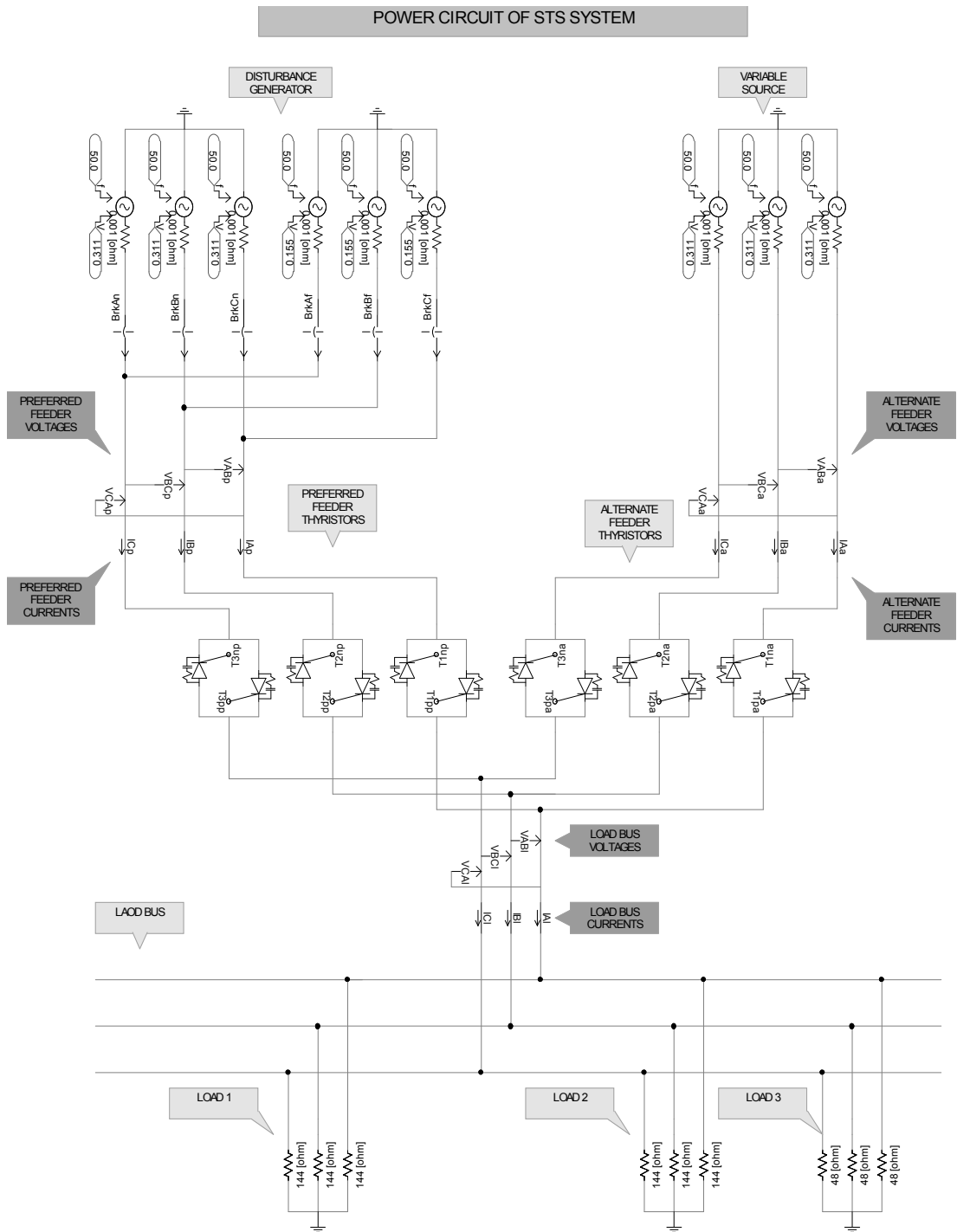


Figure 5.9. Simulation model of STS power circuit

The simulation model of STS control system is shown in Figure 5.10. The control system is consisting of PLL (adaptive filter), sag detection, transfer and

gating blocks for each feeder. The details and operating principles of proposed STS control system are mentioned in Section 5.2.2.

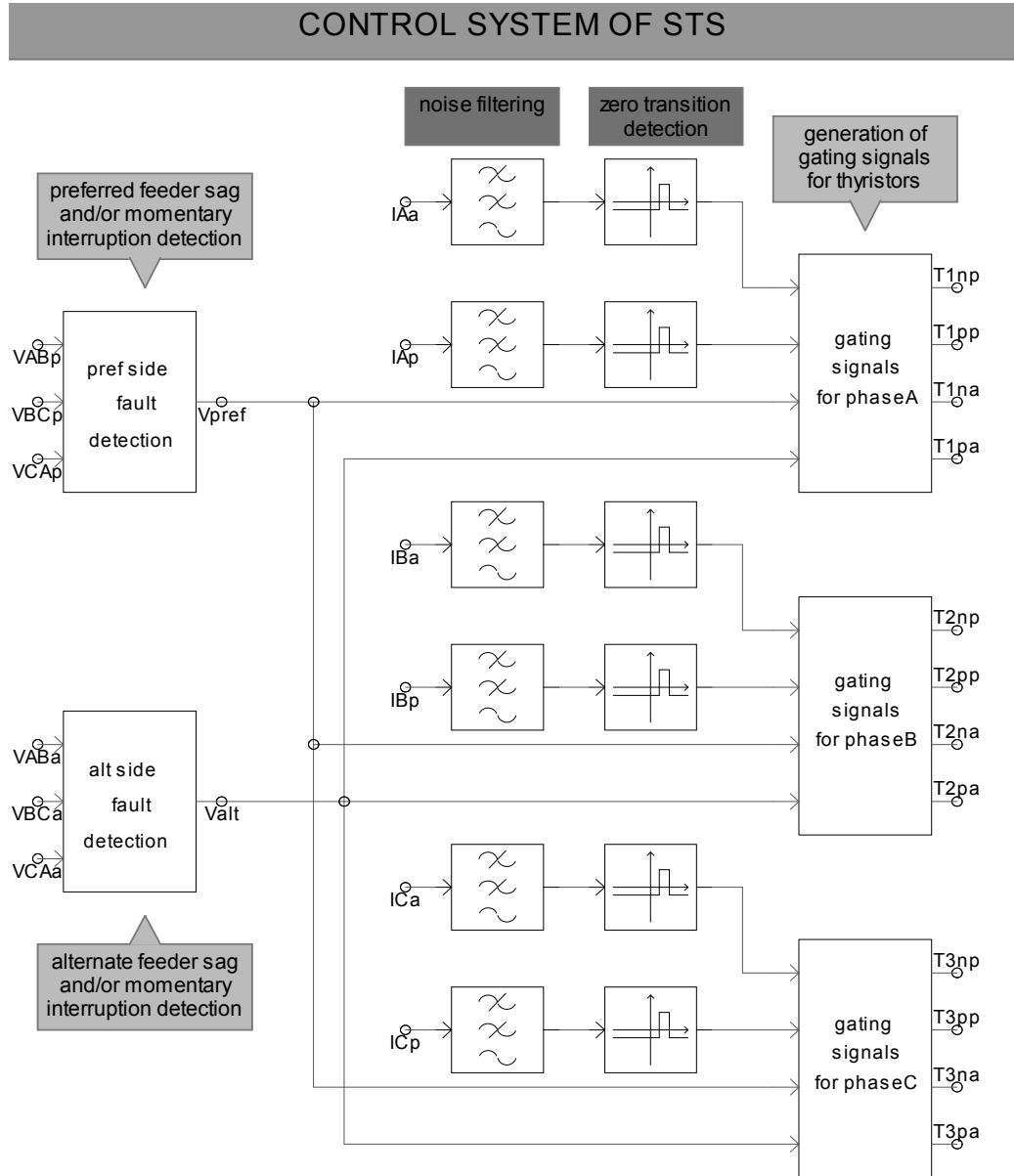


Figure 5.10. Simulation model of proposed STS control system

Table 5.1 gives the parameters of the simulated STS system shown in Figures 5.9 and 5.10.

Table 5.1. Parameters of simulated STS system

| Description                 | Value / profile                                                                                                                               |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Preferred source and feeder | Disturbance generator composed by a fixed source, a variable source (ln-ln 0-380 Vrms) and circuit breakers. Feeder impedances are negligible |
| Alternate source and feeder | A variable source (ln-ln 0-380 Vrms) Feeder impedances are negligible                                                                         |
| Thyristors                  | SCR with snubbers                                                                                                                             |
| Load impedances / per phase | Resistive, Z1: 144 $\Omega$ , Z2: 144 $\Omega$ , Z3: 48 $\Omega$                                                                              |
| Sample time for simulation  | 25 $\mu$ s                                                                                                                                    |

### 5.3.2. Simulation Results for Proposed STS

#### 5.3.2.1. Single Phase to Ground Fault in the Preferred Feeder

Figures 5.11, 5.12, 5.13 and 5.14 show the simulation results for 12% sags on line to line AB and CA voltages caused by single phase to ground fault in the preferred feeder phase A. The voltage sags start at time 252 ms and end at time 366 ms.

Figure 5.11 is presented to show sag detection performances of proposed method and  $dq$  transformation based conventional method. As shown in Figure 5.11, the magnitude signals  $MagAB$  and  $MagCA$  are decreased. The proposed method detects (with  $V_{pref\_prop}$  signal) the sag of AB voltage, firstly. And transfer logic is started. The time for sag detection is 4.3 ms. However, the  $V_{p\_conv}$  signal used in conventional method is at sag detection limit (0.9), and the conventional method ( $V_{pref\_conv}$ ) can not detect the sag.

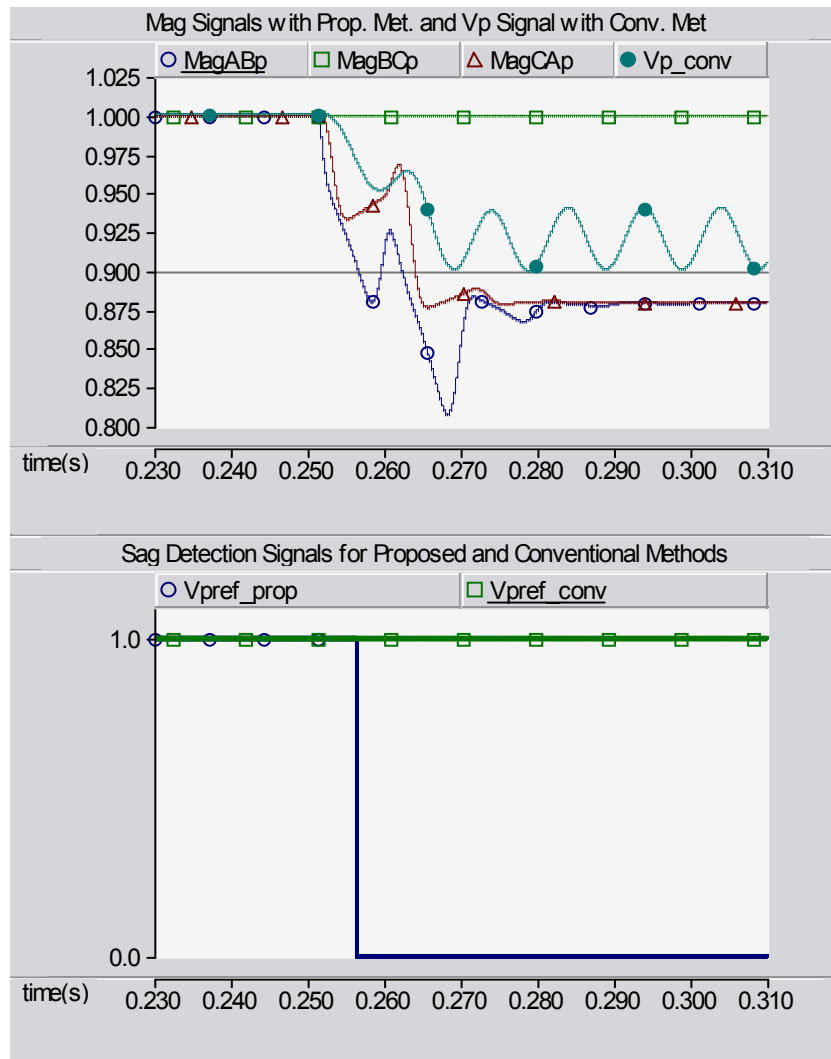


Figure 5.11. Sag detection and Magnitude signals for sag starting and sag ending in case of single phase to ground fault

Figures 5.12 and 5.13 show the voltage and current waveforms, respectively. As can be seen from Figures 5.12 and 5.13, when the voltage sag is detected, the STS transfer and gating logic is waited to zero current transition. After the zero current transitions, alternate feeder thyristors are turned on. The total detection and transfer times are 8, 4.6 and 11.3 ms for phase A, phase B and phase C currents.

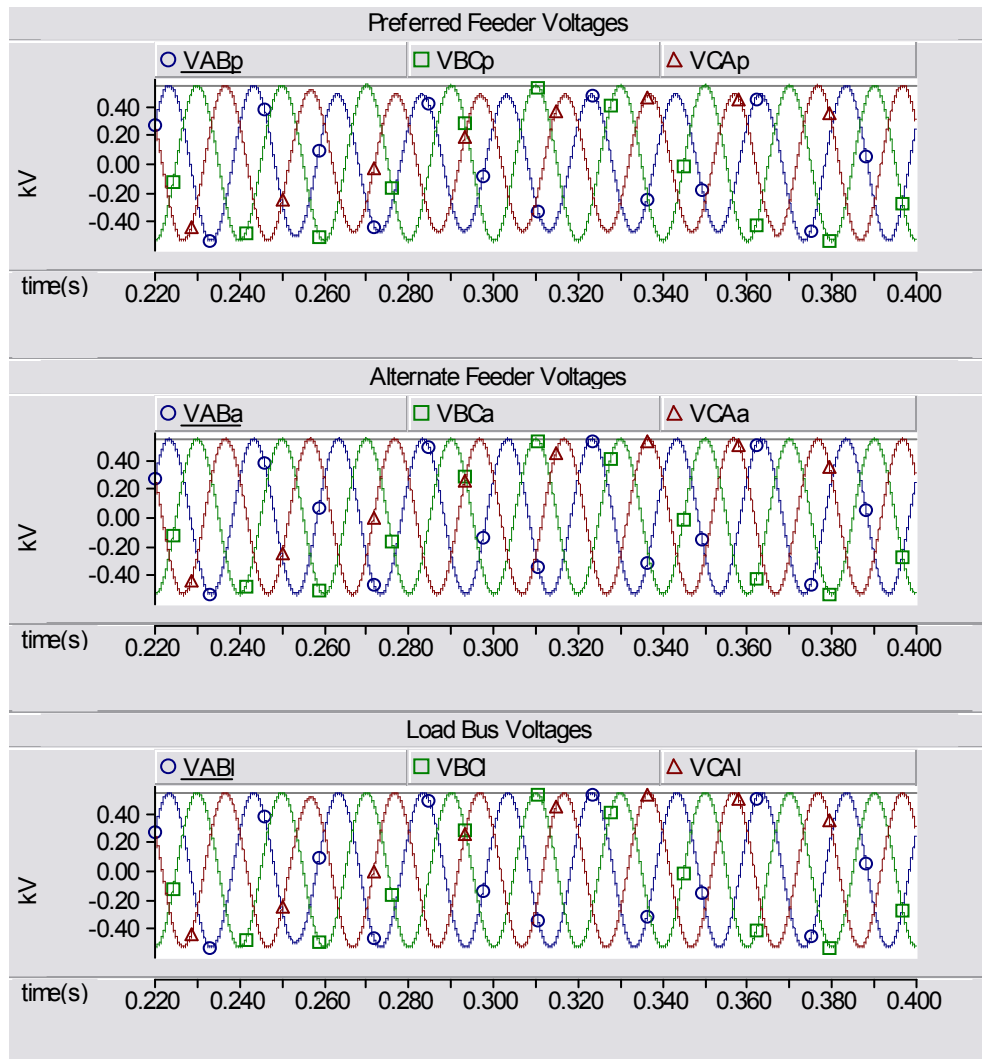


Figure 5.12. Voltage waveforms in case of single phase to ground fault

Figure 5.14 show the ending of voltage sags. Sag ends at time 366 ms and the ending time is marked with “marker x”. The detection time is marked with “marker u”. The comeback to preferred feeder becomes at time 380 ms. The transfer is late, because the detection is achieved after the zero current transition. Therefore, the transfer logic waits extra half period for phase A.

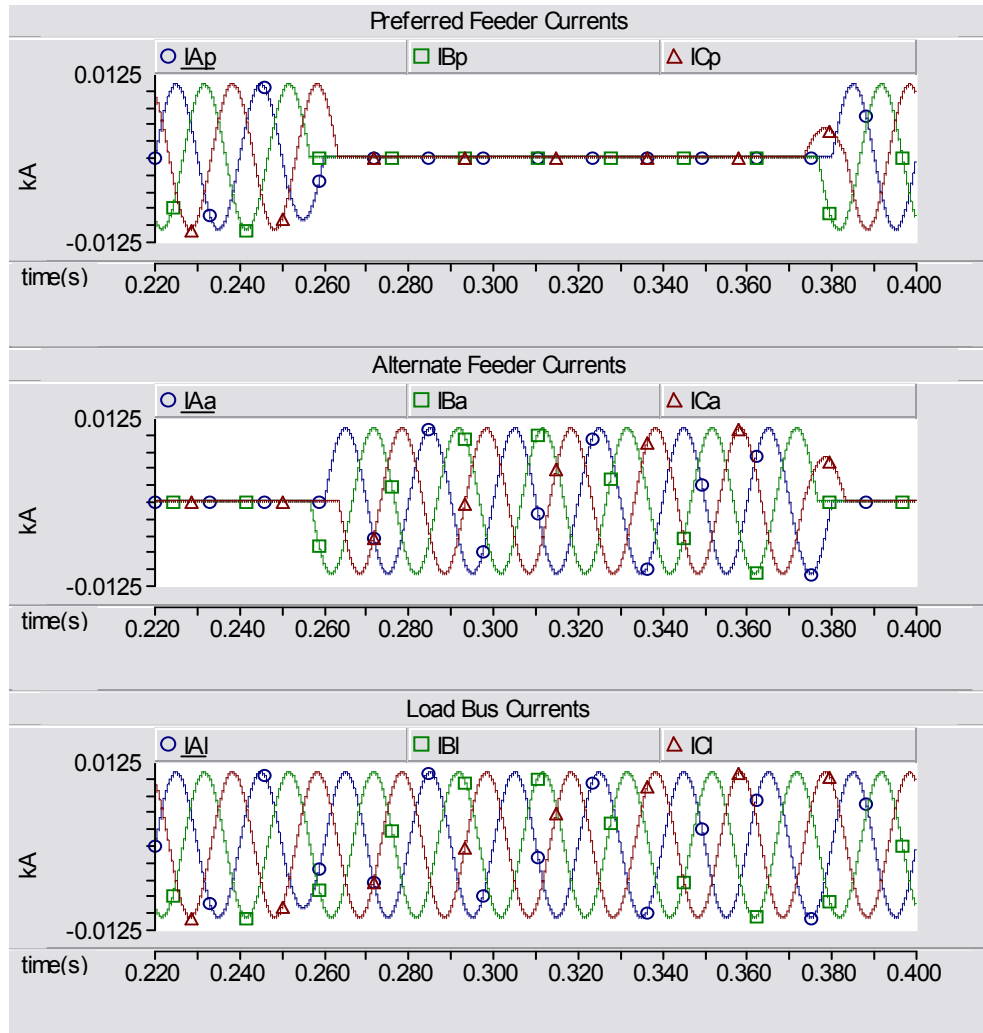


Figure 5.13. Current waveforms in case of single phase to ground fault

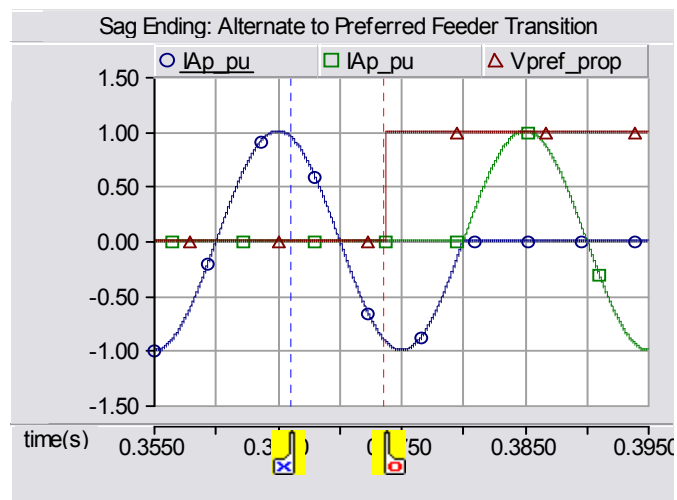


Figure 5.14. Detailed presentations of sag ending and current transition

### 5.3.2.2. Three Phases to Ground Fault in the Preferred Feeder

Figures 5.15, 5.16 and 5.17 show the simulation results for 40 % sags on all line to line voltages caused by three phase to ground fault in the preferred feeder. The voltage sags start at time 415 ms and end at time 515 ms.

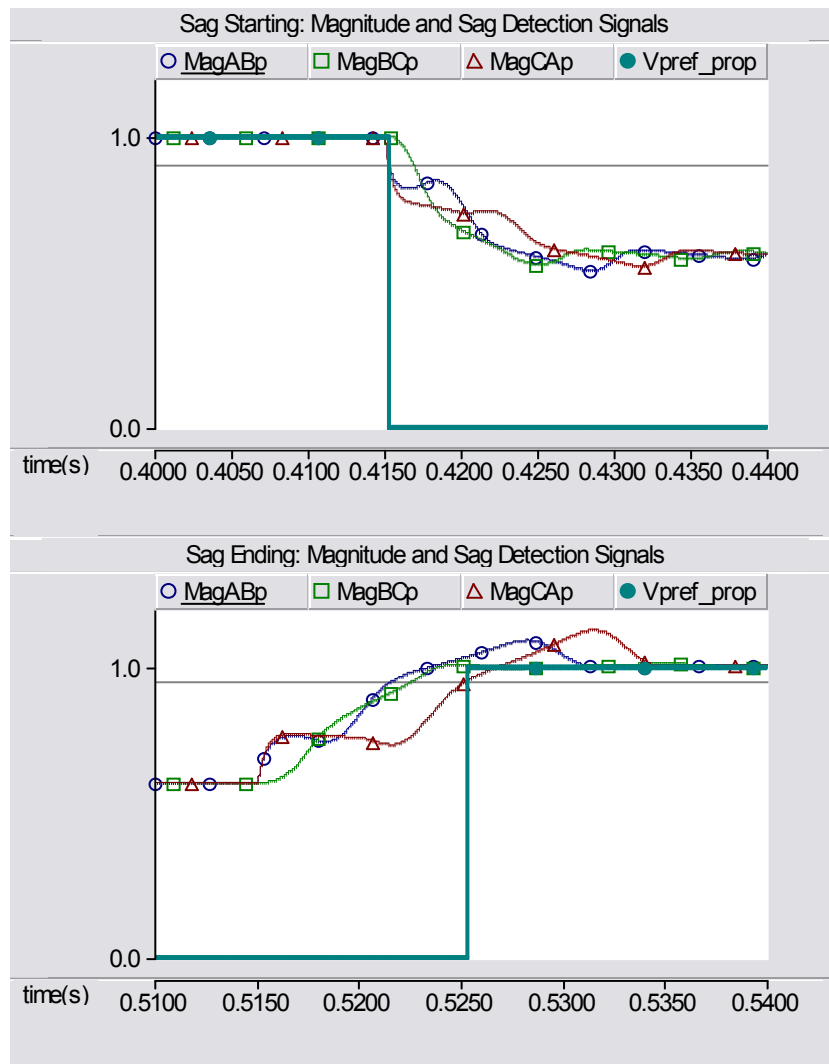


Figure 5.15. Sag detection and Magnitude signals for sag starting and sag ending in case of three phases to ground fault

Figure 5.15 is presented to show sag detection performances of proposed method in case of sags starting and sags ending. As shown in Figure 5.15, all the magnitude signals are decreased. The proposed method detects ( $V_{pref\_prop}$ ) the sag

of CA voltage, firstly. And transfer logic is started. The time for sag detection is less than 1 ms. At the ending of sags, the proposed method waits for all detection of endings. And then transfer logic is started. It is not important that length of the back transfer time, because both the feeders are healthy at this time.

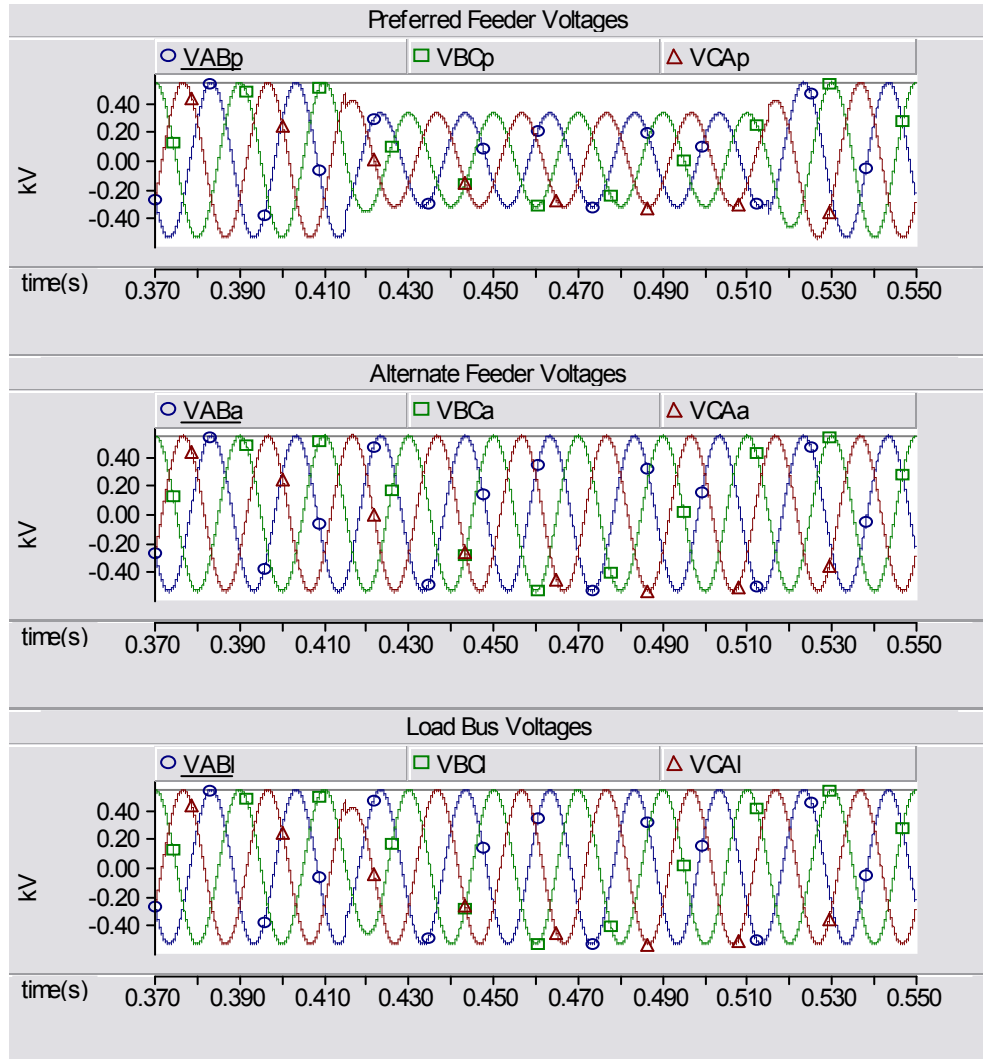


Figure 5.16. Voltage waveforms in case of three phases to ground fault

Figures 5.16 and 5.17 show the voltage and current waveforms, respectively. As can be seen from figures, when the voltage sag is detected, the transfer and gating logic controls zero current transitions for each phase. After the zero current transitions, alternate feeder thyristors are turned on. As seen from in Figure 5.17, the

total detection and transfer times are 4.8, 1.5 and 8.1 ms for phase A, phase B and phase C currents. The load bus is only affected from the phase to phase CA voltage, because the transfer time is biggest for the phase A current.

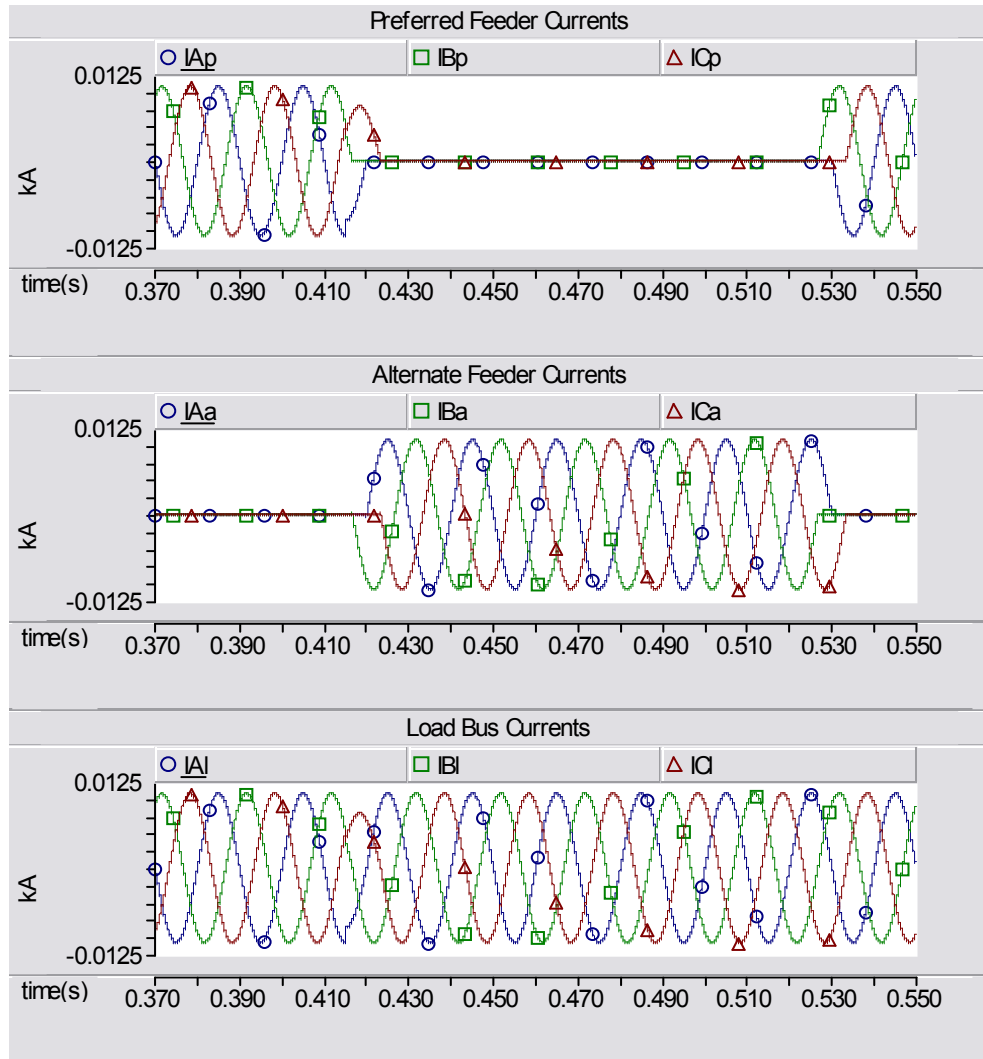


Figure 5.17. Current waveforms in case of three phases to ground fault

### 5.3.2.3. Three Phases to Ground Faults in both the Preferred and Alternate Feeders

Figures 5.18 and 5.19 show the simulation results for 30 % sags on all line to line voltages caused by three phase to ground faults in both the preferred and alternate feeders. The voltage sags start at time 565 ms and end at time 670 ms.

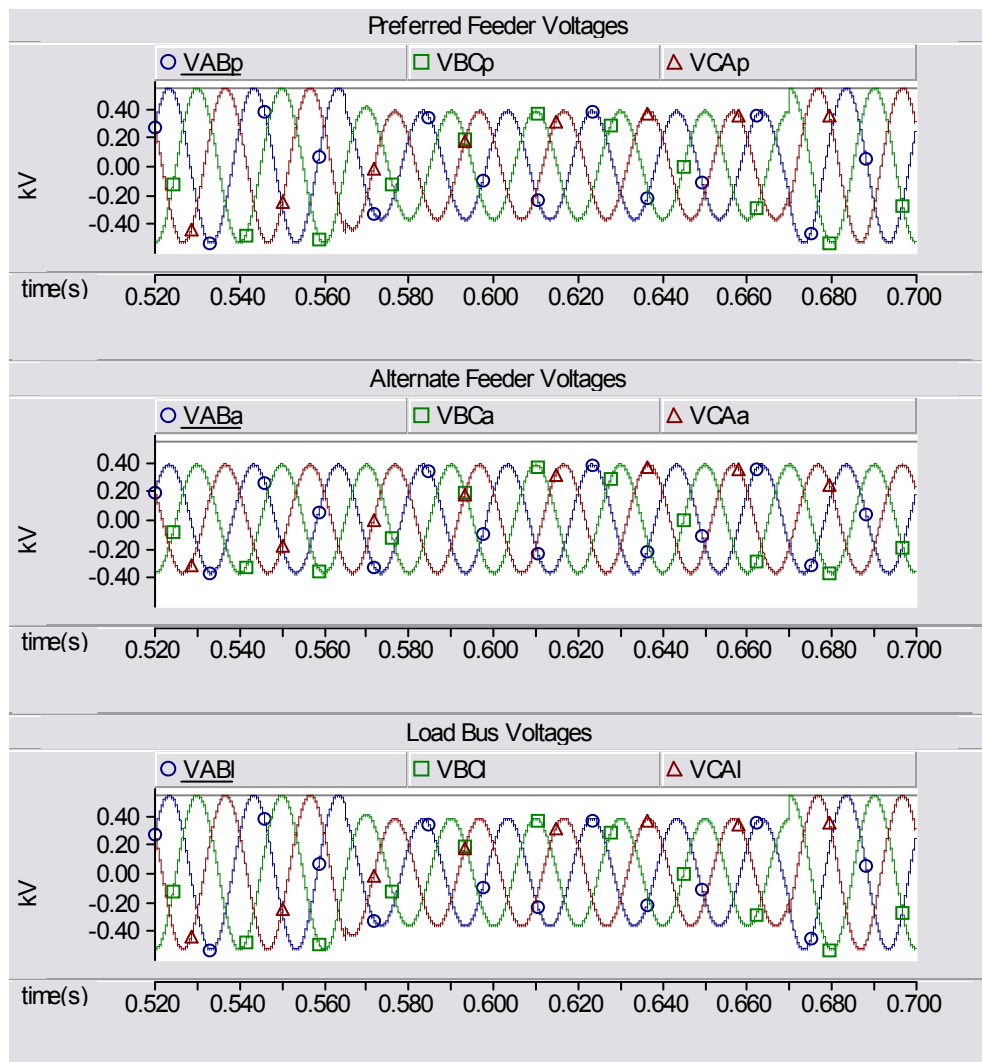


Figure 5.18. Voltage waveforms in case of three phases to ground fault in both the feeders

If there are faults in both the feeders, there must not be any load bus transfer according to transfer and gating logic of control system. As shown from Figure 5.19,

in case of the faults, the control system of STS has not realized any load bus transferring.

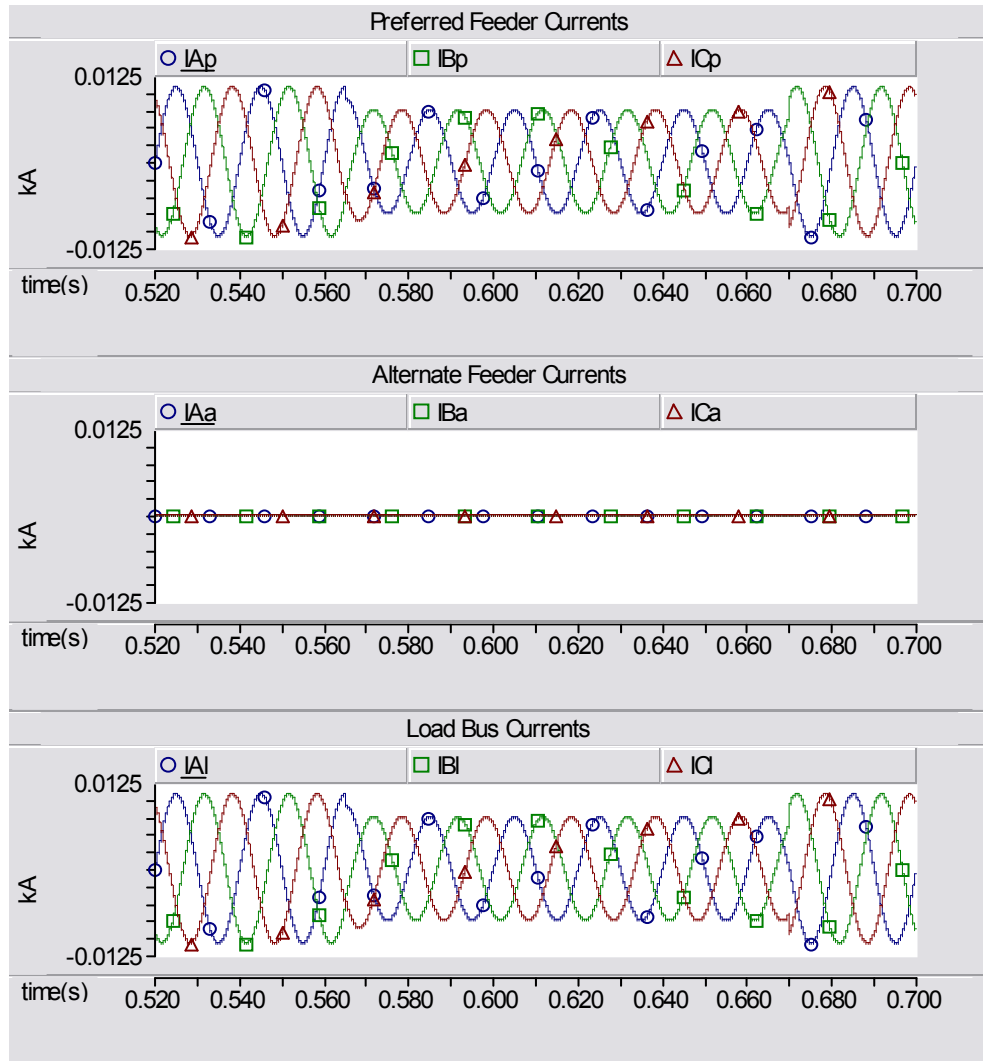


Figure 5.19. Current waveforms in case of three phases to ground fault in both the feeders

#### 5.4. Experimental Setup of Proposed STS

The block diagram of the DSP controlled experimental hardware of three-phase STS is shown in Figure 5.20. The proposed system consists of a DSP board, measurement devices, thyristor driver and SCRs.

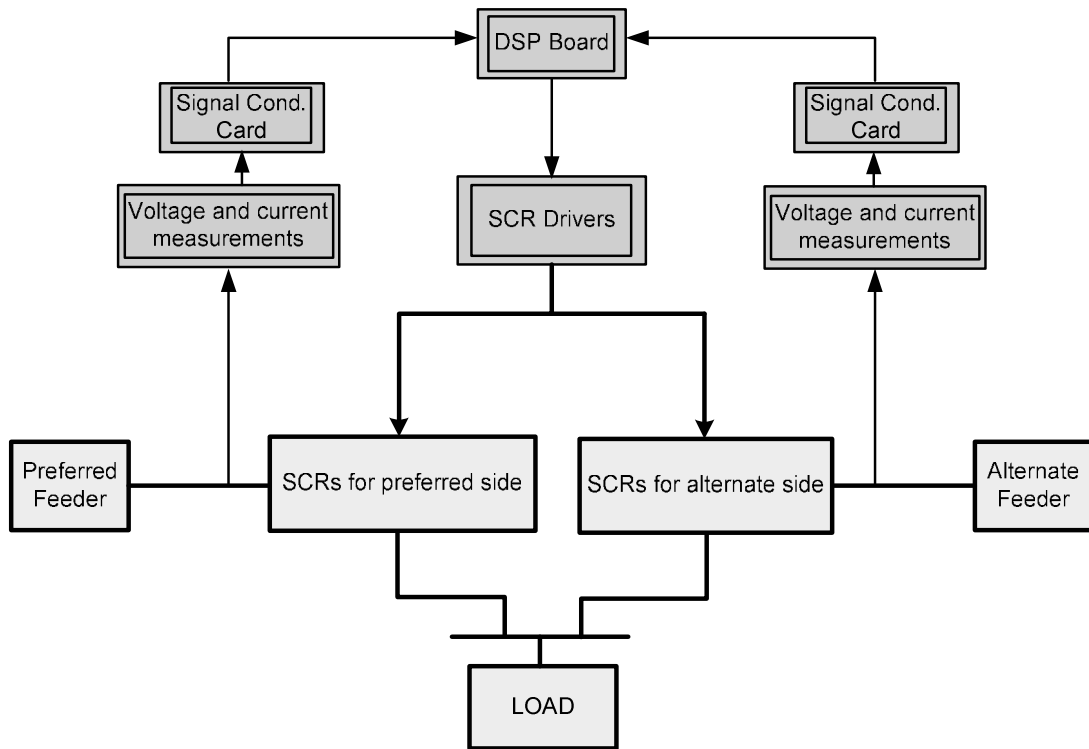


Figure 5.20. The block diagram of DSP controlled experimental hardware of STS

Static Transfer Switch is composed of thyristor device pairs connected back to back. The source voltages and feeder currents for both preferred and alternate feeders are measured using transducers. The measured signals are adapted to DSP inputs and DSP generates the required gating signals according to applied control algorithms. The gating signals should be used with the thyristor driver circuits to trigger the SCR correctly.

#### 5.4.1. Sources and Feeders

For testing STS, the disturbance generator presented in Chapter 4 is used. This disturbance generator is used as preferred source. Feeder impedances are chosen as negligible. In the alternate side, a variable source is used as alternate source.

### 5.4.2. Signal Conditioning Cards

Signal conditioning cards include signal measurements and offset circuit.

#### 5.4.2.1. Signal Conditioning Card for Voltage Measurements

The voltage measurement is achieved using voltage transducer circuit. The transducers convert  $220\text{ V}_{\text{rms}}$  value to  $1.5\text{ V}_{\text{peak}}$  sinusoidal signals. The additional offset circuit adds  $1.5\text{ V}_{\text{dc}}$  offset to  $1.5\text{ V}_{\text{peak}}$  AC signal to convert the signal  $0\text{--}3\text{ V}_{\text{peak}}$  value that is necessary for DSP input. The circuit diagram of signal conditioning for single voltage measurement is shown in Figure 5.21.

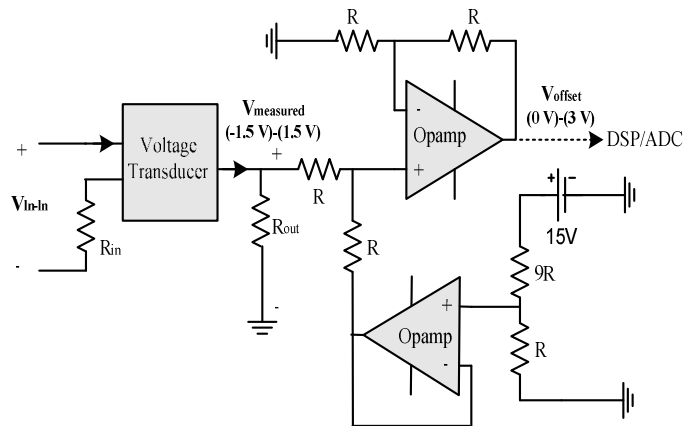


Figure 5.21. The circuit diagram of signal conditioning for voltage measurement

The signal conditioning card includes transducers, LM324 and other passive circuit components as shown in Figure 5.22.

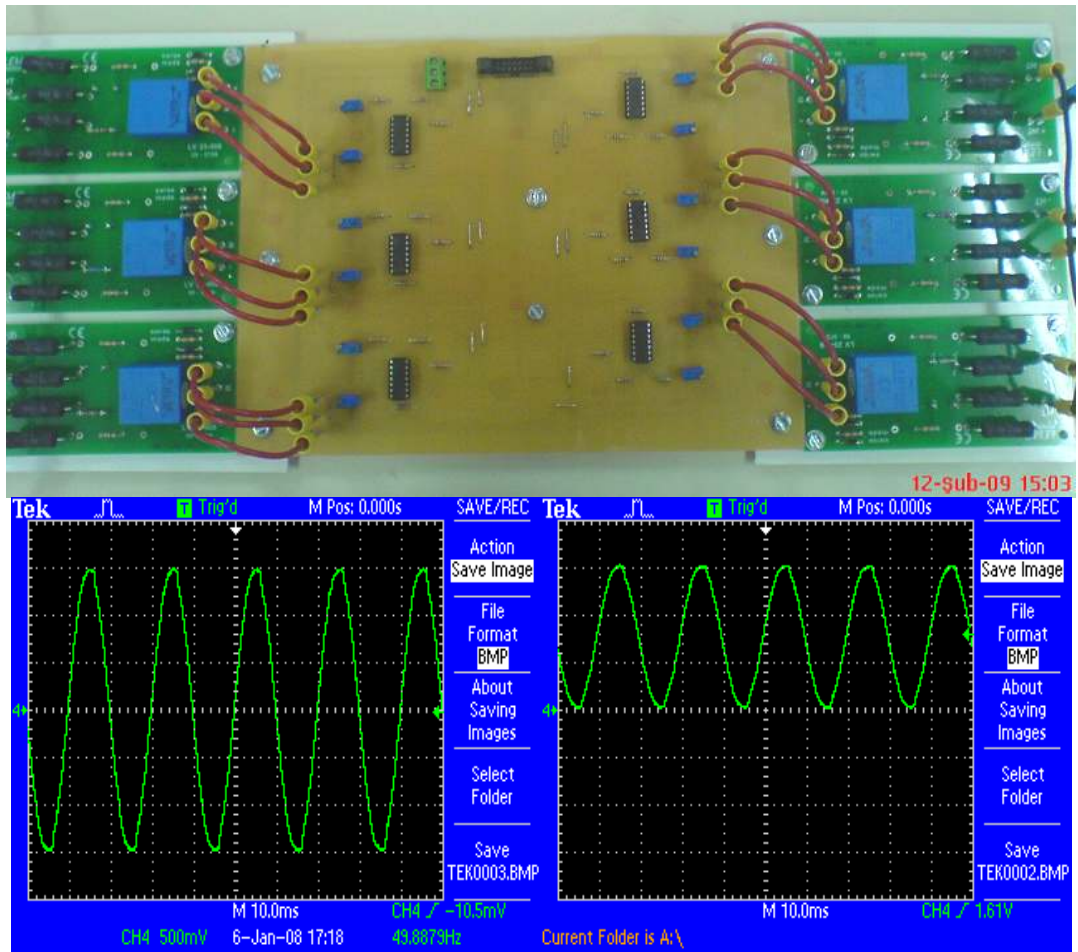


Figure 5.22. Voltage signal conditioning card and input-output waveforms of the circuit for phase A

#### 5.4.2.2. Signal Conditioning Card for Current Measurements

The current measurement is achieved using current transducer circuit. The transducers convert the current value to  $1.5 V_{\text{peak}}$  sinusoidal signals. The additional offset circuit adds  $1.5 V_{\text{dc}}$  offset to  $1.5 V_{\text{peak}}$  AC signal to convert the signal  $0-3 V_{\text{peak}}$  value that is necessary for DSP input. The circuit diagram of signal conditioning for single current measurement is shown in Figure 5.23.

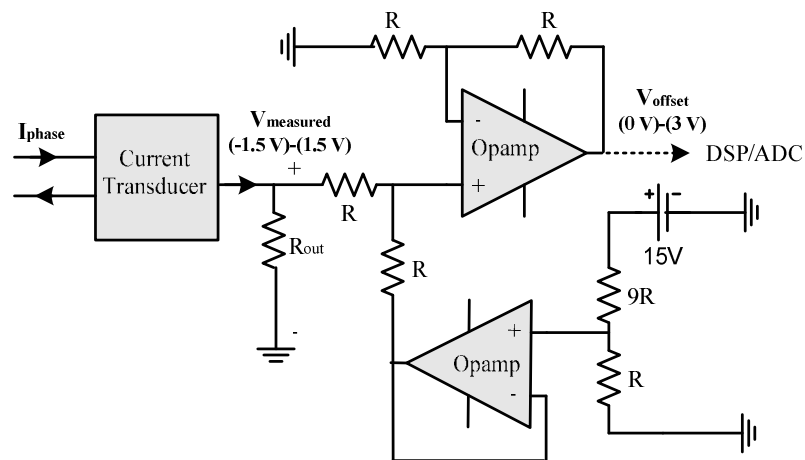


Figure 5.23. The circuit diagram of signal conditioning for current measurement

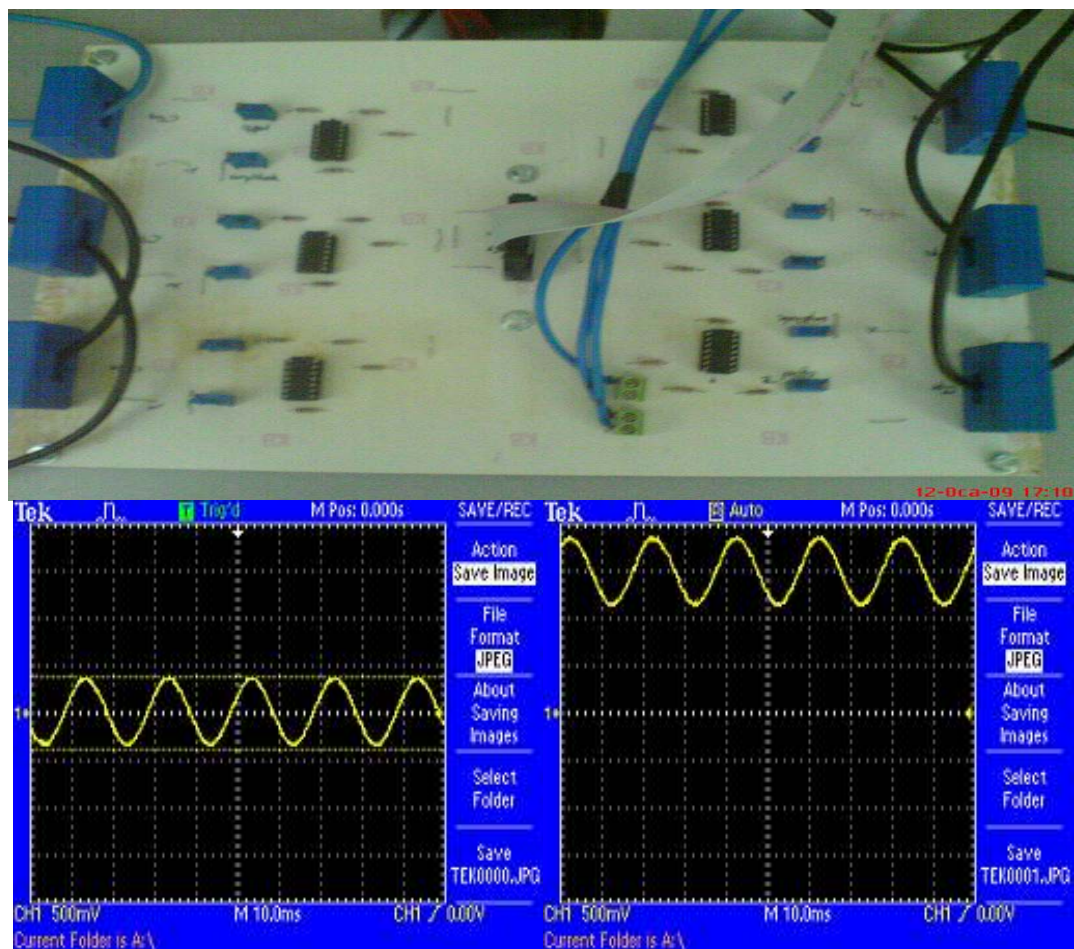


Figure 5.24. Current signal conditioning card and input-output waveforms of the circuit for phase A

The card includes transducers, LM324 and other passive circuit components as shown in Figure 5.24. The shown current signal is measured for 4.5 A, the nominal current measurement is set up as 18 A.

#### 5.4.3. DSP Controller

TMS320F2812 ezDSP is used in the experimental study as shown in Figure 5.25. DSP takes the inputs, processes them using the transfer strategy and produces square wave output signals having 0-3.3 V amplitudes.

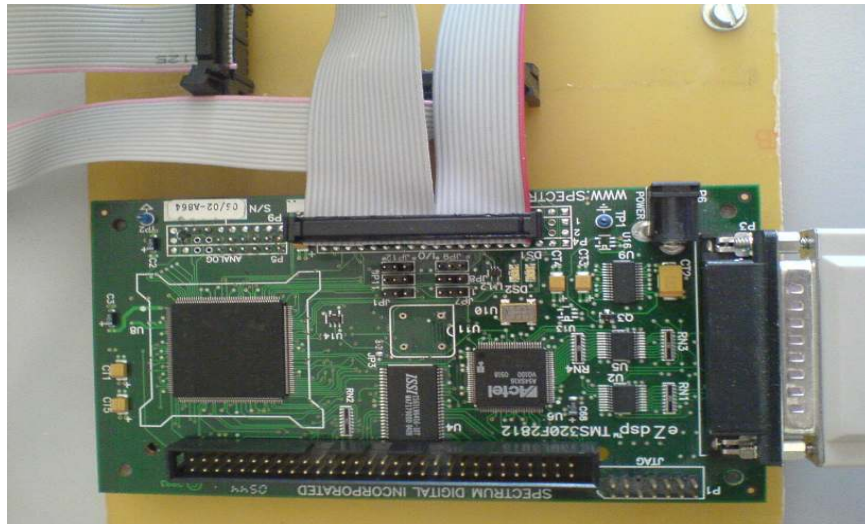


Figure 5.25. TMS320F2812 ezDSP for the STS

The control strategy in DSP is based on generation of switching signals by processing the measured signals. Proposed sag/interruption detection method is used for fault detection. BBM strategy is used to generate the required gate drive signals.

#### 5.4.4. Thyristor Driver Circuit

MOC 3023 opto-isolators are used for thyristor driver circuit. DSP outputs are not sufficient to drive MOCs. Because of this, LS241 amplifiers are used as DSP

output-MOC interface. The circuit diagram of thyristor driver for a pair of anti-parallel thyristors is shown in Figure 5.26.

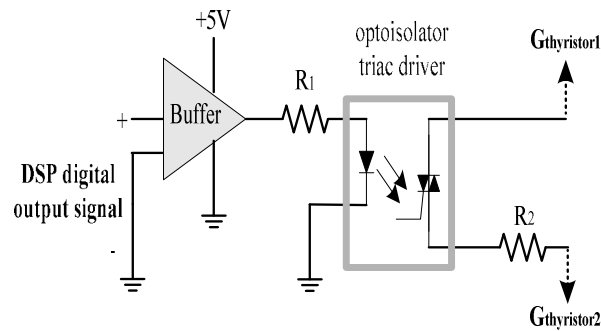


Figure 5.26. The circuit diagram of thyristor driver for a pair of anti-parallel thyristors

Figure 5.27 shows thyristor driver card including drivers for three phases of preferred and alternate feeders' thyristor modules. The card is designed in accordance with the BBM strategy.

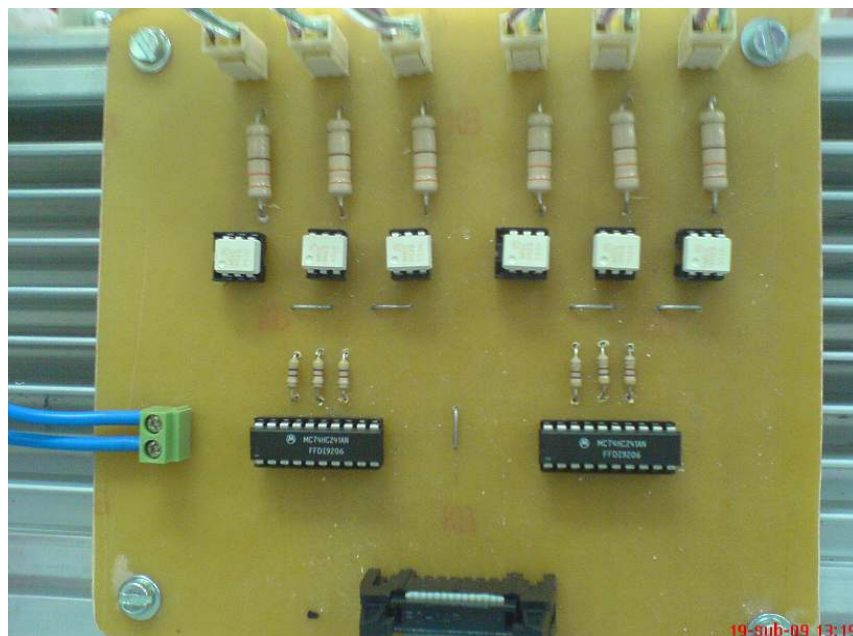


Figure 5.27. Driver Card for 6 thyristor modules

#### 5.4.5. Snubber Circuit

Snubber circuit is shown in Figure 5.28. The value of the snubber resistance and capacitance are  $47\ \Omega$  and  $22\ \mu\text{F}$ , respectively.



Figure 5.28. Snubber circuit

#### 5.4.6. Thyristor modules

Semikron SKKT 42/12E thyristor modules (including back to back SCR pairs) are used in the experimental setup of the STS. The modules have 1200 V, 40 A nominal operating values. Figure 5.29 shows the SCR modules for both the three phases of preferred and alternate feeders. The connected snubbers and driver circuit are also seen from Figure 5.29.

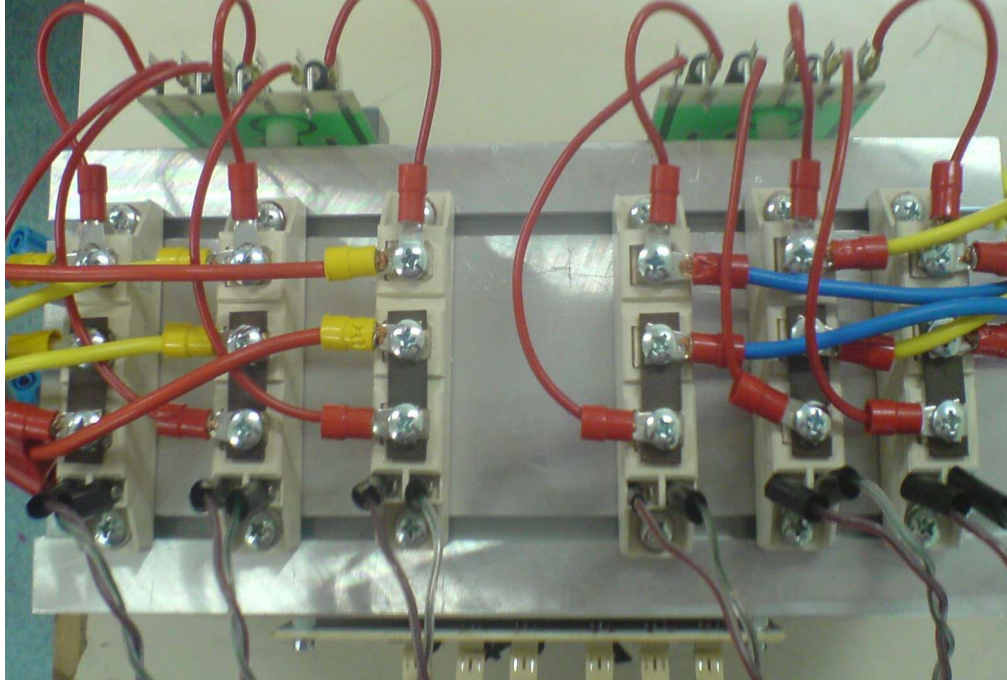


Figure 5.29. Semikron SKKT 42/12E thyristor modules in STS system

#### 5.4.7. Loads

STS protects the group of loads against voltage sags and outages. The data for the loads used for the experiment are shown in Table 5.2.

Table 5.2. Data for the loads connected to load bus

| Loads  | Rating                                    |
|--------|-------------------------------------------|
| Load-1 | 1 kW, 144 $\Omega$ /phase, pure resistive |
| Load-2 | 1 kW, 144 $\Omega$ /phase, pure resistive |
| Load-3 | 3 kW, 48 $\Omega$ /phase, pure resistive  |

#### 5.5. Experimental Results of Proposed STS

In this section, the sag detection and load bus transferring abilities of proposed STS are presented in case of various faults.

Table 5.3. Data for the STS experimental system

| Description                   |                      | Value/profile                                                                                                    |
|-------------------------------|----------------------|------------------------------------------------------------------------------------------------------------------|
| <b>VOLTAGE SOURCES</b>        | Preferred Feeder     | Disturbance (sag and/ or momentary interruption) Generator, phase to phase 0-380 Vrms                            |
|                               | Alternate Feeder     | Variable Source, phase to phase 0-380 Vrms                                                                       |
| <b>STATIC TRANSFER SWITCH</b> | Controller           | ezDSP TMS320F2812 DSP, sample time 25 $\mu$ s                                                                    |
|                               | SCR thyristors       | Semikron SKKT 42/12E, 1200V, 40 A                                                                                |
|                               | SCR drivers          | MOC 3023                                                                                                         |
|                               | Snubbers             | R: 47 $\Omega$<br>C: 22 $\mu$ F                                                                                  |
|                               | Voltage Measurement  | LEM LV25-P voltage transducer, LV25-400 transducer board                                                         |
|                               | Current Measurement  | LEM LA25-P current transducer                                                                                    |
| <b>LOAD</b>                   | Resistive Load Banks | R1: 144 $\Omega$ /phase, max 2.25 A<br>R2: 144 $\Omega$ /phase, max 2.25 A<br>R3: 48 $\Omega$ /phase, max 6.75 A |
| <b>WAVEFORM MEASUREMENTS</b>  | PQ Analyzer          | HIOKI 3196                                                                                                       |

The presented experimental results are listed below:

- Single phase to ground fault in the preferred feeder: Waveforms and RMS graphics obtained by Power Quality Analyzer
- Three phases to ground fault in the preferred feeder: Waveforms and RMS graphics obtained by Power Quality Analyzer
- Three phases to ground faults in both the preferred and alternate feeders: Waveforms graphics obtained by Power Quality Analyzer

The data of experimental setup parameters are summarized in Table 5.3.

### 5.5.1. Case 1: Single Phase to Ground Fault in the Preferred Feeder

In Figure 5.30, waveforms are given which show starting of 12% voltage sags (decreasing from 380 V to 335 V) on line to line voltages AB and CA caused by single phase to ground fault. The voltage waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder AB, BC and CA voltages, respectively. The current waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder phase A, bus phase A and alternate feeder phase A currents, respectively.

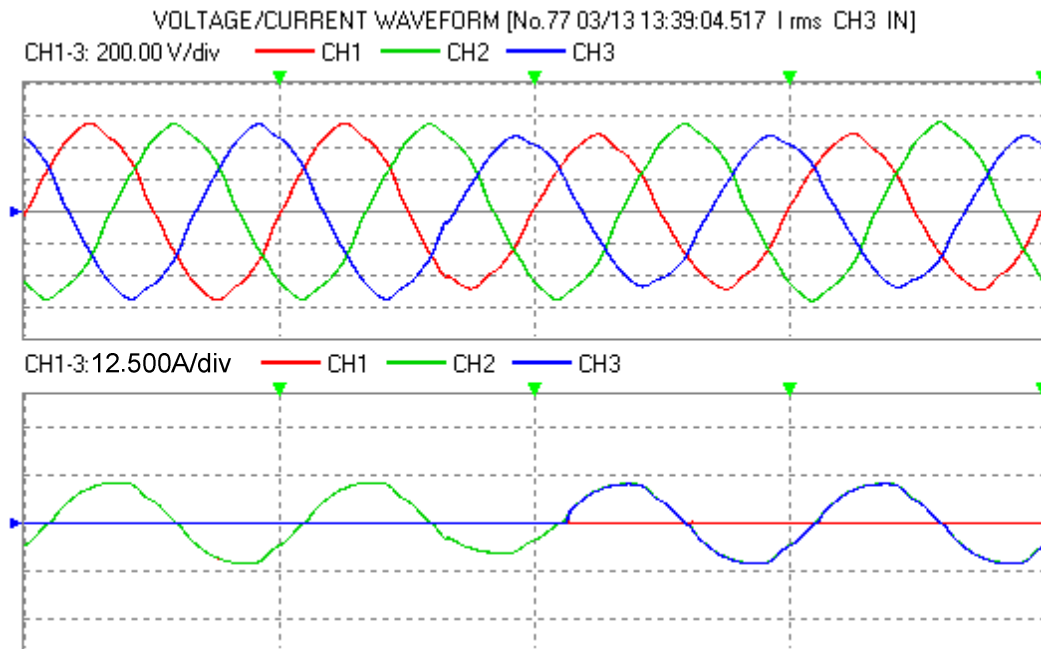


Figure 5.30. Voltage/Current waveforms for starting of a single phase to ground fault in the preferred feeder

The each division is 200 V for voltage waveforms and 12.5 A for current waveforms. As can be seen from Figure 5.30, after the fault occurring, gating signals of preferred feeder thyristors are removed and zero crossing of the preferred feeder current is waited, and then the alternate feeder thyristors are turned on. In this situation, the bus currents are supplied by alternate feeder. As seen from Figure 5.30, there is no any source paralleling.

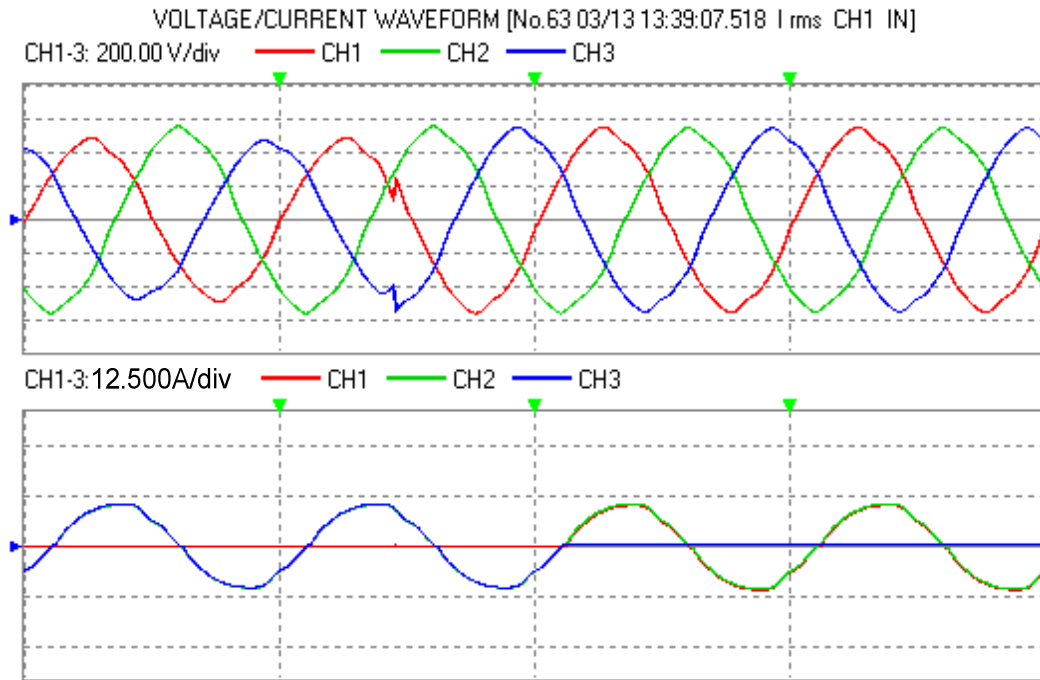


Figure 5.31. Voltage/Current waveforms for ending of a single phase to ground fault in the preferred feeder

Figure 5.31 shows the voltage and current waveforms at ending of single phase to ground fault of which starting is shown in Figure 5.30. A few milliseconds after clearing fault in the preferred feeder, this situation is detected by the control system. But the zero crossing is not caught during the negative half period because of the sag detection delay. With the zero crossing of positive half period, the preferred feeder thyristor are turned on.

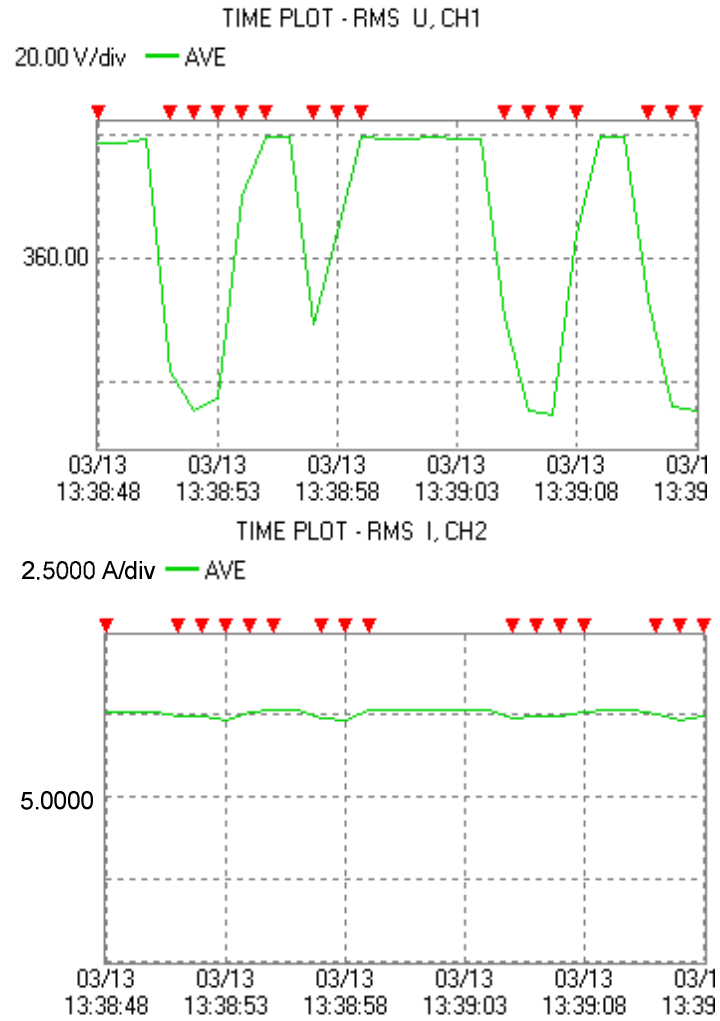


Figure 5.32. RMS voltage trends for 12% voltage sags

RMS results of 12% voltage sags caused by single phase to ground faults occurring at different time instants are shown in Figure 5.32. Ch1 voltage measurement (U-Ch1) indicates the rms values of preferred feeder AB voltage, and Ch2 current measurement (I-Ch2) indicates the rms values of bus phase A current. Although the faults occurred in preferred feeder, the bus current is almost kept in its nominal value as seen from the rms results. This is achieved by the transferring load bus to healthy feeder.

### 5.5.2. Case 2: Three Phases to Ground Fault in the Preferred Feeder

Figure 5.33 shows the waveform results for 40% sags (decreasing from 380 V to 235 V) on three line to line voltages of preferred feeder.

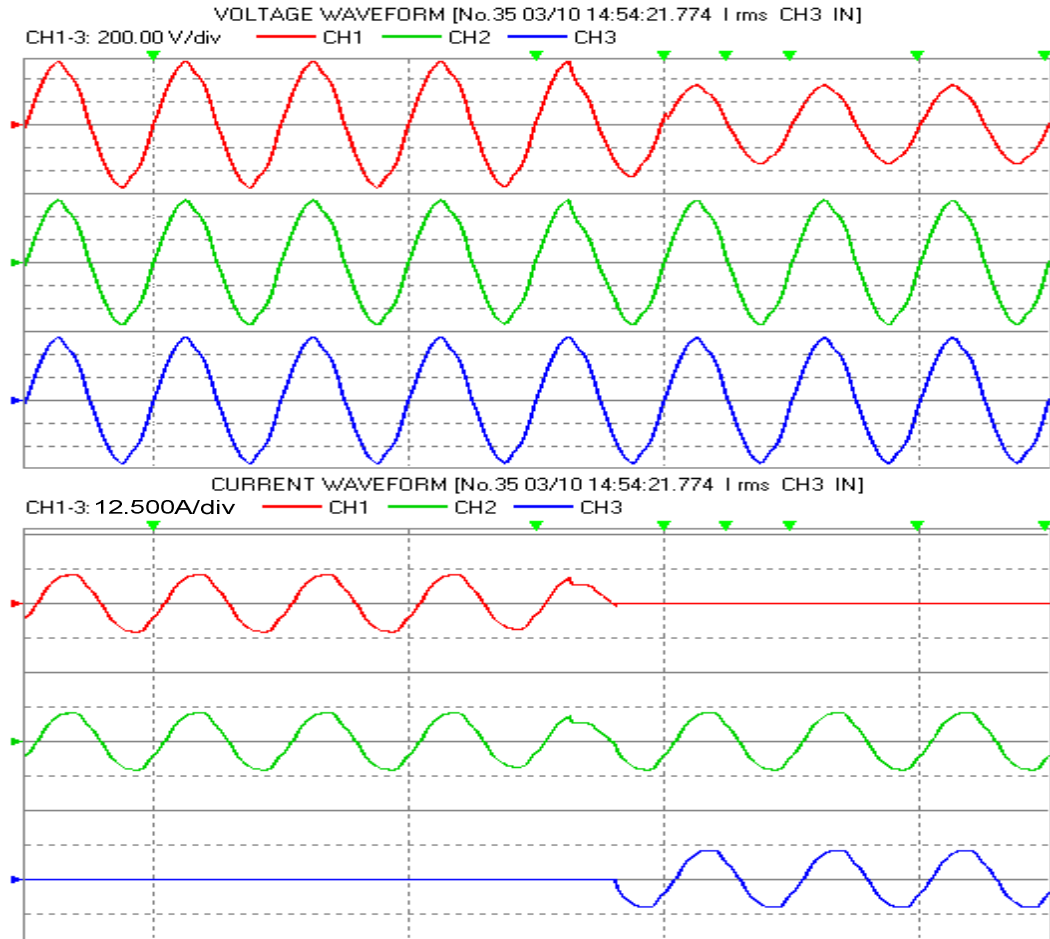


Figure 5.33. Voltage/Current waveforms for three phases to ground fault in the preferred feeder

In Figure 5.33, the voltage waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder AB, bus AB and alternate feeder AB voltages, respectively. Similarly, the current waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder phase A, bus phase A and alternate feeder phase A currents, respectively. As seen from Figure 5.33, in case of voltage sag, the load bus is transferred to alternate feeder and load bus voltage kept in its nominal value.

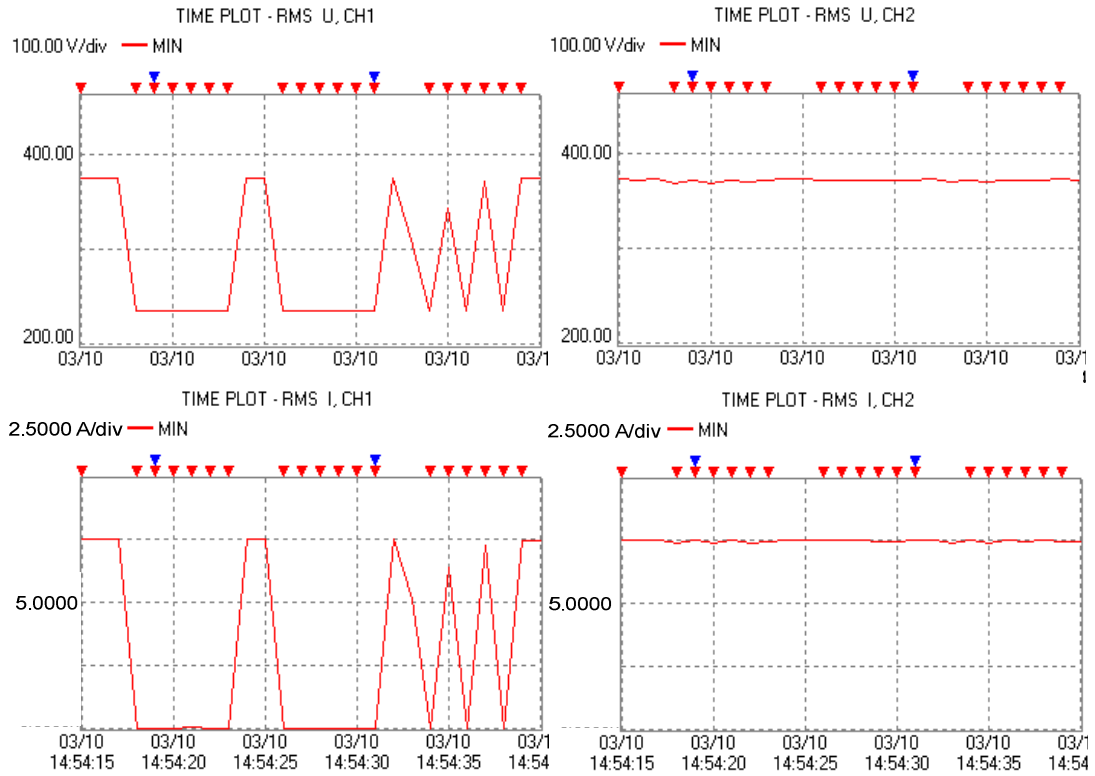


Figure 5.34. RMS voltage trends for 40% voltage sags

In Figure 5.34, Ch1 and voltage measurements indicate the preferred feeder AB and bus AB voltages, respectively. Similarly, the current waveforms of Ch1 and Ch2 indicate the preferred feeder phase A and bus phase A currents, respectively. As can be seen from the RMS results shown in Figure 5.34, the preferred feeder current is flow when the preferred feeder voltage is in its nominal value. Despite the faults occurred in preferred feeder at different times, the bus voltage and current are kept in their nominal values (380 V and 7.5 A). This is achieved by the use of the proposed STS.

### 5.5.3. Case 3: Three Phases to Ground Faults in both the Preferred and Alternate Feeders

Figure 5.35 shows the waveform results for 30% sags (decreasing from 380 V to 266 V) on three line to line voltages of both the preferred and alternate feeders.

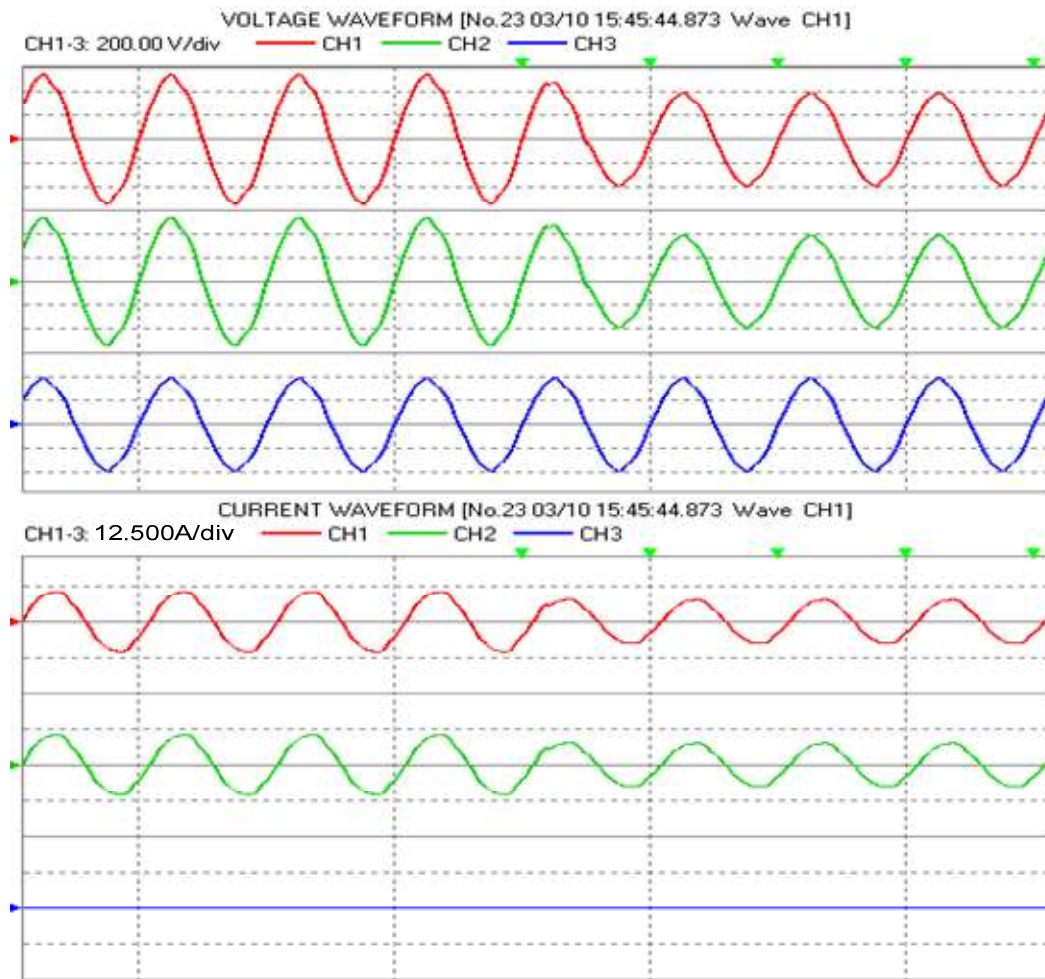


Figure 5.35. Voltage/Current waveforms for three phases to ground fault in both the preferred and alternate feeders

In Figure 5.35, the voltage waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder AB, bus AB and alternate feeder AB voltages, respectively. The current waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder phase A, bus phase A and alternate feeder phase A currents, respectively. It is known that, the preferred feeder is main feeder and it has priority. If there are faults in both the feeders, there must not be any load bus transfer. As shown in Figure 5.35, in case of the faults, the control system of STS has not realized any load bus transferring.

## 6. CUSTOM POWER PARK

### 6.1. Literature Review

In 1992, the concept of the power quality park also mentioned as “Custom Power Park (CPP)” (Hingorani, 1998), “Premium Power Park (PPP)” (Alvarez et al, 2000), “Premium Power Quality Park (PPQP)” (Domijan et al, 2005) and “Custom Power Plaza (CPPL)” (Chung et al, 2004) was introduced by Westinghouse (now Siemens FPQD) in order to meet customer needs. According to this concept, the tenants of an industrial/commercial park would be provided with a guaranteed level of electrical service quality made possible by new custom power devices (Ecm, 2009b).

In the literature, there are various studies about a high quality power park concept apart from CPP (unlike CPP). One of the most important studies is the PPQP (Domijan et al, 2005). The classification of customers is the distinguishing feature of PPQP and CPP. PQP does not classify their customers while CPP classifies the customers, so that each customer can be offered different tariff rates for required power quality needs.

The power park studies are listed below:

In (Hingorani, 1998), types of custom power supply services in a CPP are Solid State Transfer Switches (SSTS), DVR, Standby Generator and Active Filter (AF). The study is a suggested scenario for a Custom Power Park. AF and DVR are combined together. DVR makes the load-side voltage free from voltage dips, distortion and unbalance. Active filter minimizes harmonic content in the common bus bar connection between the two SSTS and the CP bus. The standby generator starts to operate when both feeders are off. This study is a theoretical study.

In (Alvarez et al, 2000), types of custom power supply services in a PPP are DVR, DSTATCOM and Solid State Breaker (SSB). The study is a suggested scenario for a CPP.

In (Domijan et al, 2005), types of custom power supply services in a PPQP are DVR, Fast Transfer Switch (FASTRAN), Solid State VAR Compensator (SSVC).

The study is a simulation for a premium power quality park. The DVR can compensate for voltage sags, voltage harmonics and the balancing of voltage asymmetric systems. FASTRAN is a high-voltage transfer switch that can provide nearly uninterruptible power to critical distribution-served customers who have two independent power sources. SSVC achieves VAr compensation to maintain constant voltage with no flicker.

In (Chung et al, 2004), types of custom power supply services in CPP are DVR, DSTATCOM, SSTC, Phase Controlled Rectifier and APF. DVR compensates voltage sags and swells. DSTATCOM can control the voltage variation by controlling the magnitude and the polarity of injection current. SSTC can protect a sensitive load from the voltage disturbance by quickly transferring the load to a healthy feeder in case of a voltage sag or interruption in the preferred supply feeder. PCR is used to generate the harmonic current. APF is used to compensate current harmonics. The CPP is being constructed with the fund of the National Project in Korea.

In (Ghosh et al, 2004a), types of custom power supply services in a CPP are DSTATCOM, Diesel Generator and STS. DSTATCOM compensates for distortion and unbalance in the load such that a balanced sinusoidal current flows through feeder. DVR compensates for sag/swell and distortion in the supply side voltage such that load voltage remains balanced sinusoid. Diesel Generator supplies the electrical energy for the most sensitive loads during the total line outages. The study is a simulation for a CPP

In (Ghosh, 2005), types of custom power supply services in a CPP are STS, DVR, Diesel Generator and DSTATCOM. STS make a sub-cycle transfer from the preferred feeder to the alternate feeder during a voltage dip or fault in the power park. DVR protects the voltage of the most critical load of the park, the DSTATCOM protects the entire CPP bus voltage and therefore provides distortion-free sinusoidal voltage to all the loads of the park. DG supplies power when a catastrophic failure causes both the incoming feeders to trip. The study is a simulation for a CPP.

As seen from the above paragraphs, there are a few simulation studies related to the CPP. Furthermore, there is no any experimental study related to the CPP.

In this thesis, the following studies are performed:

- Literature survey of the CPP,
- Design of the CP,
- Modeling of the CPP; the custom power devices in the CPP are designed and modeled with new control methods,
- Experimental implementation and verification of the CPP.

## **6.2. Design of Proposed CPP**

### **6.2.1. Configuration of CPP Power Circuit**

The CPP offers a high quality power (grades of A, AA and AAA) to customers and meets the needs of sensitive loads with an Industrial/Commercial power park. Figure 6.1 shows the single line diagram of the CPP including the STS, the DVR, Backup Generator (BG), circuit breakers and loads.

The STS protects sensitive loads against voltage sags and interruptions. The STS ensures a continuous high quality power supply to sensitive loads by transferring, within a time scale of half period, the load from a faulted bus to a healthy one (Anaya et al, 2002). The DVR is connected in series to the distribution circuit by means of a set of single-phase injection transformers and has capable of voltage injection.

The loads in the park are divided into three categories. The Loads L-A, L-AA and L-AAA are balanced and harmonic-free loads. L-AA and L-AAA are sensitive loads and they require almost an uninterrupted electrical power. L-AAA is the most critical load and can not tolerate any disturbances. The CPP has two incoming feeders designed for an improved grounding and insulation. Thus, all loads benefit from a high quality power supply. L-A, L-AA and L-AAA receive the powers QP-A, QP-AA and QP-AAA, respectively, as shown in Figure 6.2.

The following loads/customers may be assumed for the L-A; Computer Hardware Co., Office Building, Shopping Mall. The following loads may be assumed for the L-AA; Software Development Co., Hospital, Data Processing

Center. And, the following loads may be assumed for the L-AAA; Semiconductor Chip Co.; Biotech Co.; Hospital, Data Processing Center.

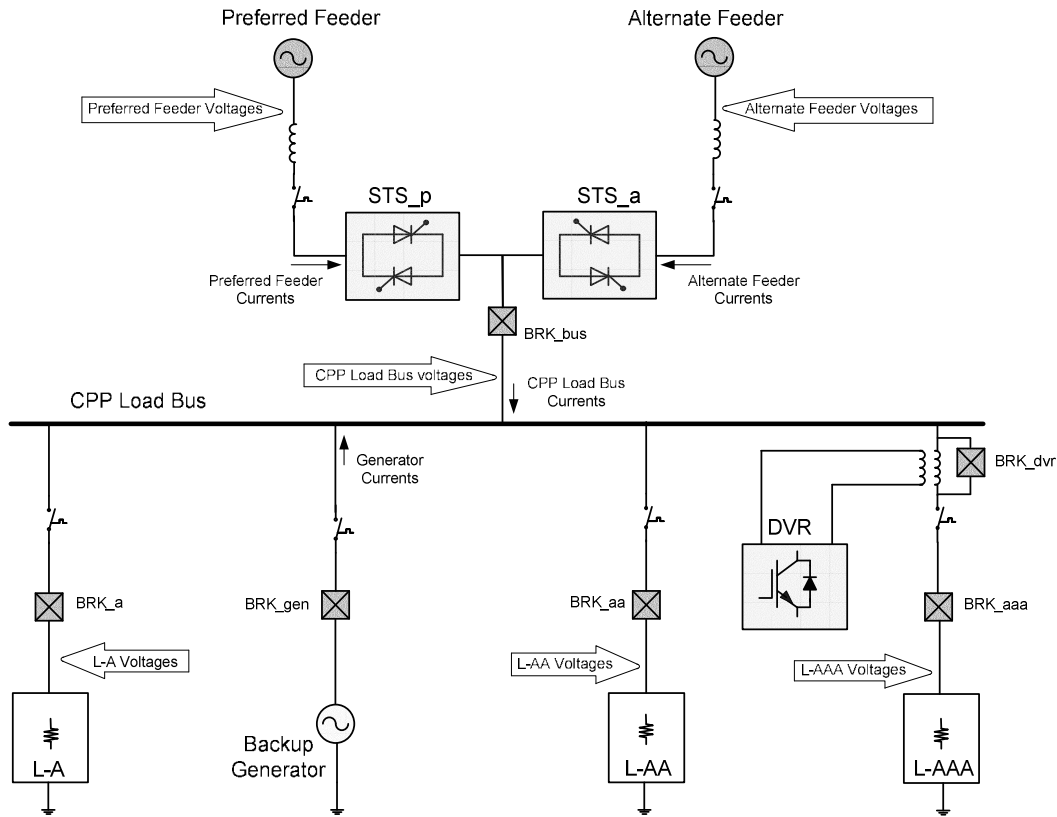


Figure 6.1. The single line diagram of the CPP

The grades of the powers are explained below.

**Qualified Power-A (QP-A):** This grade power requires the use of the STS. The STS reduces the duration of the voltage sag or the interruption to 5-10 milliseconds by rapidly transferring the loads to a healthy feeder.

**Qualified Power-AA (QP-AA):** The grade of QP-AA is over from the grade of QP-A and it receives the benefit of a DG which can come up to about 5-10 seconds in the case of two feeder loss caused by the transmission line faults (faults in both the preferred and alternate feeders).

**Qualified Power-AAA (QP-AAA):** Grade QP-AAA is over grade QP-AA and it receives the benefit of DVR.

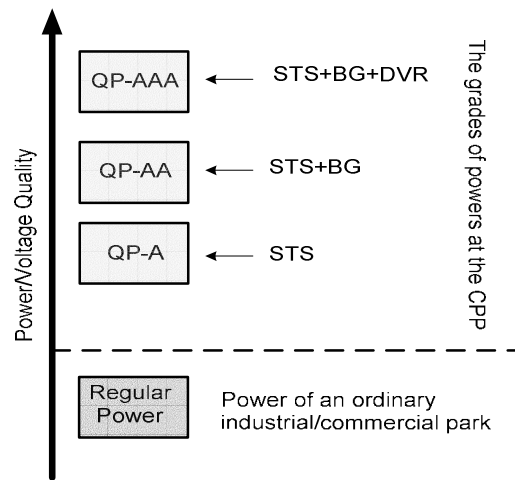


Figure 6.2. The grades of the powers at the CPP

Consequently, the loads of the CPP receive the superior quality power compared to the regular power of ordinary loads. In addition, a more sensitive load gets more power quality in the CPP as shown in Figure 6.2.

The coordination of CP devices and the other equipments in the CPP is clearly described in the following subsection.

### 6.2.2. Configuration of CPP Control System

When different types of devices are used to solve multiple disturbances simultaneously, a coordination of these devices is needed. For the flexibility of the system, some control functions may be centralized (Domijan et al, 2005). On-Off states of the proposed CPP equipments are shown in Table 6.1 and these devices are controlled by the Power Quality Control Centre (PQCC). The distribution system voltage is assumed faultless if the voltage is within  $\pm 10\%$  of the nominal value. CP devices are operated when the system voltage exceeds these limits as given in Table 6.1.

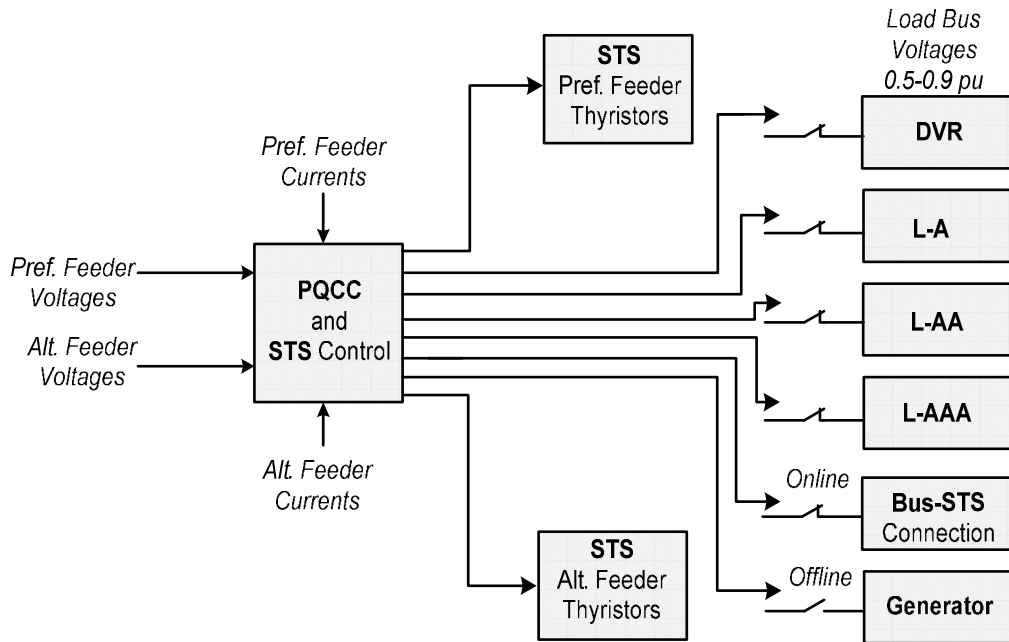


Figure 6.3. Block diagram for the coordination of the CPP equipments

The main CP device is the STS in the power park, and it uses the same controller with PQCC. The DVR is designed to compensate 10-50% sag as in similar studies (Anaya et al, 2002), (Hingorani, 1998), (Naidoo et al, 1999). The STS monitors both the feeder voltages and the DVR monitors the load bus voltages. The online-offline conditions of the loads, the Backup Generator and the DVR are controlled by PQCC via breakers. Block diagram for the coordination of the CPP equipments is shown in Figure 6.3.

The voltage waveforms of both the feeders are monitored by the PQCC and power quality events are captured and managed for a periodic assessment of the service being provided. The voltage sags higher than 50% are considered as an interruption, as given in Table 6.1. The Backup Generator normally stays off and is not connected to the CPP load bus. When both of the feeders are lost (more than 50% sag or interruption), the generator is started-up immediately and connected to the CPP load bus. It should take 10 seconds (Condition 5 in Table 6.1) for the generator to come on line and pick up the loads of both L-AA and L-AAA. L-AA and L-AAA experience power loss only for 10 seconds during this event. However, only L-A does not receive power until one of the feeders is back in service (condition 6).

Table 6.1. Fault Scenarios for the CPP

| Conditions                                                                                                             | STS_p | STS_a | DVR | BG  | L-A | L-AA | L-AAA |
|------------------------------------------------------------------------------------------------------------------------|-------|-------|-----|-----|-----|------|-------|
| 1. Less than 10% sag on preferred and alternate feeder (normal operation) line to line voltages                        | On    | Off   | Off | Off | On  | On   | On    |
| 2. Less than 10% sag on preferred feeder, between 10-90% sag or interruption on alternate feeder line to line voltages | On    | Off   | Off | Off | On  | On   | On    |
| 3. Between 10-90% sag or interruption on preferred feeder, less than 10% sag on alternate feeder line to line voltages | Off   | On    | Off | Off | On  | On   | On    |
| 4. Between 10-50% sag on preferred and alternate feeder line to line voltages                                          | On    | Off   | On  | Off | On  | On   | On    |
| 5. More than 50% sag or interruption on preferred and alternate feeder line to line voltages during start-up delay     | On    | Off   | Off | Off | Off | Off  | Off   |
| 6. More than 50% sag or interruption on preferred and alternate feeder line to line voltages after start-up delay      | On    | Off   | Off | On  | Off | On   | On    |

When the Condition 4 occurs, DVR protects L-AAA against voltage disturbances. This is the distinguishing feature of L-AAA from L-AA. During this condition, L-A, L-A2 and L-AA are subject to these disturbances. During Condition 3, CPP voltage remains at desired values by transferring the entire loads to an alternate feeder. However, for the conditions 1 and 2, there is no need to transfer the loads because the CPP load bus voltage remains within desired values of nominal voltage (EN50160, 1999).

The most important part of the PQCC is the sag/interruption (fault) detection unit. In the PQCC, the fault detection unit of the STS mentioned in Chapter 5 is used.

### 6.3. Simulation Study of Proposed CPP

#### 6.3.1. Simulation Model of Proposed CPP

The designed CPP is modeled and simulated by using PSCAD/EMTDC program. The simulation model of CPP control system is shown in Figure 6.4. The simulation model of CPP Power Circuit is shown in Figure 6.5. The details of proposed CPP power circuit are mentioned in Section 6.2.1. Table 6.2 gives the parameters of the simulated CPP system shown in Figures 6.4 and 6.5.

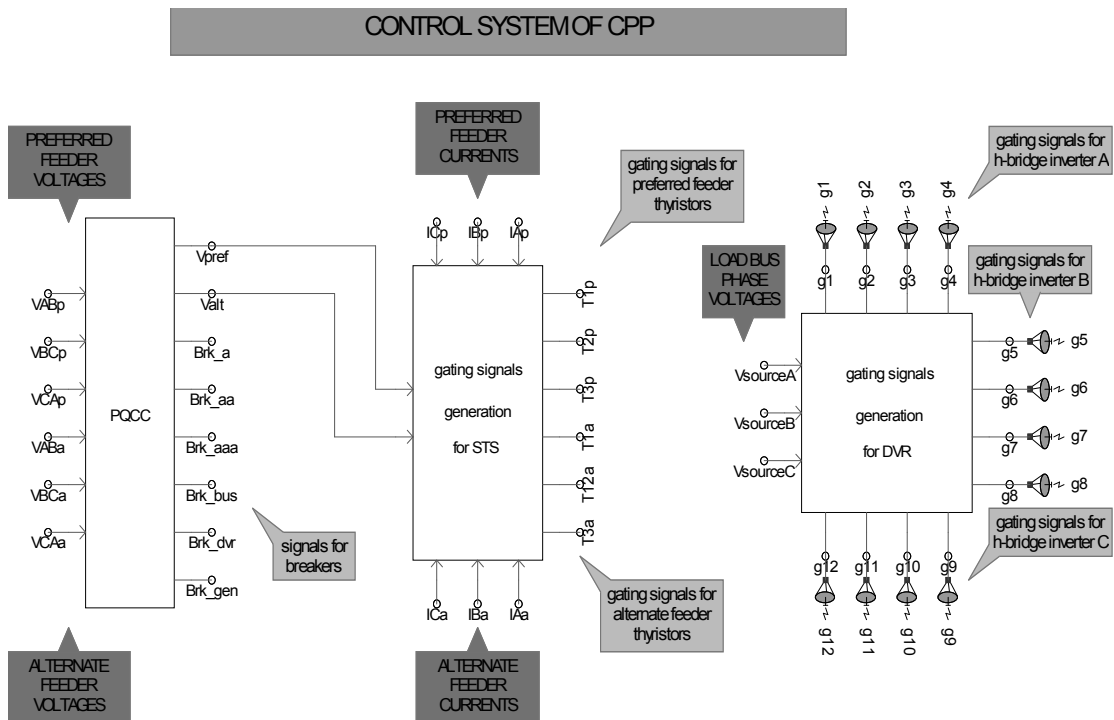


Figure 6.4. Simulation model of proposed CPP control system

Table 6.2. Parameters of simulated CPP system

| Description                | Value / profile  |
|----------------------------|------------------|
| Static Transfer Switch     | STS, 5 kVA       |
| Dynamic Voltage Restorer   | DVR, 1.5 kVA     |
| Loads                      | L-A, L-AA, L-AAA |
| Sample time for simulation | 25 $\mu$ s       |

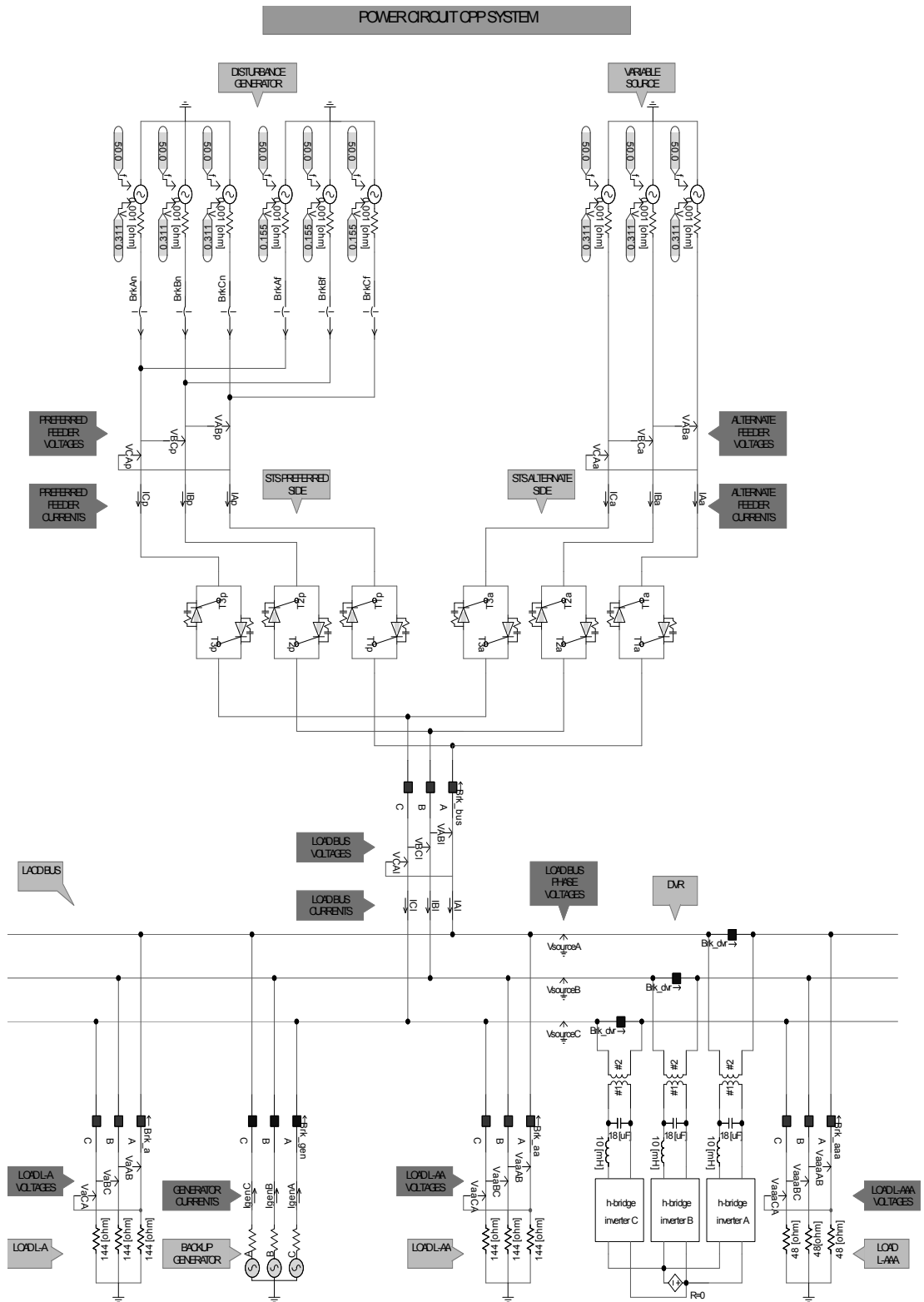


Figure 6.5. Simulation model of CPP power circuit

### 6.3.2. Simulation Results for Proposed CPP

#### 6.3.2.1. Simulation Results for the Conditions 1 and 2

Figures 6.6 and 6.7 show the simulation results for the Conditions 1 and 2 that the preferred feeder voltages are at 91% of nominal. Furthermore, an interruption occurs in alternate feeder at time 400 ms. As seen from the figures, the loads are fed by preferred feeder according to PQCC fault scenarios.

Figure 6.6 shows the waveforms of the preferred feeder, alternate feeder and load bus line to line voltages.

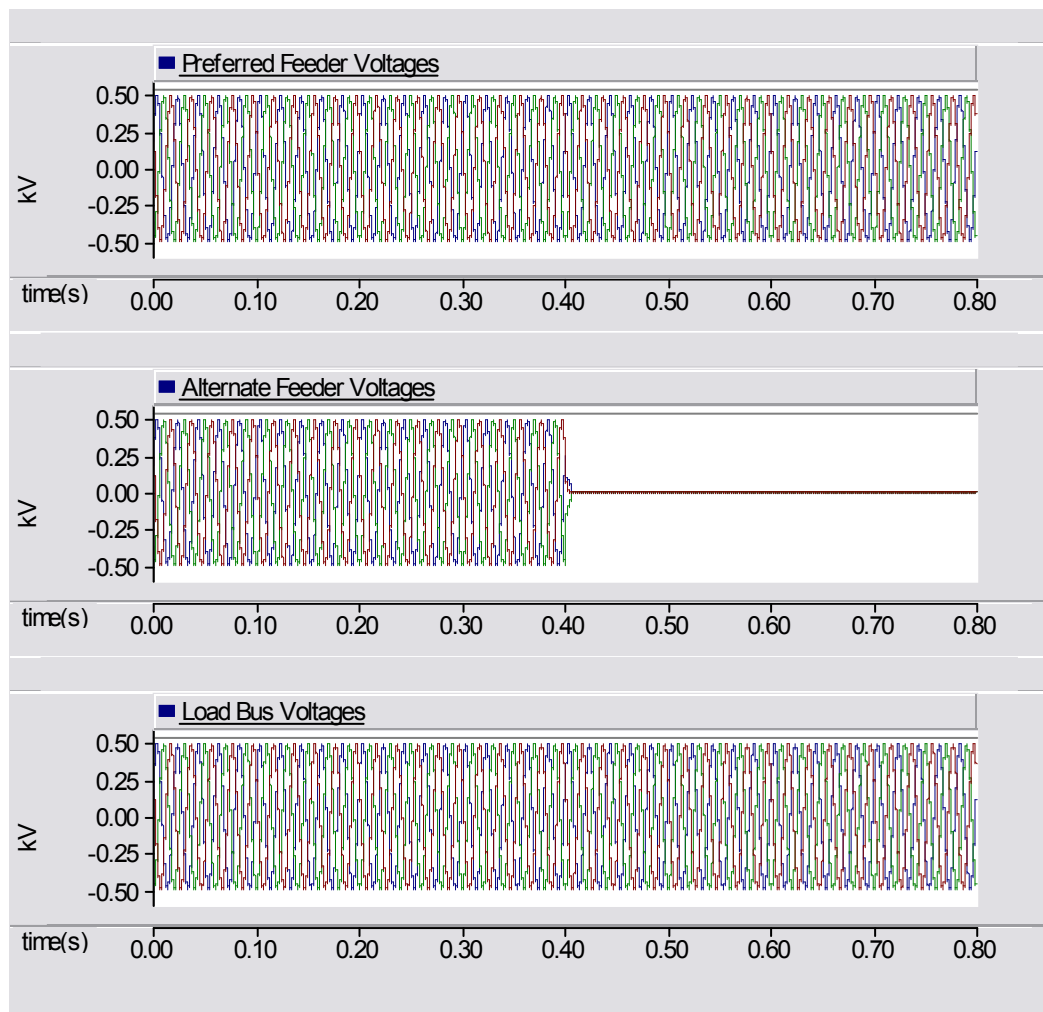


Figure 6.6. Voltage waveforms for the Conditions 1 and 2

Figure 6.7 shows the waveforms of the preferred feeder, alternate feeder and load bus currents.

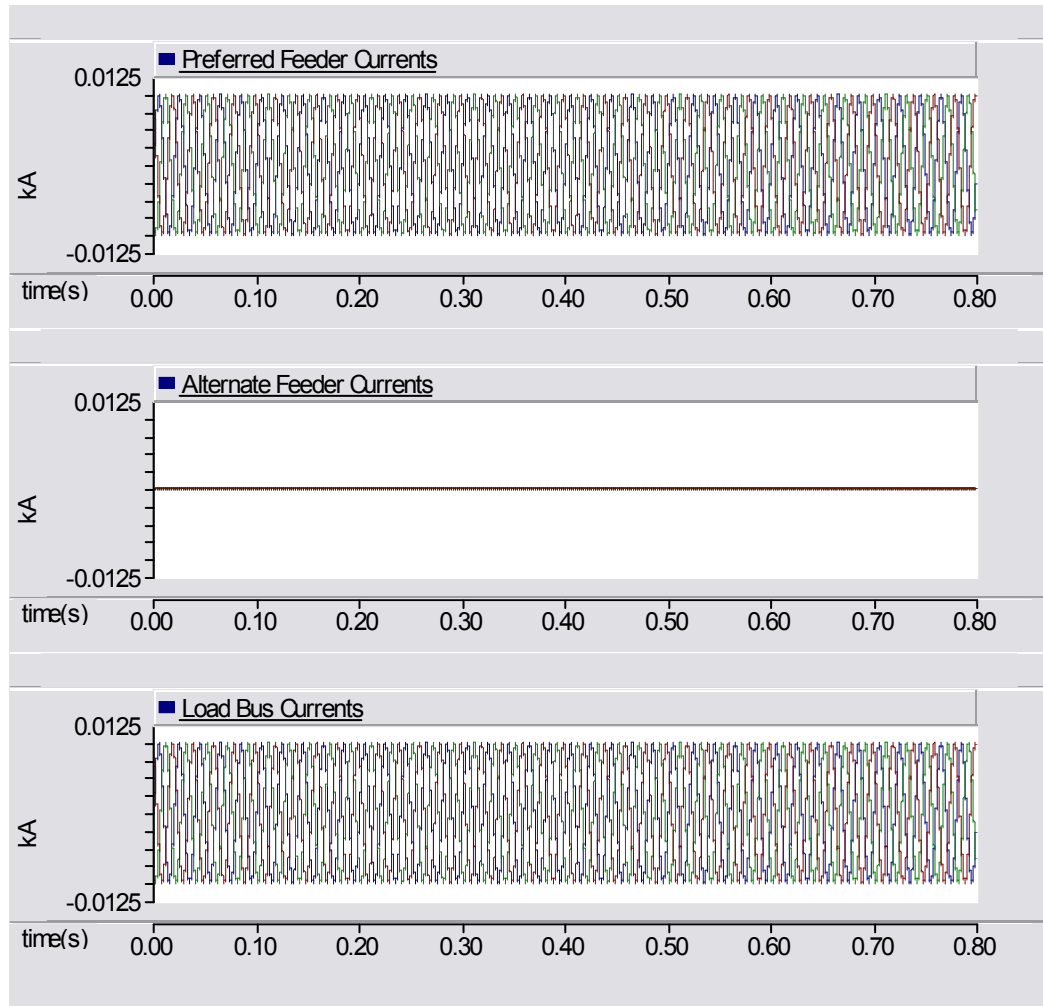


Figure 6.7. Currents waveforms for the Conditions 1 and 2

### 6.3.2.2. Simulation Results for the Condition 3

Figures 6.8 and 6.9 show the simulation results for 30 % sags on all line to line voltages caused by three phase to ground fault in the preferred feeder. The voltage sags start at time 200 ms and end at time 550 ms.

As can be seen from the figures, when the voltage sag is detected, the STS transfer and gating logic is waited to zero current transitions for each phase. The load bus is not affected by the sags on preferred feeder voltages.

Figure 6.8 shows the waveforms of the preferred feeder, alternate feeder and load bus line to line voltages.

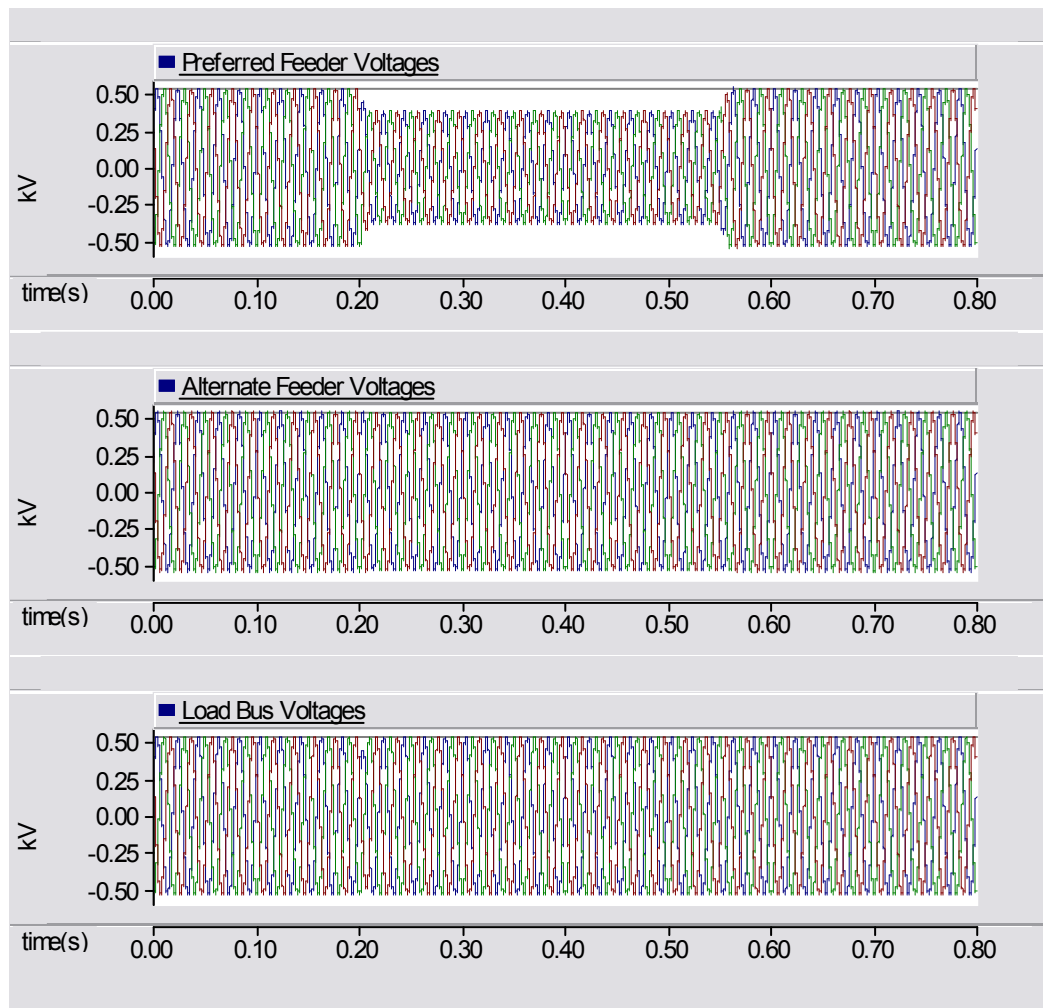


Figure 6.8. Voltage waveforms for the Condition 3

Figure 6.9 shows the waveforms of the preferred feeder, alternate feeder and load bus currents.

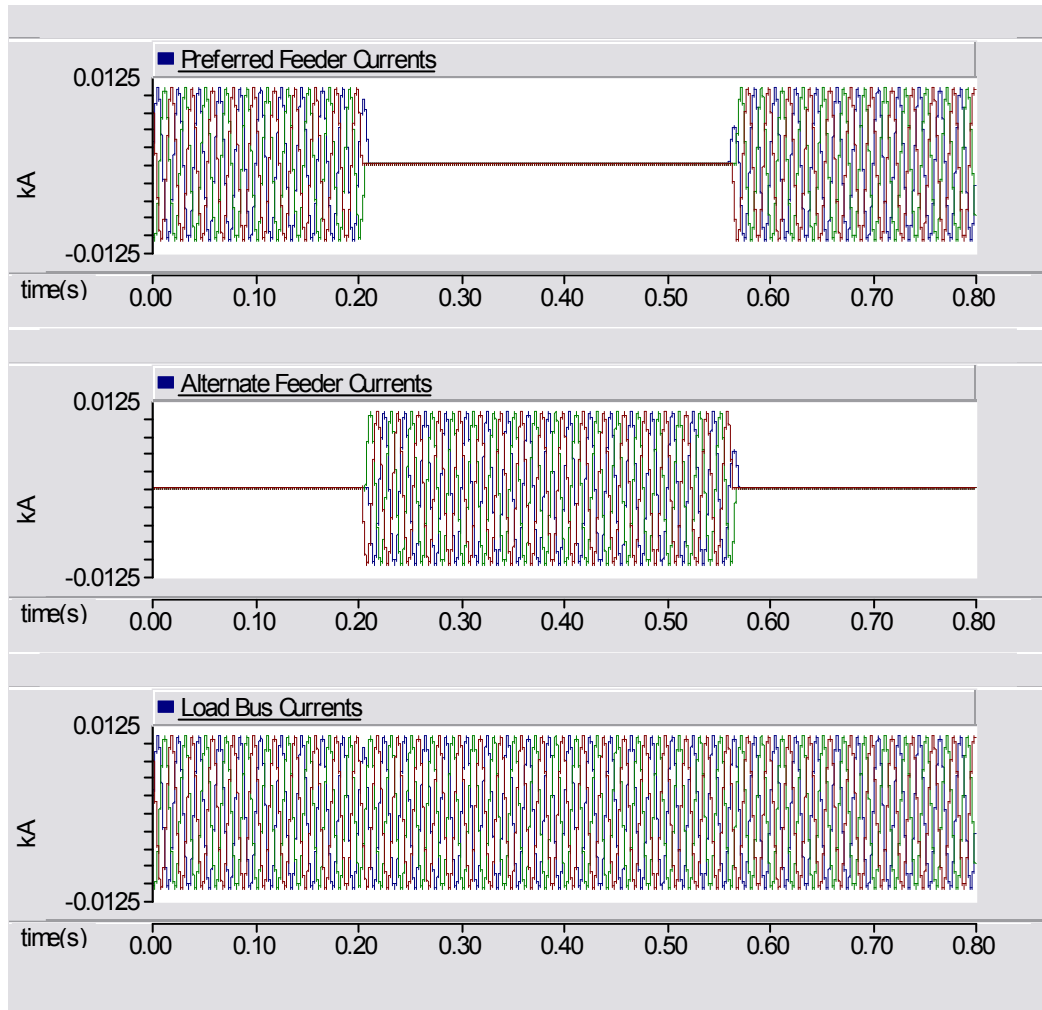


Figure 6.9. Current waveforms for the Condition 3

#### 6.3.2.3. Simulation Results for the Condition 4

Figures 6.10 and 6.11 show the simulation results for 30 % sags on all line to line voltages caused by three phase to ground faults in both the preferred and alternate feeders. The voltage sags start at time 200 ms and end at time 550 ms.

Figure 6.10 shows the waveforms of the preferred feeder, alternate feeder and load bus line to line voltages.

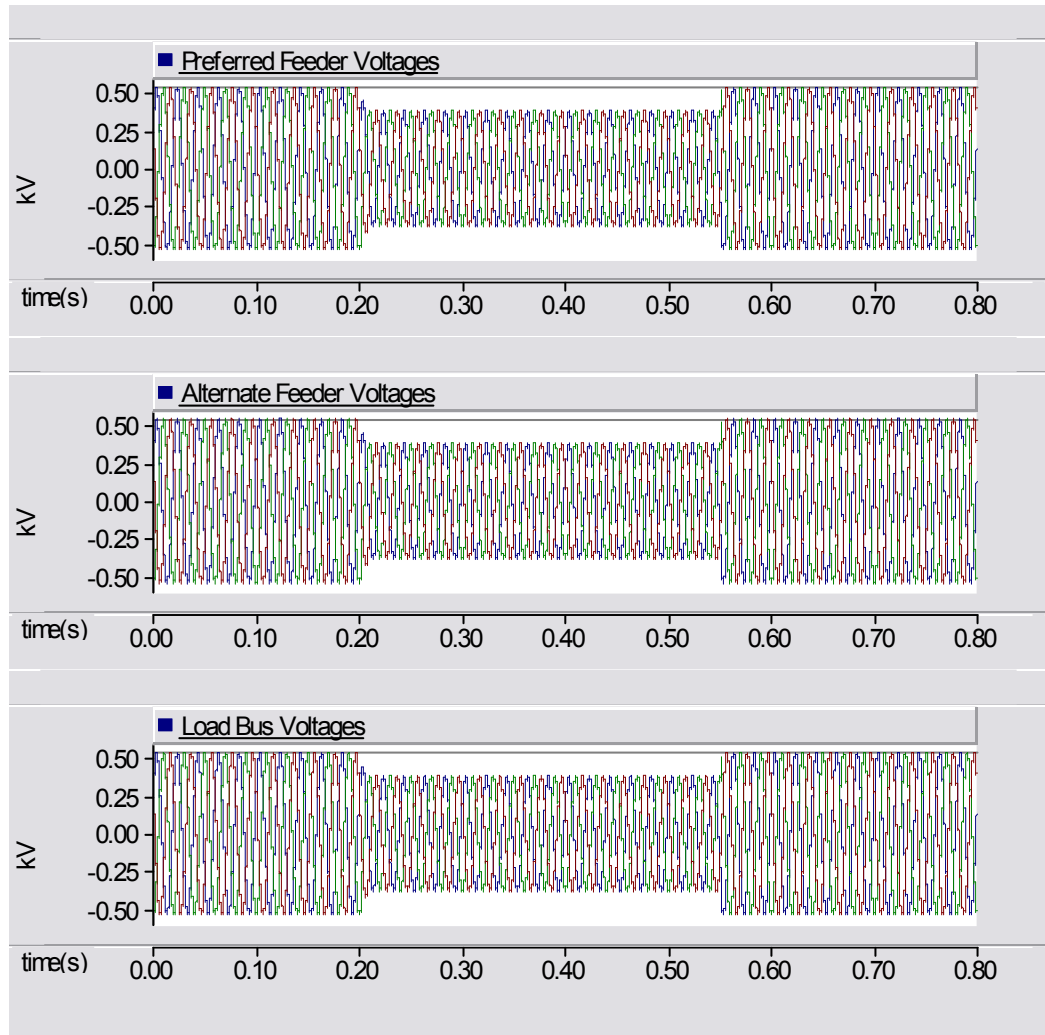


Figure 6.10. Voltage waveforms for the Condition 4

Figure 6.11 shows the operating of the DVR in the CPP in case both the feeders are faulty. This scenario indicates the Condition 4. The loads are fed by preferred feeder, but the most sensitive load Load-AAA is protected by the DVR against the voltage sag.

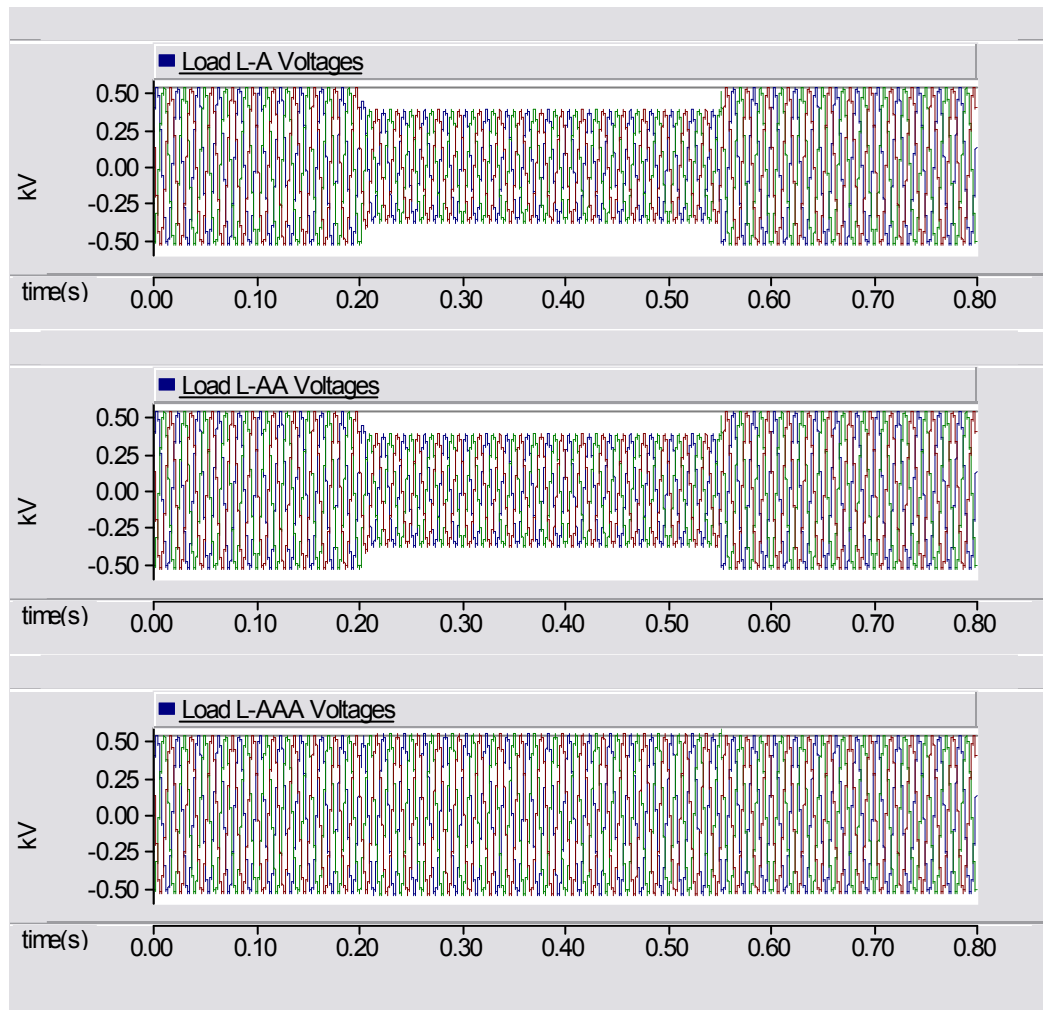


Figure 6.11. Voltage waveforms of the loads for the Condition 4

#### 6.3.2.4. Simulation Results for the Conditions 5 and 6

Figures 6.12 and 6.13 show the simulation results for interruption (96 % sags) on all line to line voltages caused by three phase to ground faults in both the preferred and alternate feeders. The voltage sags start at time 150 ms. Figures show the operating of the Backup Generator in the CPP in case both the feeders are lost. This scenario indicates the Conditions 5 and 6.

Figure 6.12 shows the waveforms of the preferred feeder, alternate feeder, L-A, L-AA and L-AAA line to line voltages.

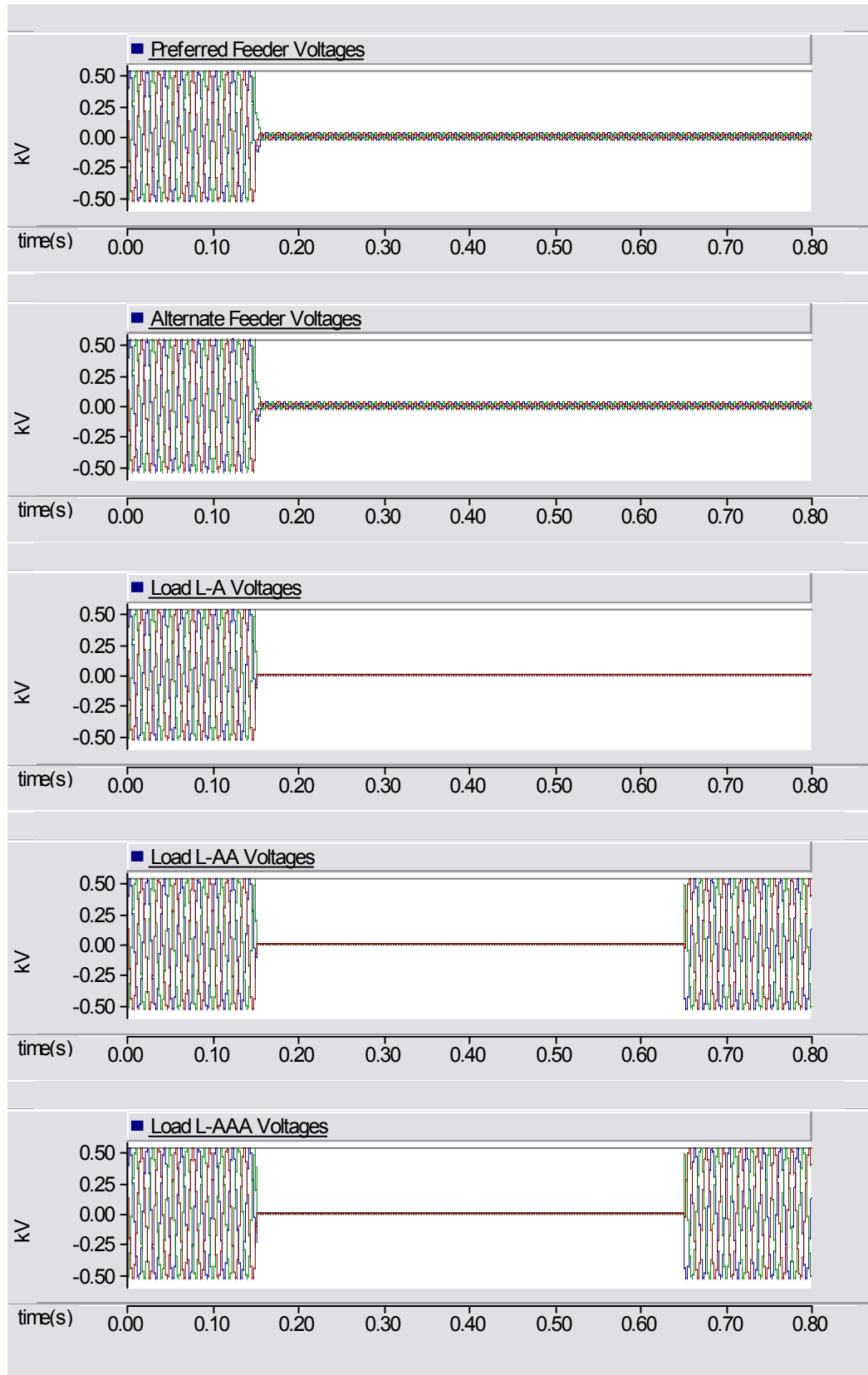


Figure 6.12. Voltage waveforms of for the Conditions 5 and 6

Figure 6.13 shows the waveforms of the preferred feeder, alternate feeder, load bus and generator currents. As seen from the figures, The time delay required for the generator startup is selected as 500 ms in simulation study in order to see clearly. All the loads are offline during the startup delay, after the startup, the loads L-AA and L-AAA are online and fed by the backup generator.

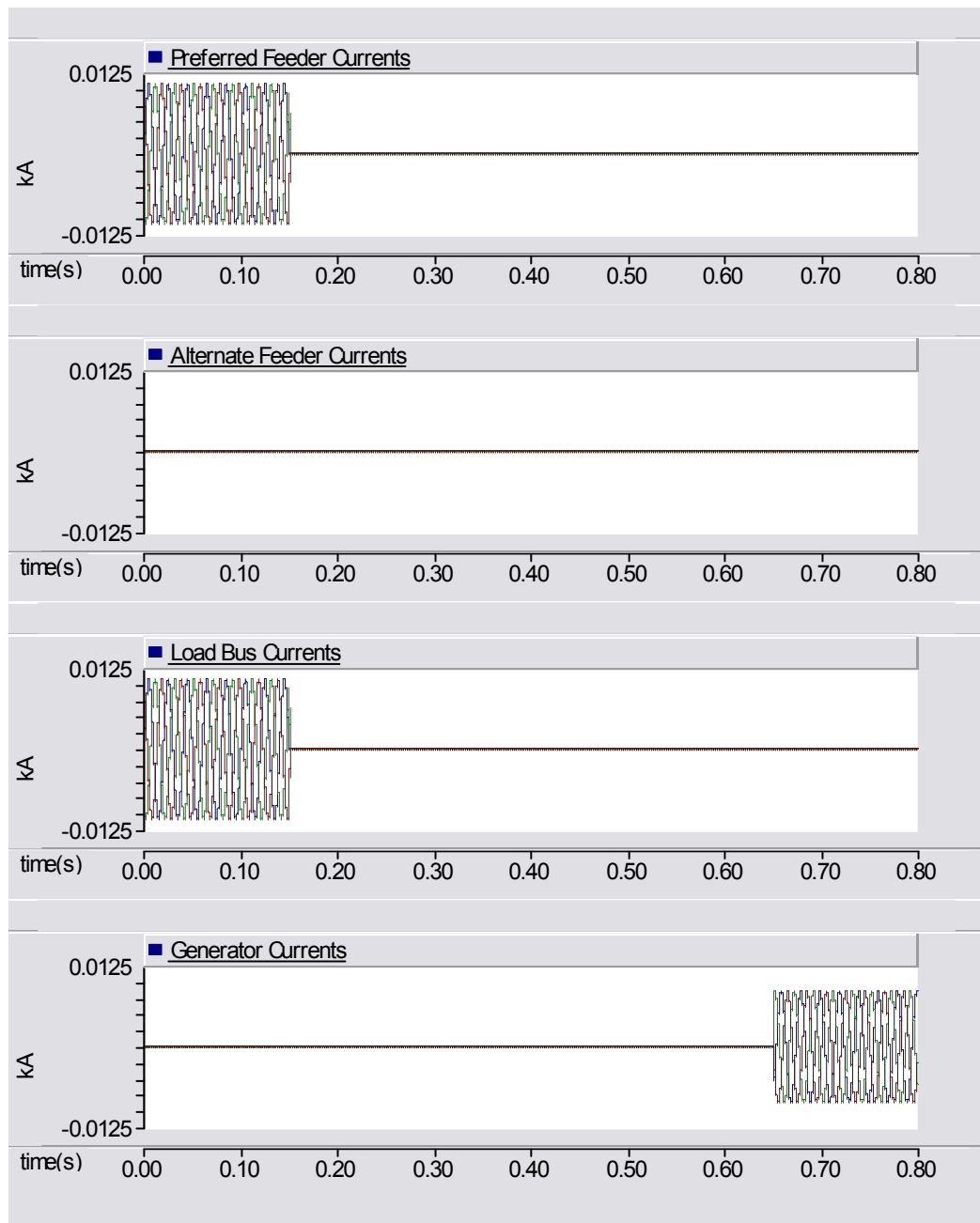


Figure 6.13. Current waveforms of for the Conditions 5 and 6

#### 6.4. Experimental Setup of Proposed CPP

The designed and modeled CPP with the proposed configuration and proposed control methods is constructed experimentally. The circuit diagram for the experimental setup of the CPP is shown in Figure 6.14. The summarized data for this circuit diagram is given in Table 6.3. For the experimental setup, firstly an experimental panel is constructed. The STS and DVR hardware prototypes are integrated with this panel. A DSP and a control card are also used for the coordination of the loads, STS and DVR. The experimental panel and control cards are presented in the following sections.

Table 6.3 Data for the experimental CPP

| Symbol in Figure 6.14                       | Description                                                     | Value / profile           |
|---------------------------------------------|-----------------------------------------------------------------|---------------------------|
| SR <sub>p</sub> and SR <sub>a</sub>         | Preferred and Alternate AC Sources                              | Ph-Ph 380 V               |
| STS <sub>p</sub> and STS <sub>a</sub>       | Preferred and Alternate Side thyristors for STS                 | -----                     |
| Disturbance Generator                       | Sag/Interruption Generator                                      | Ph-Ph 0-380 V             |
| Z <sub>pref</sub> , Z <sub>alt</sub>        | Pref. And Alt. Feeder Impedances                                | Negligible                |
| VT                                          | Voltages Measurements                                           | -----                     |
| CT                                          | Currents Measurements                                           | -----                     |
| BRK                                         | Contactors as Circuit Breakers, Normally Open or Normally Close | -----                     |
| Z <sub>a</sub>                              | Load L-A Impedance / per Phase                                  | Resistive 144 $\Omega$    |
| Backup Gen                                  | Backup Generator                                                | Ph-Ph 380 V               |
| Z <sub>aa</sub>                             | Load L-AA Impedance / per Phase                                 | Resistive 144 $\Omega$    |
| TR <sub>inj</sub>                           | Injection Transformer                                           | Single phase, 1:1, 1 kVA  |
| C <sub>filter</sub> and L <sub>filter</sub> | Capacitor and Inductor of Filter                                | 18 $\mu$ F and 10 mH      |
| VSI <sub>DVR</sub>                          | Voltage Source Inverter of DVR                                  | 1-phase H-bridge inverter |
| DC                                          | DC Source of DVR                                                | 155 V                     |
| Z <sub>aaa</sub>                            | Load L-AAA Impedance / per Phase                                | Resistive 48 $\Omega$     |
| -----                                       | Sample Time CPP Control                                         | 33 $\mu$ s                |

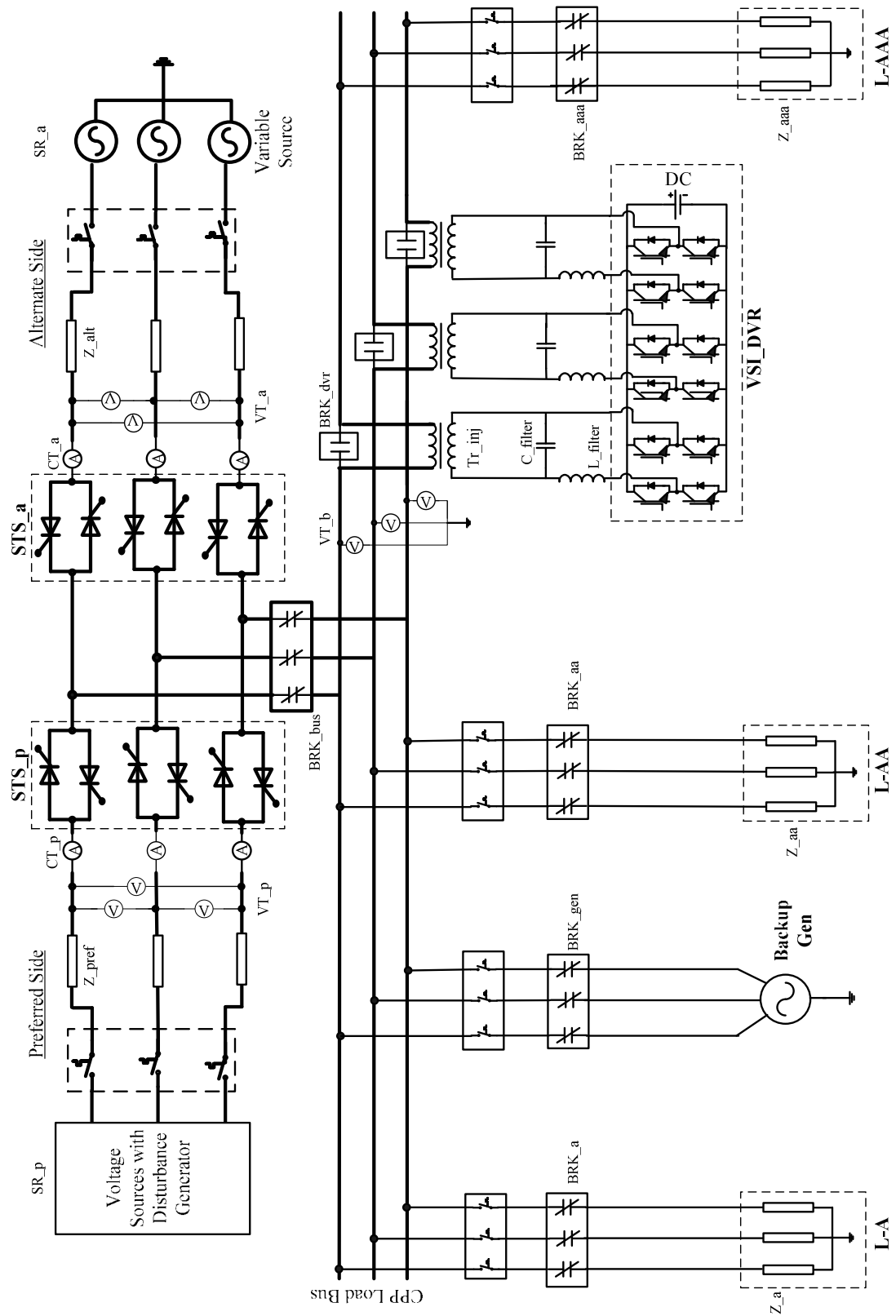


Figure 6.14. Circuit diagram of the experimental CPP

#### 6.4.1. Experimental Panel for the Proposed CPP System

The construction stages for the experimental panel of the CPP are shown in Figure 6.15. The first four pictures show the construction processes of the panel and the last two pictures show the major parts of experimental hardware prototypes of the DVR (number 5) and the STS (number 6).



Figure 6.15. The construction stages for the experimental panel of the CPP

The experimental panel of CPP with the STS and DVR are as indicated in Figure 6.16 after the construction.

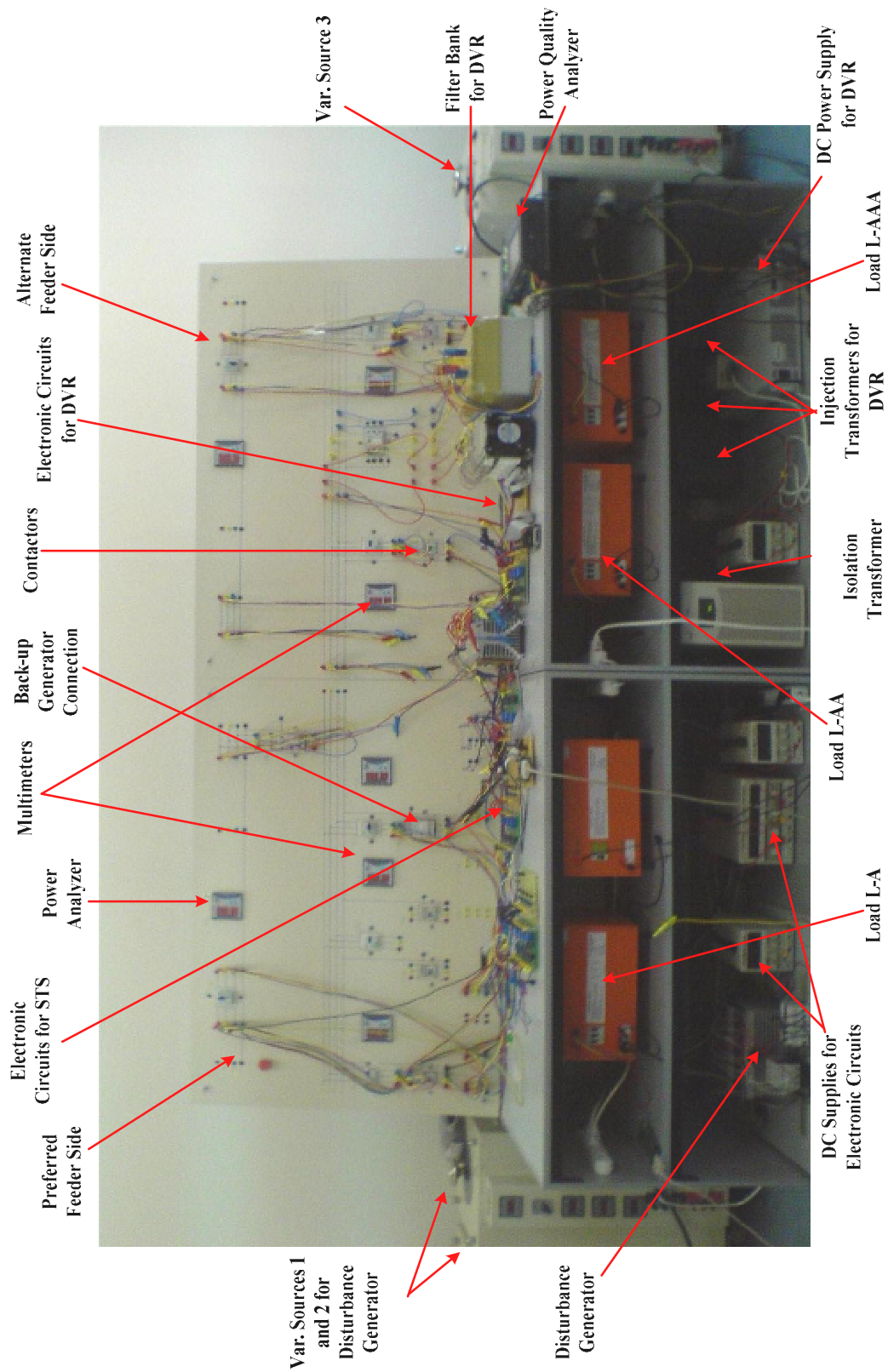


Figure 6.16. The experimental panel of the CPP

### 6.4.2. Control Card for the Proposed CPP System

The coordination of the park equipments such as STS, DVR, Backup Generators, Loads are achieved by the DSP. The DSP used in STS is also used for this coordination. A control card is used for online-offline conditions of the Loads, the Backup Generator and the CP devices. This card controls the relays. In this way, the contactors connected to the loads are controlled. The circuit diagram and picture of the control card are shown in Figure 6.17 and 6.18, respectively.

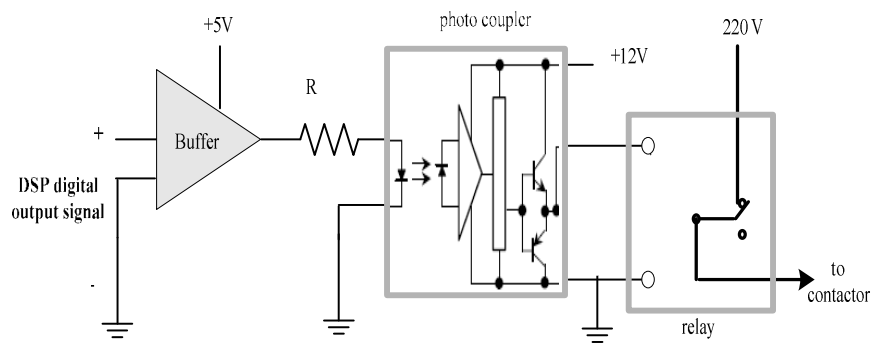


Figure 6.17. Circuit diagram for the control card of the CPP

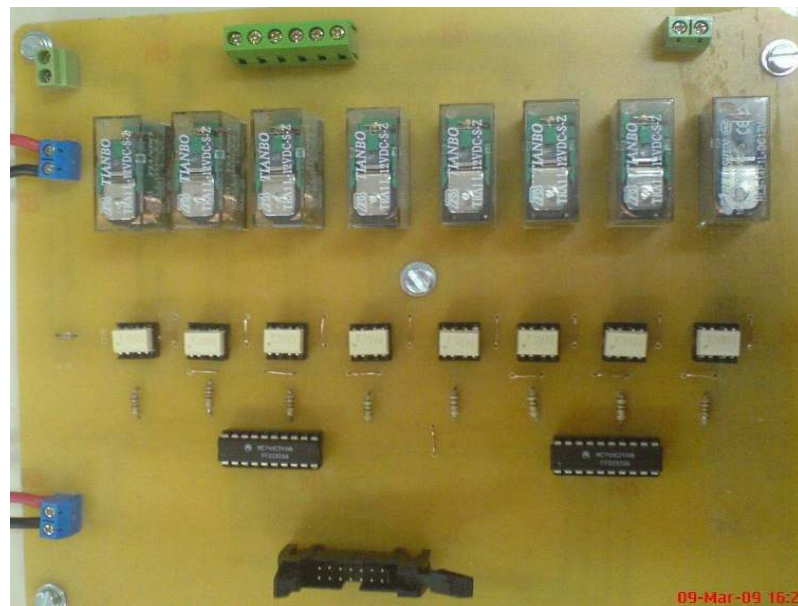


Figure 6.18. The control card for offline-online conditions of the CPP equipments

### 6.5. Experimental Results of the Proposed CPP

In this section, the voltage quality improvements with proposed CPP are presented in case of various faults. The data for the experimental setup are summarized in Table 6.3 given in Section 6.4.

The presented experimental results for various fault conditions are listed below.

i) Less than 10% sag on preferred and alternate feeder (normal operation) line to line voltages

ii) Less than 10% sag on preferred feeder, between 10-90% sag or interruption on alternate feeder line to line voltages

iii) Between 10-90% sag or interruption on preferred feeder, less than 10% sag on alternate feeder line to line voltages

iv) Between 10-50% sag on preferred and alternate feeder line to line voltages

v) More than 50% sag or interruption on preferred and alternate feeder line to line voltages during start-up delay

vi) More than 50% sag or interruption on preferred and alternate feeder line to line voltages after start-up delay

These fault scenarios are also presented in Table 6.1 given in Section 6.2.

#### 6.5.1. Experimental Results for Operating of the STS and DVR together in the Proposed CPP

Figures 6.19, 6.20, 6.21, 6.22, 6.23, 6.24 and 6.25 show the experimental results related with the operating of the STS and DVR together in the CPP (Conditions 1-4 in Table 6.1 or experimental results list). In this experiments, various fault scenarios are examined between the time interval 12:08:55-12:09:51. These fault scenarios have been caused various single phase and/or three phase 30% voltage sags. In these Figures 6.19-6.25; The voltage waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder line to line AB, the alternate feeder line to line AB, and the Load-AAA line to line AB voltages, respectively. The current waveforms of

Ch1, Ch2 and Ch3 indicate the preferred feeder phase A, the alternate feeder phase A and the Load-AAA phase A currents, respectively.

The normal operating condition that the loads are fed by preferred feeder is shown in Figure 6.19. Both the feeders are healthy. This scenario indicates the Condition 1 in CPP fault scenarios.

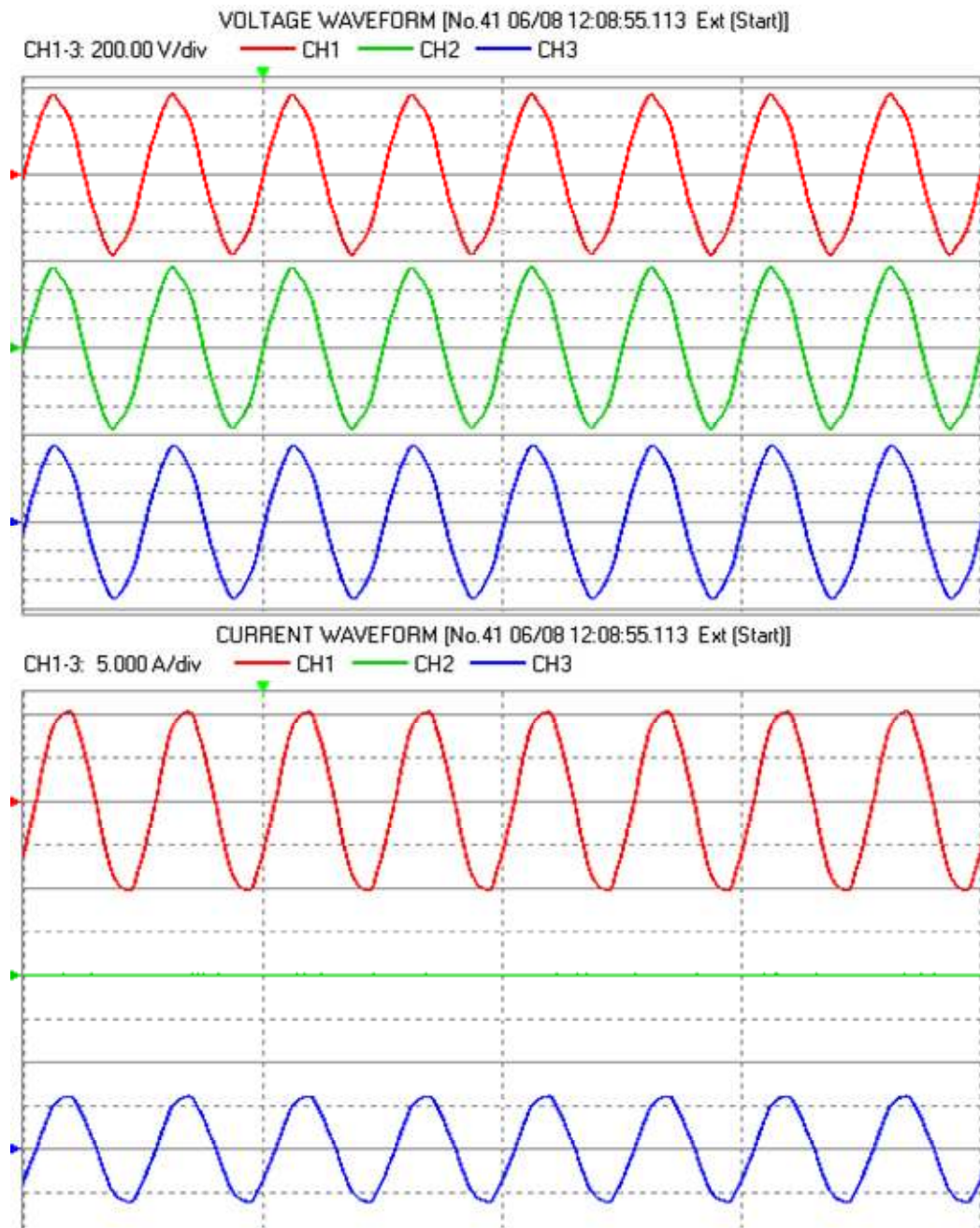


Figure 6.19. Experimental results for the Condition 1

The operating of the STS in the CPP is shown in Figure 6.20. The alternate feeder is healthy and a 30% voltage sag occurs on line to line voltages of preferred feeder. This scenario indicates the Condition 3. The loads are transferred to alternate feeder after the sag detection.

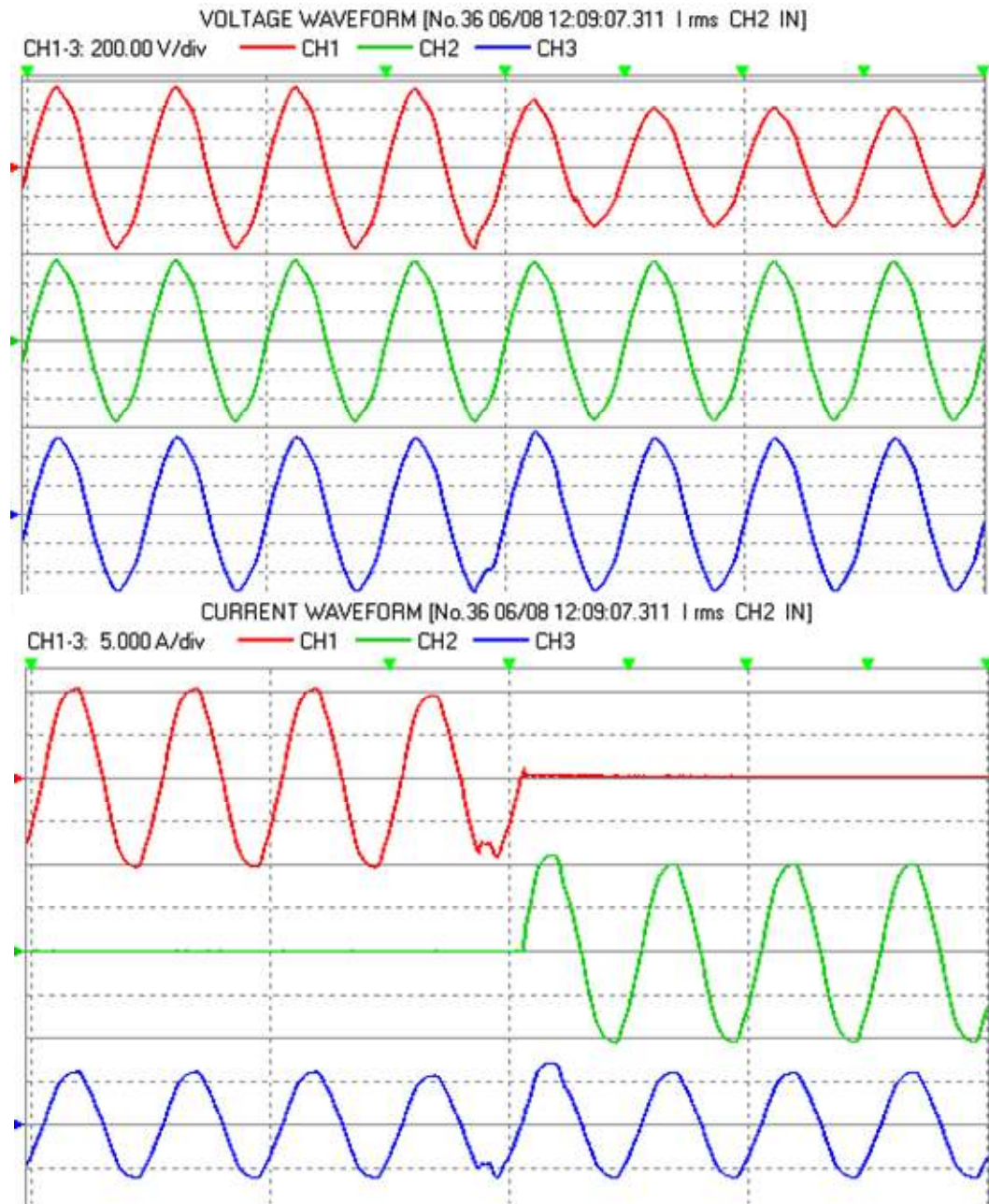


Figure 6.20. Experimental results for the Condition 3 during sag starting

Figure 6.21 shows the operating of the STS in the CPP in case the sag ending. This scenario indicates the Condition 1. The loads are transferred to preferred feeder after the ending of sag.

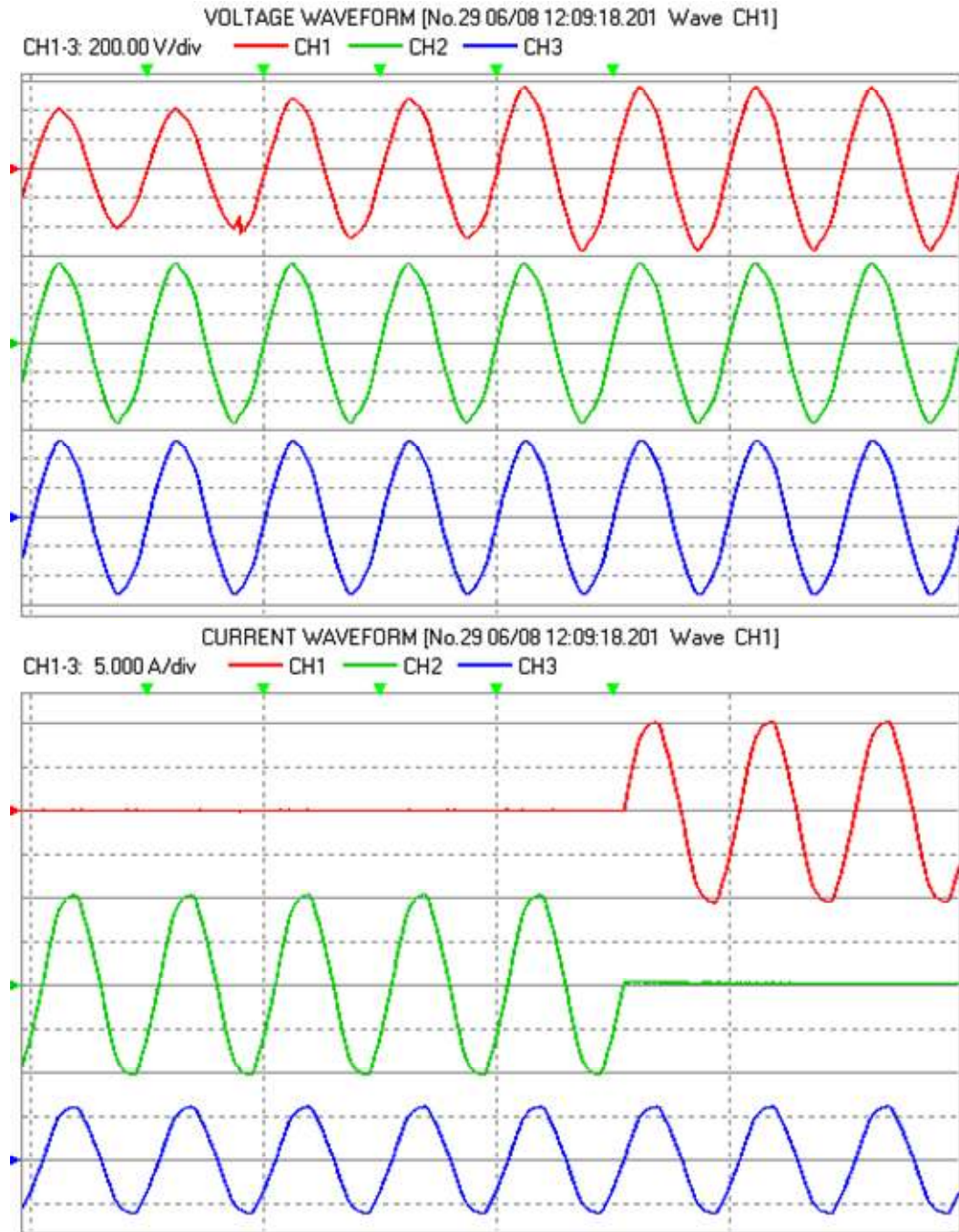


Figure 6.21. Experimental results for the Condition 3 during sag ending

In Figure 6.22, the preferred feeder is healthy, but voltage sag occurs o line to line voltages of alternate feeder. This scenario indicates the Condition 2. The loads are fed by preferred feeder.

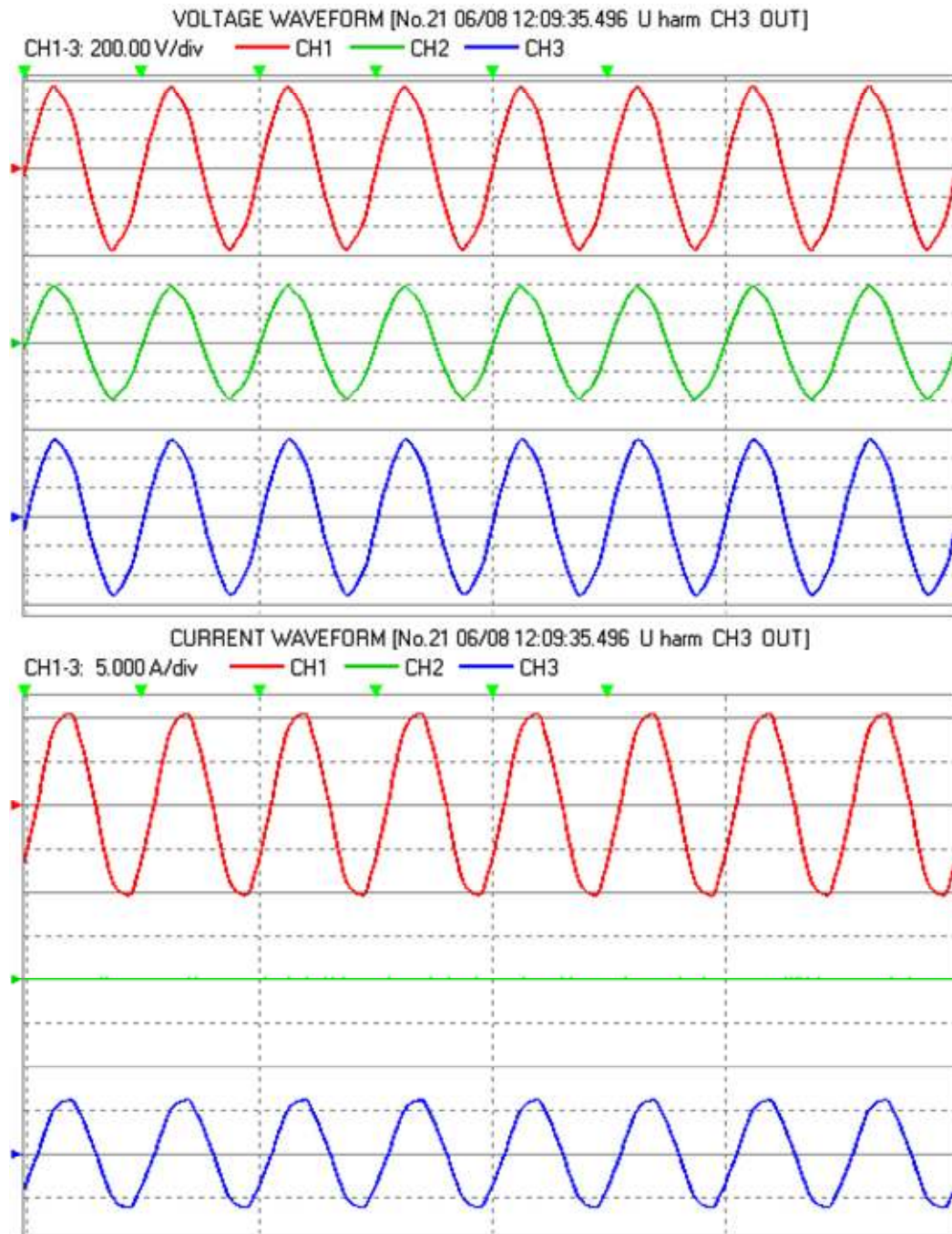


Figure 6.22. Experimental results for the Condition 2

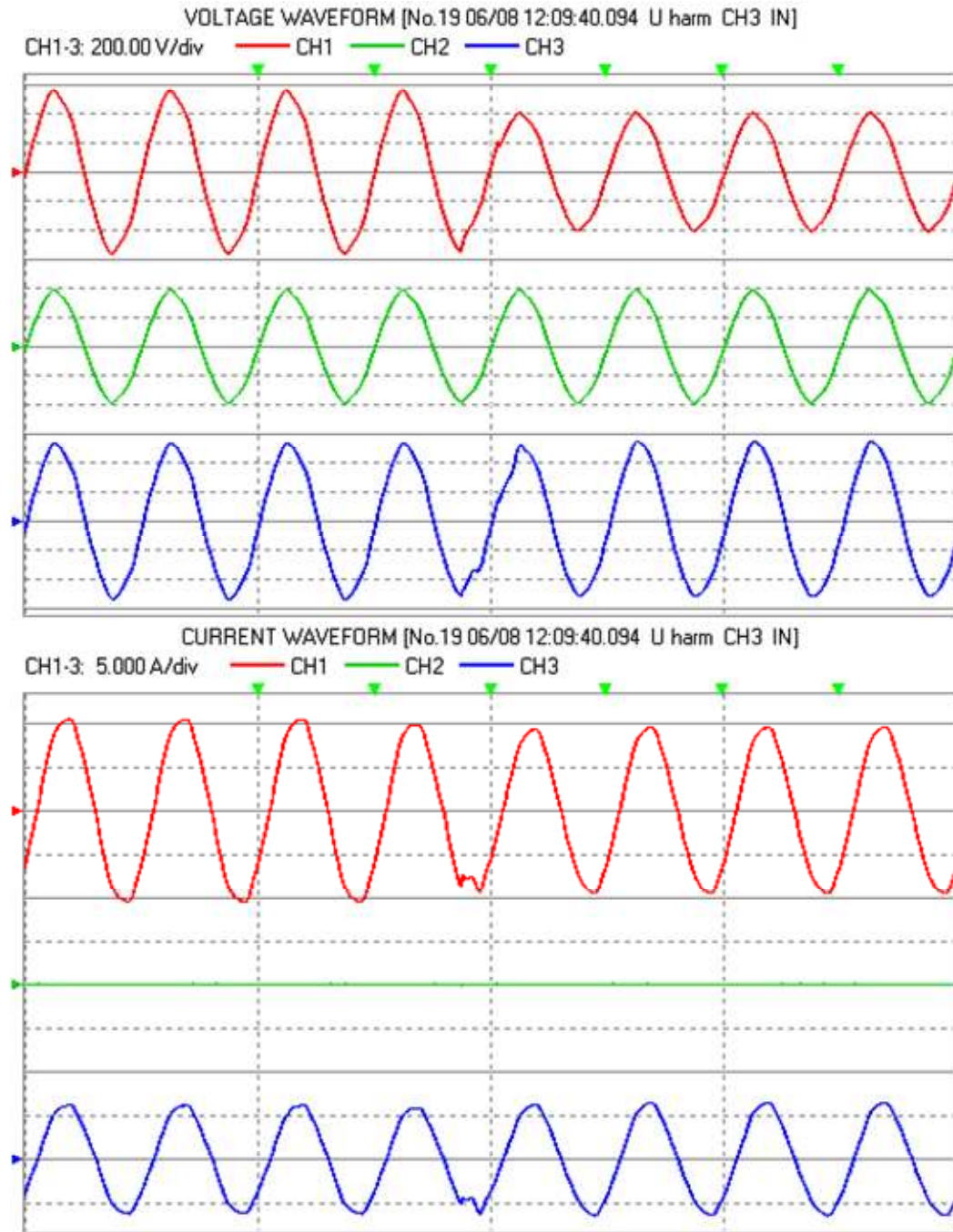


Figure 6.23. Experimental results for the Condition 4 during sag starting

The operating of the DVR in the CPP in case both the feeders are faulty is shown in Figure 6.23. This scenario indicates the Condition 4. The loads are fed by preferred feeder, but the most sensitive load Load-AAA is protected by the DVR against the voltage sag. At normal operating conditions, the THDs of preferred

feeder, alternate feeder and Load-AAA voltages are 2.79%, 2.80% and 2.44%, respectively. In case the Condition 4, the THD of Load-AAA voltages are 3.34%.

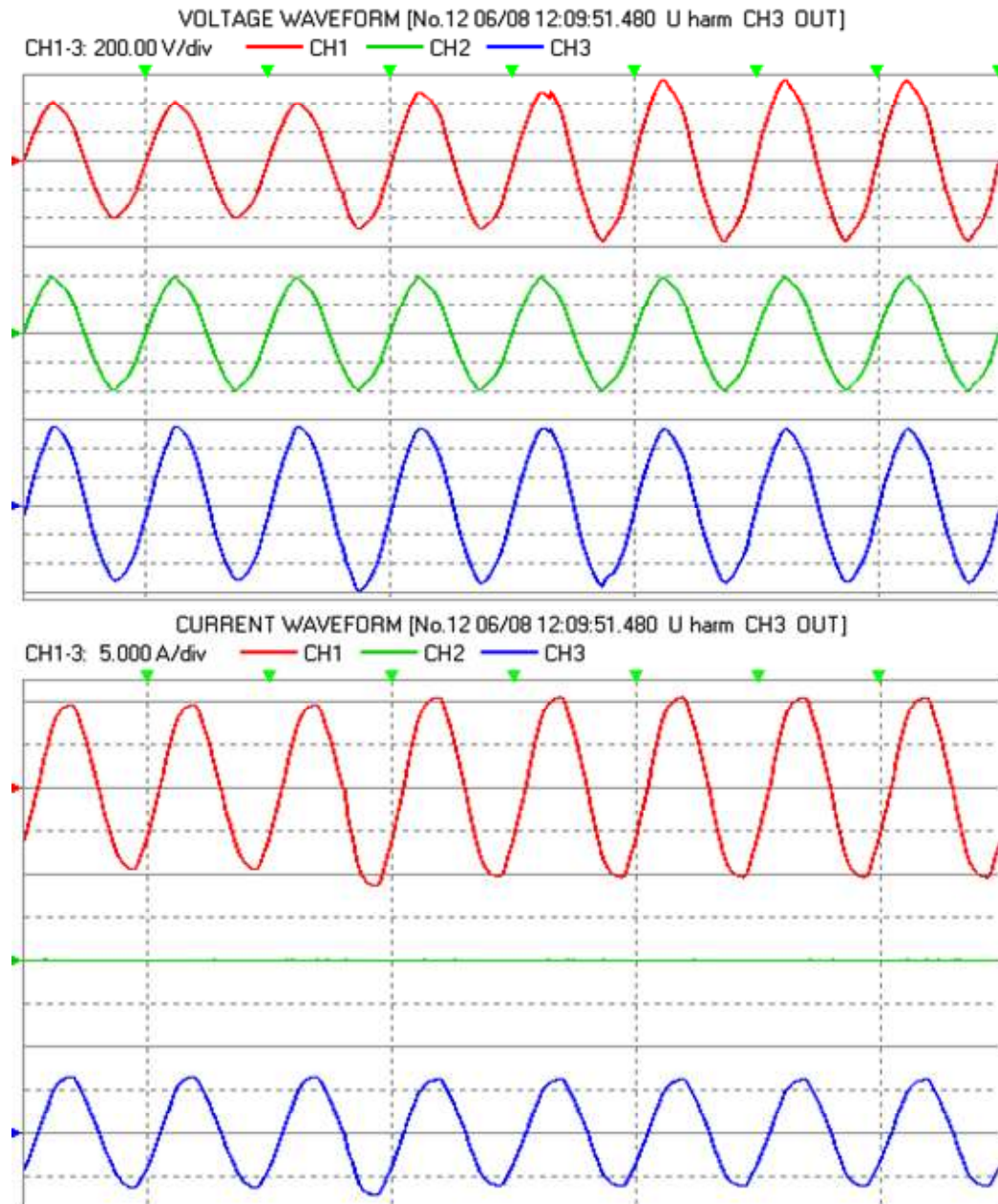


Figure 6.24. Experimental results for the Condition 4 during sag ending

Figure 6.24 shows waveforms for the sag ending on preferred feeder line to line voltages. This scenario indicates the normal operation condition. The DVR is not needed to work in this condition.

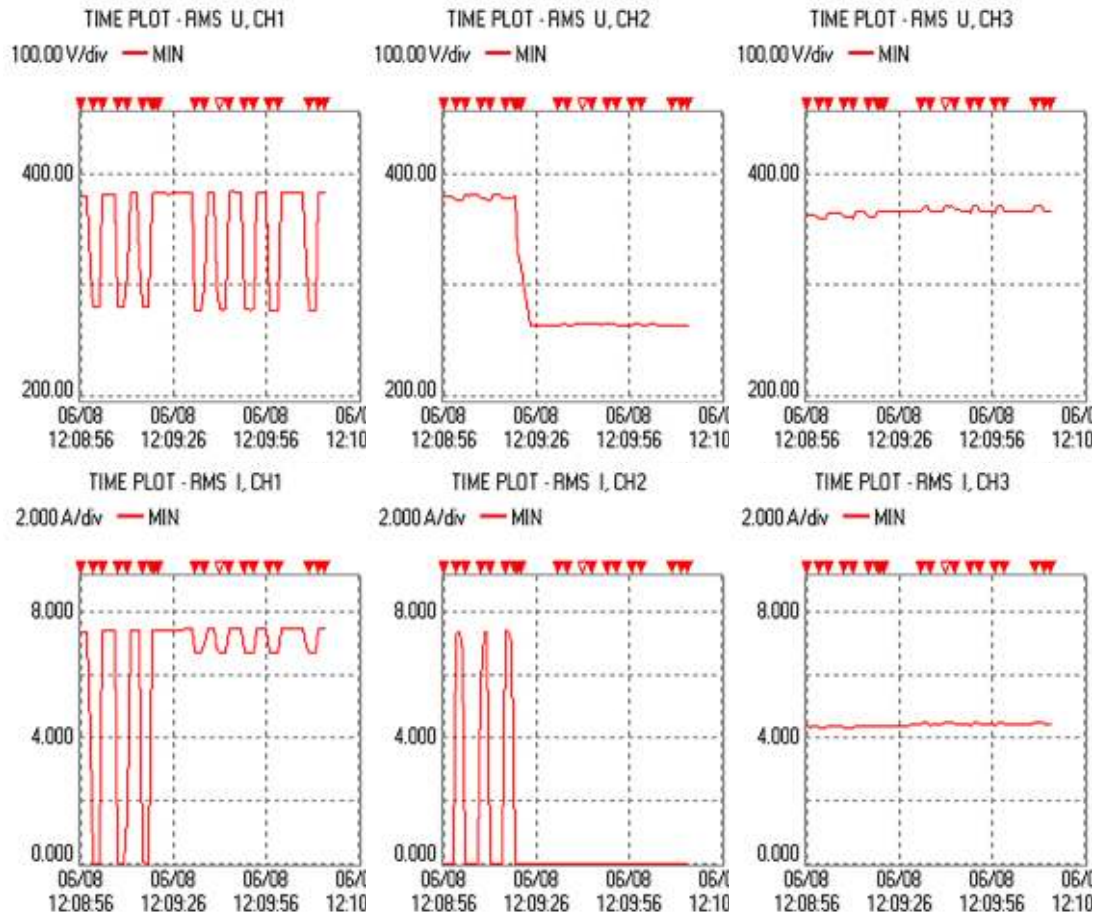


Figure 6.25. Experimental results as RMS graphics for the Conditions 1,2,3 and 4

RMS results for operating of the STS and DVR together in case various voltage sags occurring at different time instants are shown in Figure 6.25. This figure is also represents the events shown in Figures 6.19-6.24. The power quality improvements of CPP for fault scenarios can be seen from Figure 6.25. Despite the various fault scenarios, the Voltages and Currents of Load AAA are almost kept at nominal values.

### 6.5.2. Experimental Results for Operating of Backup Generator in CPP

Figures 6.26, 6.27, 6.28, 6.29 and 6.30 show the experimental results related with the operating of Backup Generator in the CPP (Conditions 5-6). In this

experiments, a fault scenario are examined between the time interval 14:52:12-12:52:53.

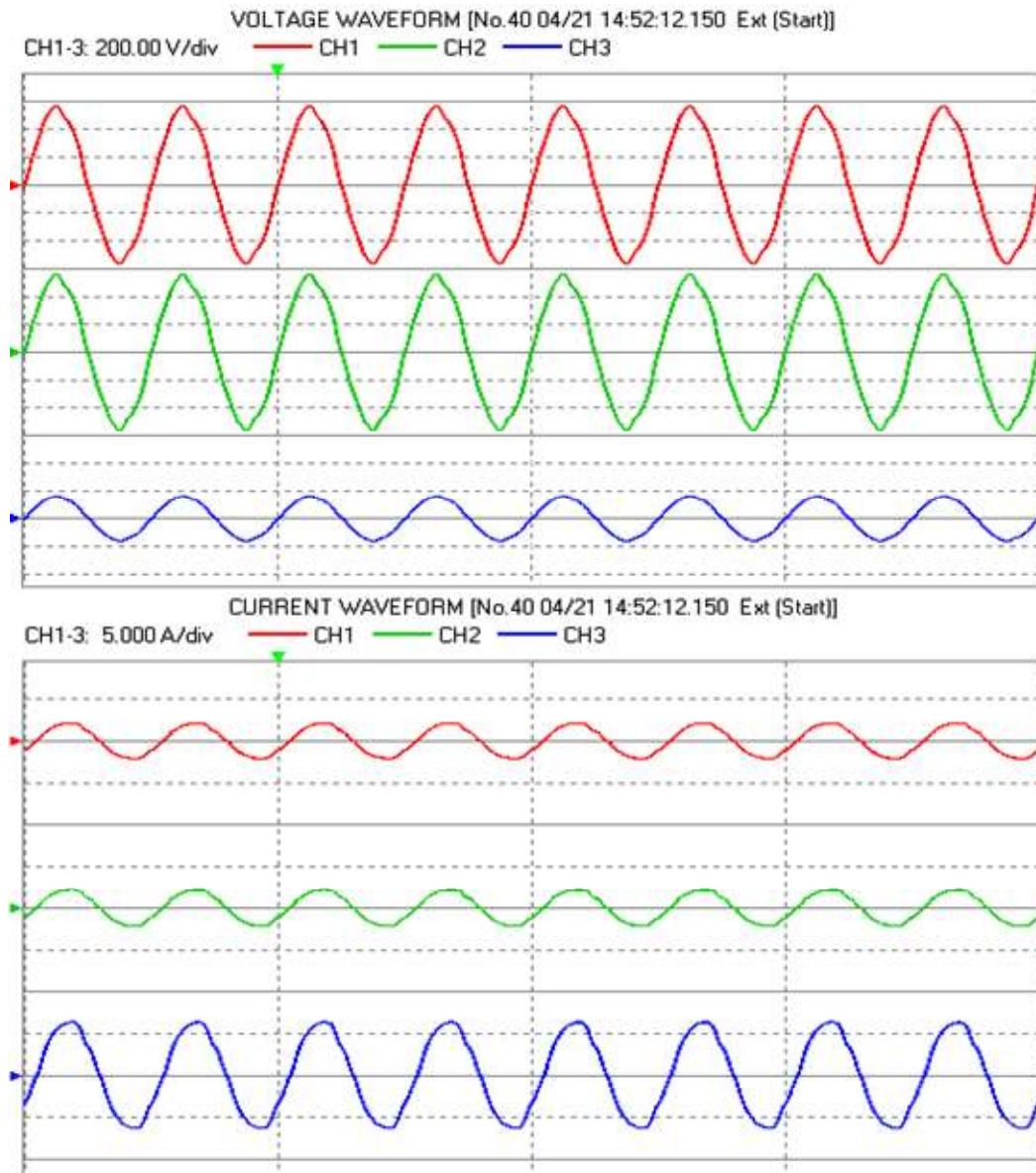


Figure 6.26. Experimental results for the Condition 2 before both the preferred and alternate feeder loss

In this fault scenario, the alternate feeder line to line voltage is at 30% of its nominal value (380 V to 112 V) and the preferred feeder line to line voltage is decreased to 4% of its nominal value (380 V to 14 V). In Figures 6.26-6.30; the voltage waveforms of Ch1, Ch2 and Ch3 indicate the preferred feeder line to line

AB, the load bus line to line AB, and the alternate feeder line to line AB voltages, respectively. The current waveforms of Ch1, Ch2 and Ch3 indicate the Load-A phase A, the Load-AA phase A and the Load-AAA phase A currents, respectively.

Figure 6.26 shows the conditions that the loads are fed by preferred feeder. Preferred feeder is healthy. This scenario indicates the Condition 2 in CPP fault scenarios.

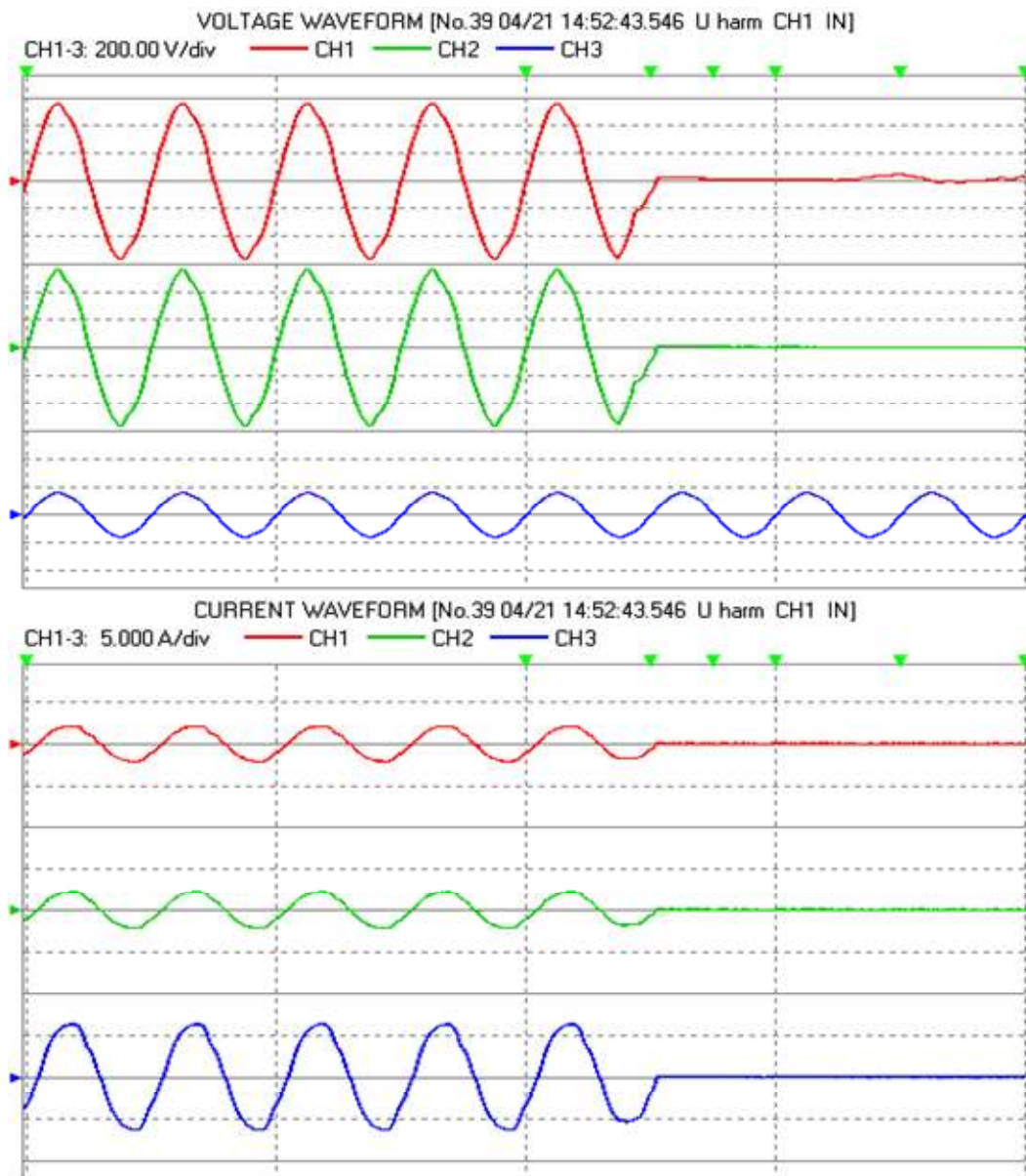


Figure 6.27. Experimental results for starting of the Condition 5

Figure 6.27 shows the starting of the Condition 5. At this condition, both the preferred and alternate feeders' line to line voltages have more than 50% sags.

Figure 6.28 shows the Condition 5. The control system waits to generator start up for 10 seconds. During this period, all the loads and DVR are off line. The STS-bus connection is disconnected.

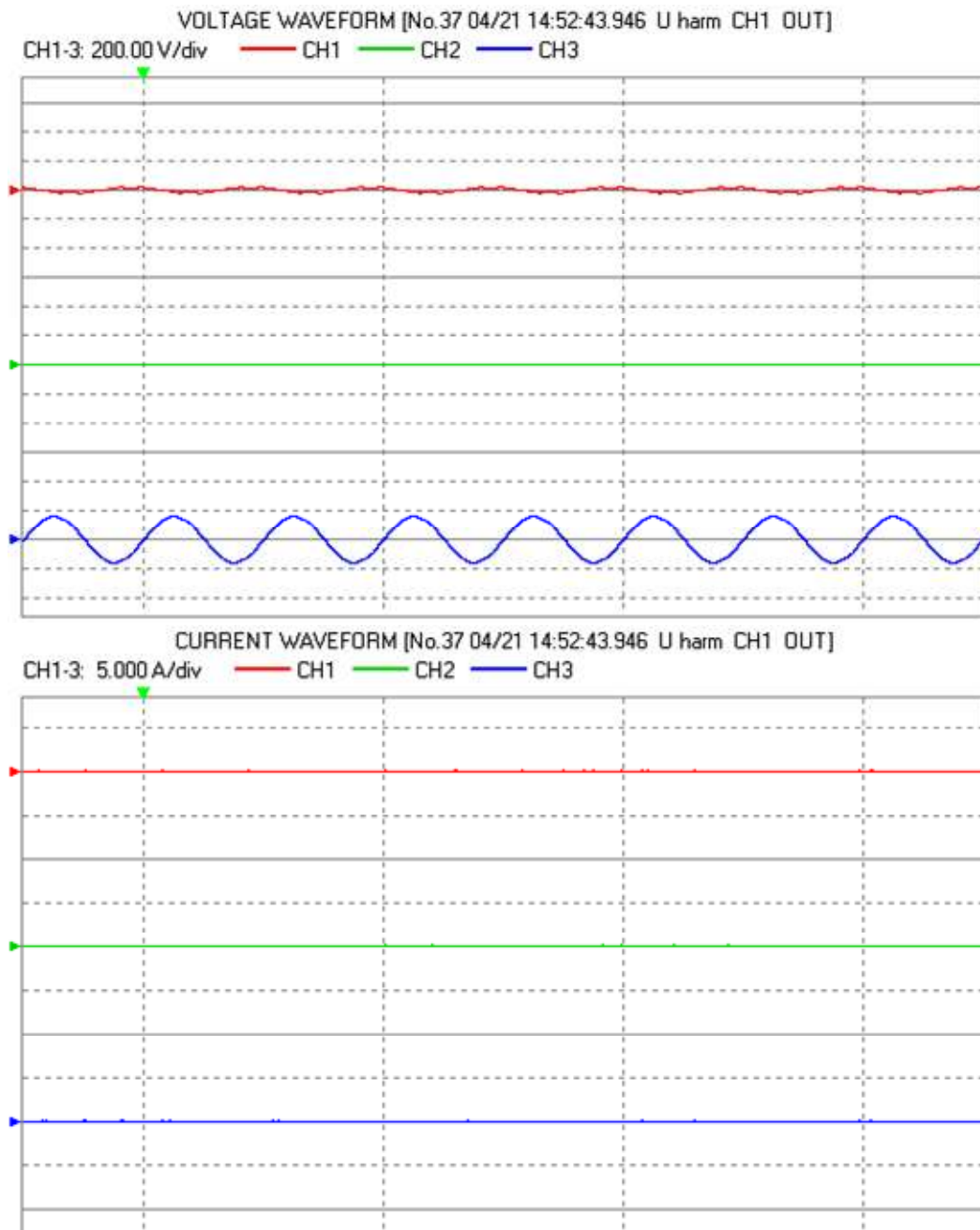


Figure 6.28. Experimental results for the Condition 5

Figure 6.29 shows the Condition 6. After the time for the Backup Generator startup, the Load-AA and the Load-AAA are started to feed by the generator.

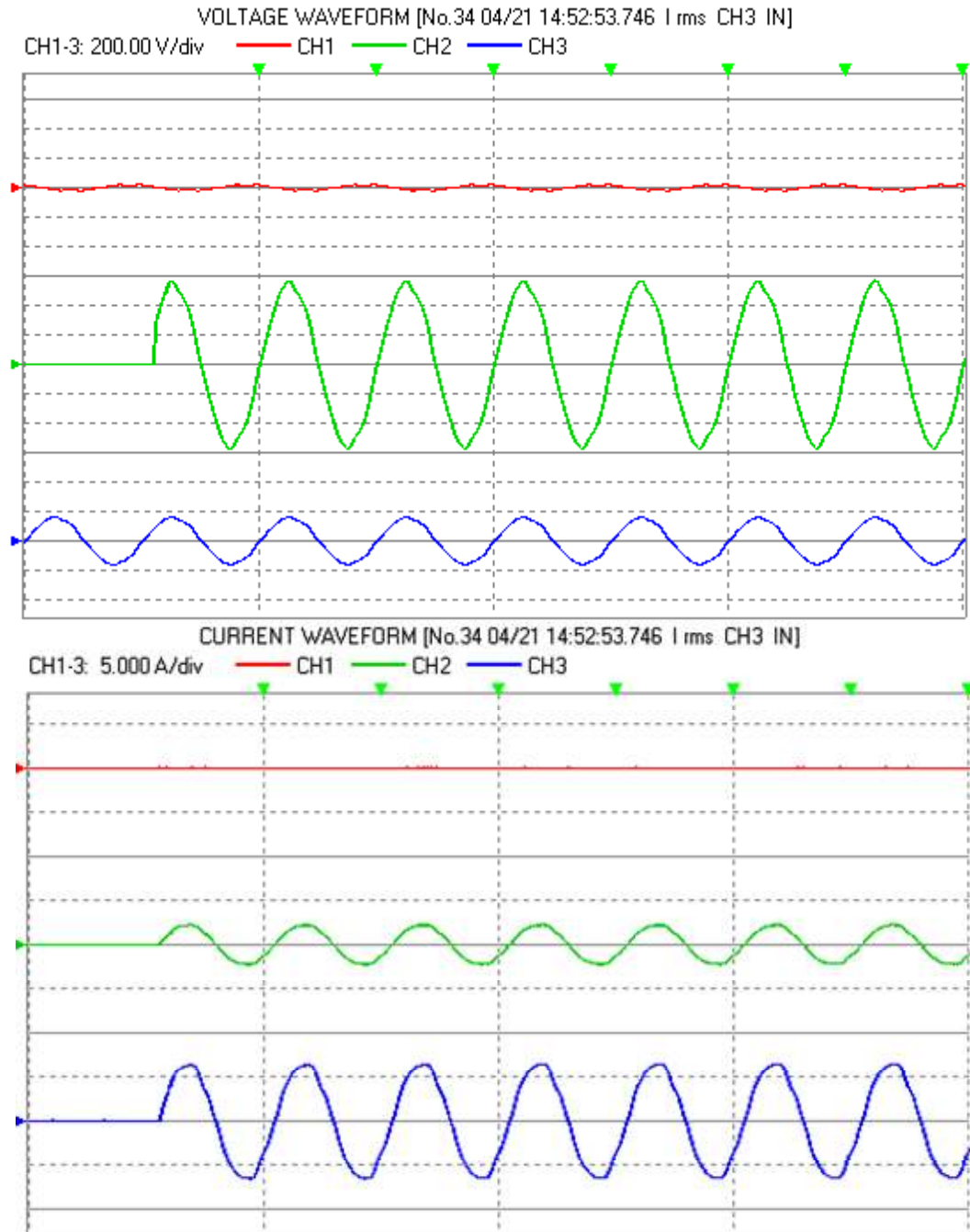


Figure 6.29. Experimental results for the Condition 6

RMS results for operating of the Backup Generator in case both the feeders voltage sags are shown in Figure 6.30. This figure is also represents the events shown in Figures 6.26-6.29. The power quality improvements of CPP for fault scenarios 5-6 can be seen from Figure 6.30. Despite the both feeders lost, the Load-AA and the Load AAA are started to fed by generator after 10 seconds.

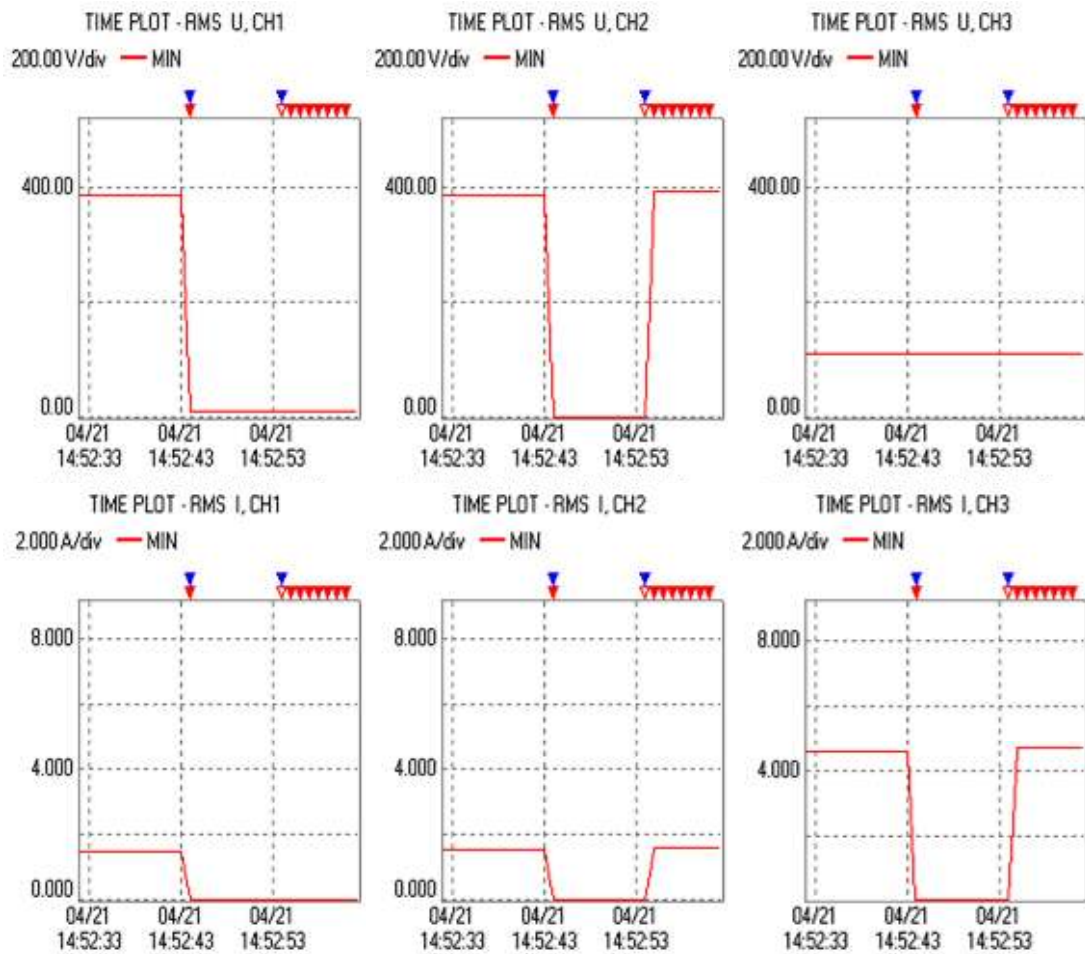


Figure 6.30. Experimental results as RMS graphics for the Conditions 2, 5 and 6

## 7. CONCLUSIONS AND FUTURE WORK

There are two classes of power quality problems according to causes. First, voltage disturbances (voltage quality problems) cause faults in the power system. The second covers phenomena due to low quality of current (current quality problems) drawn by the load caused by nonlinear loads. The most significant and critical power quality problems are voltage sags and complete interruptions of the energy supply. These problems may cause tripping of “sensitive” electronic equipment with disastrous consequences in industrial plants where tripping of critical equipment can cause the stoppage of the whole production with high costs associated.

The concept of Custom Power is the employment of power electronic or static controllers in medium or low voltage distribution systems for the purpose of supplying a level of power quality that is needed by electric power customers that are sensitive to rms voltage variations and voltage transients. The Custom Power devices are basically of two types – network reconfiguring type and compensating type.

The STS belongs to network configuring type. STS is usually a thyristor based device that is used to protect sensitive loads from voltage sags or interruptions. It can perform a sub-cycle transfer of the sensitive load from a supplying feeder to an alternate feeder. Typically a rather inexpensive device, the Mechanical Transfer Switches (MTS) has been used for many years. Unfortunately, due to the nature of the electromechanical switches used in the MTS, an uninterrupted transfer is not obtainable. Typical transfer times can range from about 100 ms up to approximately ten seconds. For that reason, transfer systems using mechanical switches have been applied as an effective counter-measure against only long interruptions.

The DVR is a series connected compensating device. The main purpose of this device is to protect sensitive loads from voltage sags in the supply side. This is accomplished by rapid series voltage injection to compensate for the drop in the supply voltage. DVR costs less compared to the UPS systems. Taking the UPS as an example, this has two major implications. First, the energy that a UPS is required to store is based upon the long duration of a typical voltage outage or blackout, not

relatively short duration voltage sag. Secondly, UPS systems are typically designed for small loads, such as a computer mainframe or low power safety critical systems.

As mentioned above, DVR is a compensating type Custom Power device, however STS is a network reconfiguring type Custom Power device. DVR usually designed to mitigate voltage sags with magnitude lower than 50%. This is based on a Voltage Source Converter (VSC) that generates a compensation voltage, which is then injected in the distribution feeder by means of a series-injection transformer. The STS is able to limit the duration of interruptions and voltage sags to less than one half-cycle, by transferring the load from the affected line to a back-up feeder. This high speed of response is obtained by using two static switches, constituted each by two anti parallel thyristors, to perform the transfer of the load. The DVR is not suitable to compensate for interruptions of the supply voltage and the range of sags that it can mitigate depends on the size of the energy storage. On the other hand, the STS cannot mitigate sags that affect both feeders.

As a new Custom Power concept of improving power quality, attention has been paid to Custom Power Park which is able to offer customers high quality of power. The concept requires integration within the park of multiple Custom Power devices (such as STS and DVR), which have previously been deployed independently. In a Custom Power Park all customers of the park should benefit from high quality power supply. Even the basic form of this supply is superior to normal power supply from a utility. The loads in the park are divided into three categories. The Loads L-A, L-AA and L-AAA are balanced and harmonic-free loads. The L-AA and the L-AAA are sensitive loads and they require almost an uninterrupted electrical power. The L-AAA is the most critical load and can not tolerate any disturbances.

In this thesis a Custom Power Park is presented. The focus of this thesis is the “Voltage Quality Enhancement with Custom Power Park”. A Custom Power Park prototype is designed, modeled with PSCAD simulation program, experimentally implemented and the voltage quality enhancement with custom power park is presented. The custom power devices integrated to the park are the STS and DVR. Firstly, the devices are implemented and then integrated to the Custom Power Park.

A power quality control center is developed to coordination of park equipments such as the STS, DVR, Backup Generator and loads.

The study on DVR focused on applying a new sag detection method and a new reference voltage generation method. The conventional sag detection method is unable to detect the voltage sags lower than a definite level. As an instance, a single phase to ground fault resulting voltage sag cannot be determined by this method because the method used the average of the three phase voltage and sees the single phase voltage sag as an average value of three phases. Besides another restriction of this method is the use of low pass filter. This filter reduces the response speed of the detection scheme. To overcome the disadvantages of the conventional sag detection method, the proposed method is used in this thesis. With the proposed method, the controller is able to detect balanced, unbalanced and single phase voltage sags without an error. Simulation and experimental Results show that, the proposed DVR successfully protects the most critical load against voltage sags.

The proposed sag detection method is also used for the STS. With the proposed method, the faults in distribution system that can not be detected with conventional method are detected, effectively. As transfer and gating method, Break Before Make transfer strategy used in the STS. In this strategy, load transfer to the alternate feeder is not performed until the anti-parallel thyristor pairs of preferred side are turned off. As seen from the simulation and experimental results, STS successfully protects the loads against sags and short and/or long time interruptions.

There are a few simulation studies related to the Custom Power Park. Furthermore, there is no any experimental study related to the Custom Power Park. This study is the first experimental study on the Custom Power Park. The voltage quality improvements with proposed Custom Power Park are presented in case of various fault scenarios. The simulation and experimental results show that the loads in the Custom Power Park benefit from high quality power supply superior to normal power supply from a utility.

The implemented methods and experiences obtained from experimental studies also give help to literature. However, there is no enough background on

power quality, voltage quality issues and CP devices in Turkey. This study will also contribute to the concept “finding solutions to the electric power quality problems” and this will also pioneer the using of CP devices in Turkey.

As an extension to this study, the following studies are suggested: i) A shunt APF may be integrated to the Custom Power Park and it may be examined the compensation of current harmonics drawn by the nonlinear loads. iii) New control methods may be developed for both the STS and DVR experimental prototypes. iii) An additional solution may be implemented to prevent the power interruption during generator startup.

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