ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A CASE STUDY ON POWER QUALITY PERFORMANCE OF ELECTRICAL POWER DISTRIBUTION NETWORK AND RECOMMENDATIONS FOR A POWER QUALITY DIAGNOSIS APPROACH

M.Sc. Thesis by

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ANKARA

A CASE STUDY ON POWER QUALITY PERFORMANCE OF ELECTRICAL POWER DISTRIBUTION NETWORK AND RECOMMENDATIONS FOR A POWER QUALITY DIAGNOSIS APPROACH

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **‘‘A CASE STUDY ON POWER QUALITY PERFORMANCE OF ELECTRICAL DISTRIBUTION NETWORK AND RECOMMENDATIONS FOR A POWER QUALITY DIAGNOSIS APPROACH’’** completed by **YUNUS YALMAN** under supervision of **Assoc. Prof. Dr. KAMİL ÇAĞATAY BAYINDIR** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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A CASE STUDY ON POWER QUALITY PERFORMANCE OF ELECTRICAL DISTRIBUTION NETWORK AND RECOMMENDATIONS FOR A POWER QUALITY DIAGNOSIS APPROACH

ABSTRACT

Power quality becomes especially up to date with energy market deregulation and competition between power distribution companies. In this environment, electrical energy is treated as a ware with the quality that is most frequently specified by its technical quality – the quality of delivery and the quality of delivered energy. The problem of the quality of delivered energy, i.e. power quality, is connected with the power system stability, disturbances and mutual influences system-consumer. Power quality problems and solutions are reviewed. National and international regulations on power quality is presented and compared. Most common problems such as voltage sag is identified using real data and solutions to these problems is suggested. Available methods for power quality diagnosis is reviewed. A new algorithm that determine event direction and fault type in KCETAS distribution system is proposed. The proposed algorithm is implemented on Inavitas software and tested by real data from ION 7650 analyzer in KCETAS network. Analysis of voltage and current waveform during event confirm that the performance of proposed algorithm is satisfactory. This new power quality diagnosis approach will be helpful tool for distribution systems.

Keywords: Causes and Solution of Power Quality Problems, Inavitas Software, Power Quality Diagnosis, Fault type, Event Direction.

ELEKTRİK DAĞITIM ŞEBEKESİNİN GÜÇ KALİTESİ PERFORMANSINA İLİŞKİN ÖRNEK BİR İNCELEME VE GÜÇ KALİTESİ TEŞHİS YAKLAŞIMI İÇİN ÖNERİLER

ÖZ

Güç kalitesi, özellikle enerji piyasasının serbestleştirilmesi ve enerji dağıtım şirketleri arasındaki rekabet ile birlikte daha da güncel hale gelmektedir. Bu ortamda, elektrik enerjisi, sıklıkla dağıtım kalitesi ve verilen enerji kalitesi olarak belirtilen teknik kaliteye sahip mal olarak değerlendirilmektedir. Verilen enerjinin kalitesi, yani güç kalitesi, güç sistemi kararlılığı, bozulmaları ve sistem ile tüketici arasındaki karşılıklı etki ile bağlantılıdır. Güç kalitesi problemleri ve çözümleri incelenmektedir. Güç kalitesi ile ilgili ulusal ve uluslararası düzenlemeler sunulmakta ve karşılaştırılmaktadır. Gerilim çökmesi gibi en yaygın problemler gerçek veriler kullanılarak tanımlanmakta ve bu problemlere çözüm önerilmektedir. Güç kalitesi problemlerinin tespiti için mevcut yöntemler incelendi. KCETAS dağıtım sisteminde olay yönünü ve arıza türünü belirleyen yeni bir algoritma önerilmiştir. Önerilen algoritma, Inavitas yazılımında uygulan ve KCETAS dağıtım sistemindeki ION 7650 analizörlerinden gelen gerçek veriler ile test edilmektedir. Olay sırasındaki gerilim ve akım dalga şeklinin analizi, önerilen algoritmanın performansının tatmin edici olduğunu teyit etmektedir. Bu yeni güç kalitesi teşhis yaklaşımı, dağıtım sistemleri için yararlı bir araç olacaktır.

Anahtar Kelimeler: Güç kalitesi problemlerinin nedenleri ve çözümleri, Inavitas yazılımı, Güç kalitesi problemlerinin tespiti, Arıza tipi, Arıza yönü

CONTENTS

NOMENCLATURE

Acronyms

AC	Alternating Current
ANN	Artificial Neural Network
DC	Direct Current
DWT	Discrete Wavelet Transform
EMD	Empirical Mode Decomposition
EMT	Electromagnetic Transient
EMRA	Energy Market Regulatory Board
FL	Fuzzy Logic
HHT	Hilbert Huang Transform
HV	High Voltage
IEEE	Institute of Electrical and Electronics
LV	Low Voltage
MRA	Multi Resolution Analysis
MV	Medium Voltage
PQ	Power Quality
PWM	Pulse Width Modulation
RMS	Root Mean Square
RTU	Remote Telemetry Units
RVC	Rapid Voltage Change
STATCOM	Static Synchronous Compensator
SSSC	Static Synchronous Series Compensator
SVM	Support Vector Machine
TCR	Thyristor Controlled Reactor
THD	Total Harmonic Distortion
UPQS	Unified Power Quality Conditioner
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter
VSC	Voltage Source Converter
WT	Wavelet Transform

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CHAPTER 1

INTRODUCTION

1.1 Literature Review

Since the invention of electricity, term of power quality is common issue [1]. Term of power quality states that distribution system can utilize customers without power quality disturbance and permanent stability of power system in any emergency case like as disabling production unit or loss at distribution lines [2]. In addition, 'power quality' term can be defined as any distortion formed in voltage, current, frequency which these cause malfunction or destruction in user device [3]. At today world, Power quality is important issue, because the use of power electronic devices which cause power quality problems increase. High quality service is provided by electric power utilities, in distribution systems ensuring and installing power quality monitoring systems. Since large quantities of data will be collected from these systems for the detection and classification of PQ problems, the software or hardware to be implemented should be fast and efficient [4]. In order to restrict harmful effects occurred by non-linear loads on network, manufacturers and customers have been obliged to comply with some standards. One of these standards is the Institute of Electrical and Electronics Engineers (IEEE 519-1992) standards [5].

The aim of the companies that produce, transmit and distribute electricity provide uninterrupted, economic and quality energy to consumers. From the concept of quality in electrical energy systems, it is understood that the constant voltage and the sinusoidal form of the terminal voltage are provided at the constant network frequency [6].

Today use of non-linear loads in terms of V-I characteristic such as power electronic components, switch mode power supplies, arc furnaces, motor drives increase. Non-linear loads draw non-sinusoidal currents from the network. In other words, the currents draw currents at different frequencies from the network frequency. These currents distort the voltage and current waveforms in the network by creating a voltage drop in the frequencies outside the fundamental frequency of network. Non-sinusoidal current and voltage reduces lifetime and efficiency of motor, generator, compensation capacity and other power system components [7].

Loads are more susceptible to power quality because many new load forms contain microprocessor controlled power electronic elements [8]. Customer wants higher quality energy from producers due to increased level of knowledge about power quality [9]. The number and variety of users connected to the electricity network increases with time. Due to presence of interconnected systems, Fault in anywhere of network affect all system [10]. These reasons are increased the interest in power quality. The mains problem in distrıbution systems are voltage sags and voltage swells. The main cause of voltage sag and voltage swells is fault such as single phase ground fault, two phase ground fault, three phase ground fault and two phase fault. These faults disturb quality of service. They cause customer complaints. The another main problem is event direction. Power quality analyzer records voltage and current Etc. during event. There are a lot of studies in literature that determine fault type and fault direction using these data. These studies are given following.

In [11], two main types of classification methods for power quality disturbances are presented. The first one is the deterministic classification which includes the expert systems. The second one is the statistical classification which involves support vector machines. We use expert systems, when we have limited data and enough power system expert knowledge. This method on the other hand however, needs a set of threshold values. We can use statistical methods when large amount of data exists for training. In the paper, two critical points to assure the effectiveness of a classifier are also discussed; which are namely data segmentation and feature extraction. Segmentation of a data recording sequence describes the preprocess of partitioning the data into segments in such a way that each of them presents a time slot consisting of either an event or a transition between two events. We apply extraction of features to each segment separately.
In [11] transmission line protection for multi-generator system that uses wavelet Multi-Resolution Analysis (MRA) method with GPS is studied. The wavelet transform’s inputs are the synchronized currents measured with remote telemetry

units (RTUs) that are combined with GPS at different buses. In this paper, the classification algorithm utilizes wavelet MRA method which finds out the properties of the transient current signals. These are based on harmonics which come into existence because of the different faults of abrupt change of currents in a three-phase transmission line. All in all, the paper has a significant importance of introducing a classification algorithm that is not affected from the faults in inception angle, fault impedance, fault distance and power angle.

A new means of classifying the fault types and anticipating location of fault in the high-voltage power transmission lines that uses Support Vector Machines (SVM) and Wavelet Transform (WT) of the measured one-terminal voltage and current transient signals is introduced in [12]. The paper uses a wavelet entropy criterion to reduce the size of feature vector of wavelet detail coefficients. The technique is tested for different types of faults that frequently takes place on the transmission lines. The results prove a very good accuracy of the exact locations.

[13] is another study that proposes a new technique for classification of faults in transmission lines based on wavelet technique. To achieve its goal, the suggested method uses a single sided transmission line current measurements. The method is tested for different types of faults. The results show that the technique is highly capable of obtaining very accurate estimations of the exact locations.

In [14] the classification of power system faults is accomplished with the usage of Empirical Mode Decomposition (EMD) and Support Vector Machines (SVMs), whereas the derivation of the characteristic properties from IMFs are done by Hilbert Huang Transform (HHT). The paper suggests a multiple SVM model to classify the fault condition among different types of power system faults. Results prove that the combination of EMD and SVM can be an efficient and accurate classifier.

A novel method that uses particle swarm optimization for the training of artificial neural networks (ANN) and utilizes wavelet transforms for estimating the type of fault is proposed in [15]. Each of the wavelet components can be described as a time-domain signal that exhibits a segment of the whole frequency spectrum. The faults are broken down into a series of wavelet components by using wavelet analysis. The detailed coefficients of every phase current signal are measured at the transmitter end of a transmission line and are assigned as the parameters selected for fault classification. Finally, the data is given to the ANN to end the operation of fault classification.

In [16], a novel method to classify power quality events is proposed along with power quality disturbances that arise in every phase of the power system after a fault. To determine the type of power quality events this method uses three-phase voltage signals. To achieve this, three-phase voltage signals are normalized and segmented, while to obtain the distinctive properties of event signals a wavelet transform method is utilized. A feature vector is condensed by applying a two-stage feature extraction process. This vector represents the unique traits of three-phase event voltage signals and also reduces the data size. On the other hand, power quality event types are decided by using a support vector machine classifier. At the final stage of the recognition system, a further analysis is applied in order to determine the types of power quality disturbances regarding each fault event. According to the real data analysis results, the proposed method classifies the power quality event types very accurately.

In [17], there are four types of strong machine learning classifiers proposed to detect and identify fault types and locations over a 750KV, 600km long power transmission line. These classifiers are Bagging, Boosting, radial basis functions and naïve Bayesian. The results show that the method of machine learning is appropriate to achieve the goal and can be used to increase the protection and efficiency of power systems.

A decision-tree-based method to detect and classify fault during power swing in double circuit transmission lines, that may occur due to switching of heavy loads and lines, clearance of short-circuit faults, generator tripping and load shedding, is introduced in [18]. The decision tree used in this paper, distinguishes the no fault situation/power swing and the fault during power swing. The decision tree uses the fundamental components of currents and voltages and zero sequence currents measured at the single end of the double circuit line as its input. What makes this approach unique and beneficial is that it detects fault during power swing within half cycle time and classify the type of fault and faulty phase.

For fast and stable operation of protective relays, in [19] a fault classification technique for transmission lines that uses mainly the fault sequence components is presented. In this method, first the symmetrical components of fault current and voltage signals are obtained. Secondly, by utilizing the zero and negative sequences, the fault type is determined. Next, a criterion based on the zero and negative sequences is defined in order to define the faulted phases in ground faults; and the imaginary part of the defined criterion is used. This criterion index achieves its maximum point in the faulted phase in single-phase-to-ground faults, and its minimum point in one of the faulted phases in phase-to-phase-to-ground faults. Furthermore, to recognize the ungrounded faults, another criterion that utilizes the positive and negative sequences is proposed. The outcomes prove that this method is able to provide fast fault classification, without the requirement for a threshold.

A method to extract, detect and classify the faults of short circuit in a power distribution network is presented in [20]. A hybrid technique that uses DWT and SVM is proposed Digsilent Power Factory is used to model a reduced 88 kV power distribution network. Transient fault current signals of different types of faults are collected by an Electromagnetic Transient (EMT) study of the model. To obtain the features from transient fault currents that are measured at the source terminal of the network, a Discrete Wavelet Transform (DWT) is utilized, which are then given to a Support Vector Machine (SVM) in order to classify different types of faults. Following the fault initiation, the technique uses the initial two cycles of the transient fault current measured at the source terminal. The test results show that different types of faults in a power distribution network can be identified and classified with high accuracy.

In [21] transmission line protection for multi-generator system that uses wavelet Multi-Resolution Analysis (MRA) method with GPS is studied. The wavelet transform’s inputs are the synchronized currents measured with remote telemetry units (RTUs) that are combined with GPS at different buses. In this paper, the classification algorithm utilizes wavelet MRA method which finds out the properties of the transient current signals. These are based on harmonics which come into existence because of the different faults of abrupt change of currents in a three-phase transmission line. All in all, the paper has a significant importance of introducing a classification algorithm that is not affected from the faults in inception angle, fault impedance, fault distance and power angle.

In this thesis, Power quality definitions, causes and solution of power quality problem such as Harmonic, voltage sag, voltage swell etc. is described. Power quality regulation in different countries is given in terms of similarity to EN50160. Inavitas software used by distribution company is introduced. Fault type such as Single phase ground fault, two phase ground fault, three phase ground fault and two phase fault is simulated in order to understand properties of voltage and current waveform. New algorithm that defines fault type and direction of event is designed using real data taken from power quality analyzer in KCETAS network in Inavitas software. Examples of voltage and current waveform in Inavitas in order to verify results of algorithm is presented.

1.1.1 Objectives of the Thesis

The main goals of this thesis are defined in following.

- To define power quality definitions,
- To present cause of power quality problems,
- To describe solution of power quality problems
- To represent power quality standards in different country
- To describe UPSTREAM and DOWNSTREAM concept about event direction
- To simulate fault type in order to learn features of current and voltage waveform during event
- To describe Inavitas software used by distribution companies
- To introduce new algorithm which determines direction and type fault in distribution systems using real data recorded by ION 7650 power quality analyzer in KCETAS network

- To evaluate the performance of the proposed algorithm with Inavitas data which consist of voltage and current waveform during the events
- To describe flowchart of proposed algorithm
- To integrate proposed algorithm into Inavitas software

1.1.2 Contribution of Thesis

An extensive review of power quality problems, causes and solutions are given. PQ regulations in Turkey and other countries are reviewed. In literature there are many studies that determine fault type and event directions. However, these studies are predominantly based on simulation data. So all data about distribution systems are known. But in this study, data about KCETAS distribution systems is limited. In this thesis a new algorithm that classifies fault type and determines event direction is proposed. The proposed algorithm used real data recorded by ION 7650 power quality analyzer in KCETAS is integrated with Inavitas software used by all of distribution company in Turkey in order to automatically make sense of event data taken all of power quality analyzer in distribution system. It also helps network operator to be more understandable of big data. Design approaches of proposed algorithm are represented in detail. Confirmation of new method is investigated with current and voltage waveform in comtrade file occurred by Inavitas software.

1.1.3 Outline of the Thesis

The content of the dissertation is arranged as follows:

In Chapter 1, After a comprehensive literature review on power quality event identification in distribution systems is presented. The objectives and contributions of the dissertation is expressed.

In Chapter 2, Definitions, causes and solution of power quality problems are given. Power quality problems are classified according to RMS disturbance, Waveform disturbance and Steady state disturbance.

In Chapter 3, Power quality Regulation in different countries such as Hungary, Norway, Turkey, Sweden, Netherlands, France, Czech Republic, Portugal, Italy, USA are presented in detail.

In Chapter 4, Inavitas software used by most of Turkish distribution companies is defined. Reporting systems such as EMRA report and weekly report and report of power quality problems like flicker report, Voltage unbalance report etc. is shown.

In Chapter 5, Fault type in distribution system is simulated in order to learn properties of voltage and current waveform during PQ event. Single phase ground fault, two phase ground fault, three phase ground fault and two phase fault is realized in this simulation.

In Chapter 6, New algorithm that determining event direction and fault type is described. Flowchart of this algorithm is presented in detail. It is tested with real data taken from power quality analyzer. Example of voltage and current waveform a created by Inavitas and event data is given in order to evaluate performance of proposed algorithm results.

In Chapter 7, Conclusions of this dissertation is given.

CHAPTER 2

DEFINITIONS, CAUSES AND SOLUTIONS OF POWER QUALITY PROBLEMS

Power quality events in power systems are classified into three main categories as steady state disturbance, RMS disturbance and waveform disturbance. We can classify the steady-state disturbance into four different topics as voltage harmonics, voltage inter harmonics, current harmonics and current internal harmonics. RMS disturbance are classified into five categories as voltage swell, voltage sag, flicker, voltage spike, voltage imbalance. Waveform disturbance are classified in three different categories as notch, noise, voltage oscillations. Table 2.1 shows the classification of power quality events.

Table 2.1 Power Quality Problems

<table>
<tr><th>Steady State Disturbance</th><th>RMS Disturbance</th><th>Waveform Disturbance</th></tr>
<tr><td rowspan="5">• Voltage Harmonic
• Current Harmonic
1. Current Harmonic
2. Inter Current Harmonic</td><td>• Short Duration Voltage Variation</td><td>• Notch
• Noise
• DC offset</td></tr>
<tr><td>1. Voltage Swell
2. Voltage Sag
3. Voltage Interruption</td><td rowspan="4">• Transient
1. Impulsive Transient
2. Oscillation Transient</td></tr>
<tr><td>• Long Duration Voltage Variation</td></tr>
<tr><td>1. Undervoltage
2. Overvoltage
3. Sustained İnterruption</td></tr>
<tr><td>• Voltage Spike
• Voltage imbalance
• Voltage fluctuation
• Flicker</td></tr>
</table>

2.1 Steady State Disturbance

2.1.1 Harmonics

During the generation, transmission, and distribution of energy in electric power systems, it is desirable that the current and voltage be oscillated at a frequency of 50 Hz and in the form of a sinusoidal wave. This is one of the main factors determining the quality of electricity. However, the sinus form of current and voltage is disturbed by some of the effects of operation (the main cause of these effects is nonlinear elements in the electrical and magnetic circuits of the devices). Harmonic in this sense; In power systems, it can be defined as the periodic continuous state disturbances of the current or voltage, or both, in waveform [22]. The non-sinusoidal waveforms are periodic and it consists of the sinusoidal wave (Fundamental Wave) and the sum of other sinusoidal waves with different frequencies and amplitudes. The sinusoidal wave excluding the fundamental wave is called the "harmonic component" [22,23]. In power system due to symmetry of sinusoidal wave it has odd harmonics such as 3., 5., 7., 11. harmonic. There are no even harmonic components. Figure 11 shows the even component and harmonic components in half period [24]. In international standards, the harmonic currents and voltages on the network are limited at certain intervals. This limitation is accepted both at total harmonic distortion and at various harmonic components. Equation 2.1 shows how to calculate THD. For Turkey, this value should be below 8% in 95% of weekly measurements over 10 minute RMS measurements.

In power system, effects of harmonic components are:

- Overheating in transformer
- Increase in voltage drop
- Increase of energy consumption
- Overheating in device
- Waveform distortion of generator and network voltage
- Incorrect operation of protection elements
- Change in power factor
- Noise in audio and video systems
- Perforation of dielectric materials [24]

$$THD = \sqrt{\sum_{h=2}^{40} (u_h)^2} \quad \textbf{(2.1)}$$

2.1.1.1 Current Harmonic

Current harmonics are sinusoidal currents with an integer multiplier frequency (150 Hz, 350 Hz, 180 Hz, 420 Hz) of the fundamental frequency (50 or 60 Hz). The total harmonic distortion of the current waveform is shown in the Equation 2.2. Current harmonics cause increases in leakage flux losses and copper losses [25]. The fundamental and fifth and seventh components of the harmonic current are presented in Figure 3.1. Table 2.2 shows the harmonic current limit values according to EN 50160 standard.

$$I_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{effn}^2}}{I_{eff1}} = \sqrt{\left(\frac{I_2}{I_1}\right)^2 + \left(\frac{I_2}{I_1}\right)^2 + \cdots + \left(\frac{I_n}{I_1}\right)^2 +} \quad \textbf{(2.2)}$$

Table 2.2 Current harmonic limit [22]

Single harmonic						
I_{SC}/ I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	THD
<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
Double harmonic are restricted to 25% of the value defined for single harmonic after them						

The waveform, harmonic spectrum and THD of the current due to nonlinear loads are illustrated in Figure 2.1.

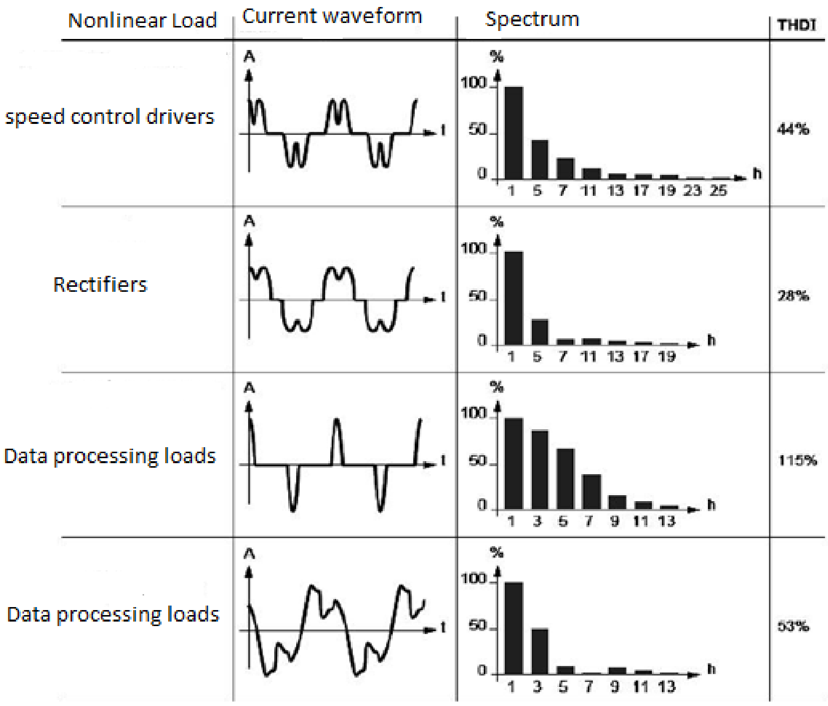


Figure 2.1 Waveform, Harmonic Spectrum and THD of Nonlinear Current [26]

2.1.1.1.1 Cause of Current harmonics

2.1.1.1.1.1 Arc Furnaces

Arc furnaces produce harmonics during steel production due to unpredictable arc changes. According to the results obtained from the measurements, second order and seventh order harmonics in the integer-order harmonic frequencies are considerably larger than inter harmonics. According to the results obtained from the measurements, 2nd and 5th harmonic components are quite suppressed compared to other harmonics. In addition, the harmonic amplitudes are reduced in comparison with their ratings. Current and voltage waveform of arc furnace are presented in Figure 2.2 Harmonic spectrum of voltage is demonstrated in Figure 2.3. In Figure 2.4 Harmonic spectrum of current is given [27].

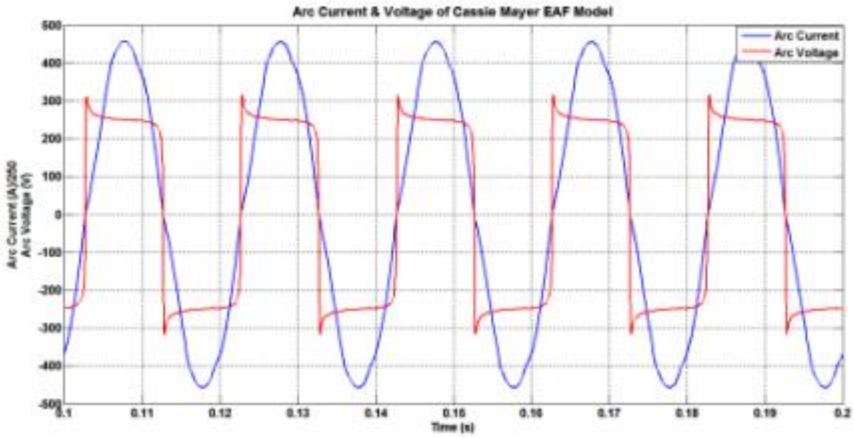


Figure 2.2 Waveform of Arc voltage and Arc current [27]

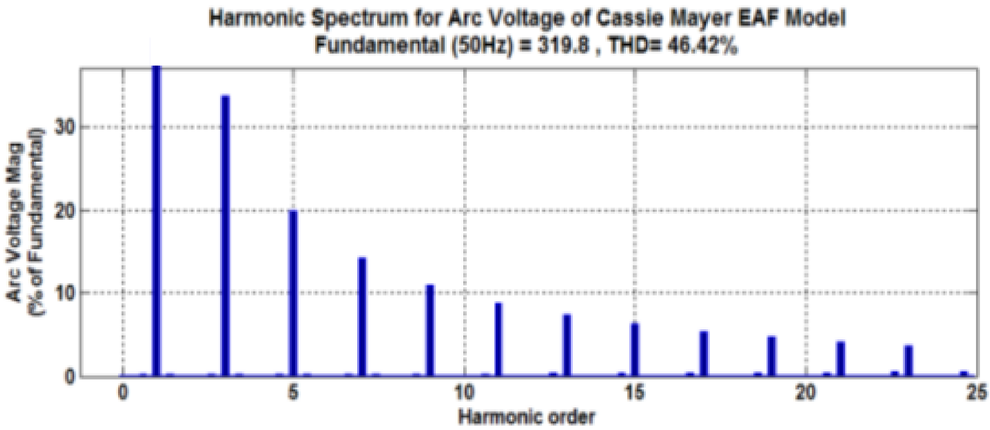


Figure 2.3 Waveform of Arc voltage [27]

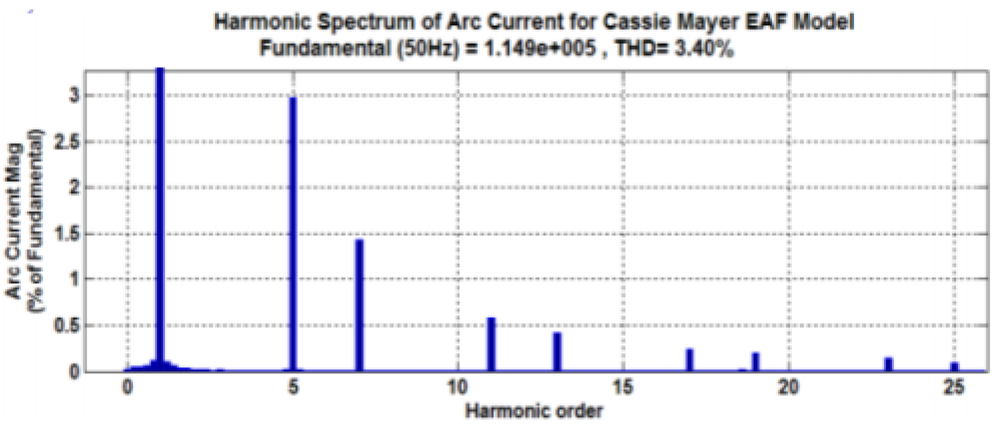


Figure 2.4 Waveform of Arc voltage and Arc current [27]

2.1.1.1.1.2 Rectifier

As a harmonic source, the rectifiers convert the mains voltage to the right voltage. In particular, it causes deterioration of current waveform. The effective value of the harmonic current is inversely proportional to the degree of harmonic. The effective value of the harmonic current can be reduced by increasing the number of pulses used in the rectifiers [28]. The 5th and 7th harmonics are dominant 6-pulse rectifier in Figure 2.5, while the 11th and 13th harmonics dominate in the 12-pulse rectifiers showed in Figure 2.6.

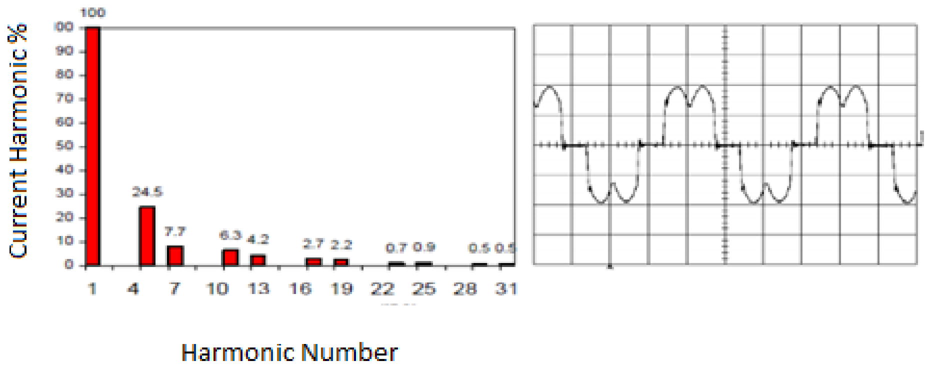


Figure 2.5 Current harmonics Spectrum and current waveform in 6 pulse rectifier [28]

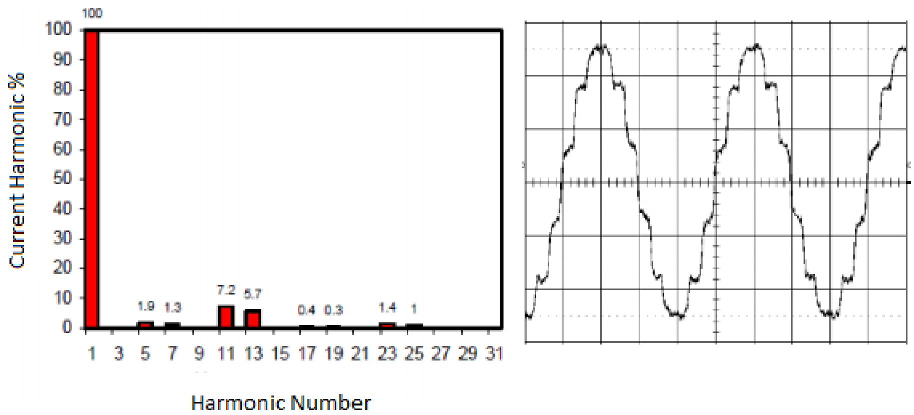


Figure 2.6 Current harmonics spectrum and current waveform in 12 pulse rectifier [28]

2.1.1.1.1.3 Switch Mode Power Supply

The Switched Power Supply rectify the AC line voltage by storing it in an energized high voltage capacitor. Circuit diagram of the SMPS, one of the switch mode power supply is demonstrated in Figure 2.7. In Figure 2.8, example of current and voltage waveform of switch mode power supply is given. Harmonic spectrum of switch mode power supply given in Figure 2.9.

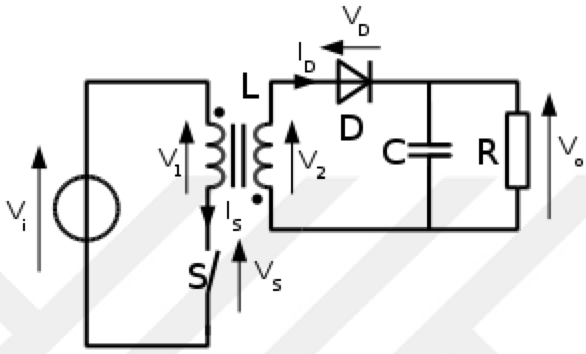


Figure 2.7 Circuit of SMPS [29]

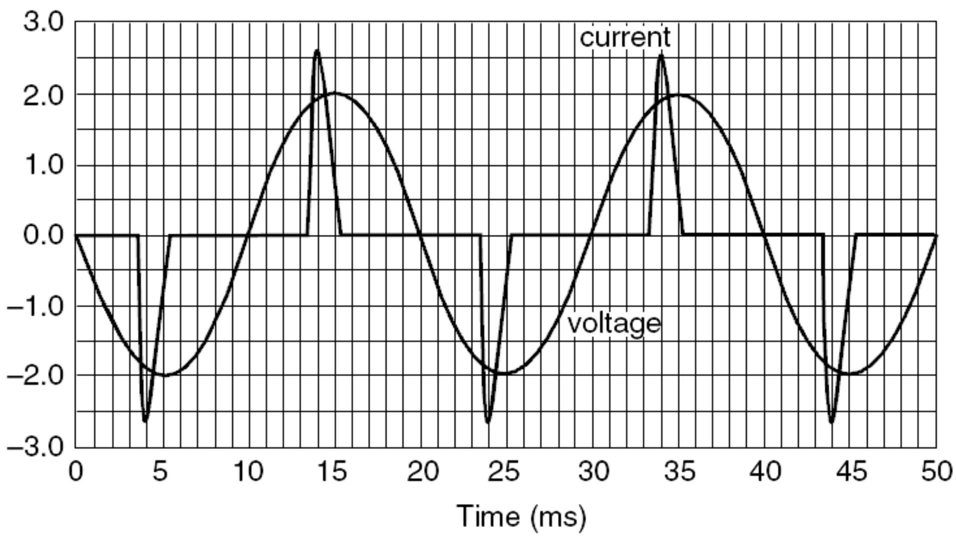


Figure 2.8 Current and voltage of Switch mode power supply [30]

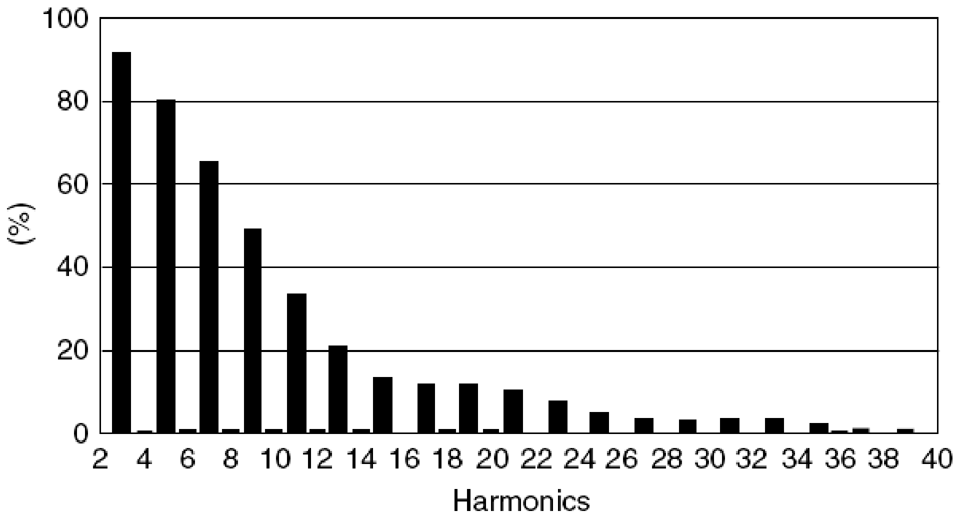


Figure 2.9 Harmonic spectrum of Switch mode power supply current [30]

2.1.1.2 Inter current harmonic

Inter-current harmonics are the currents that occur in frequencies that are not exactly multiples of the fundamental frequency. Inter current harmonics can be present in all voltage level. Inter current harmonics often appear as a consequence of frequency variation and can vary with load. Inter harmonic currents, if the interfering frequency of the variable coincides with the fundamental frequency of the system, can lead to very serious resonances on the power systems. Inter current harmonics of the induction furnace is given in Figure 2.10. Static frequency converters, cyclical converters, Induction furnaces, Arc furnaces cause inter current harmonic [31].

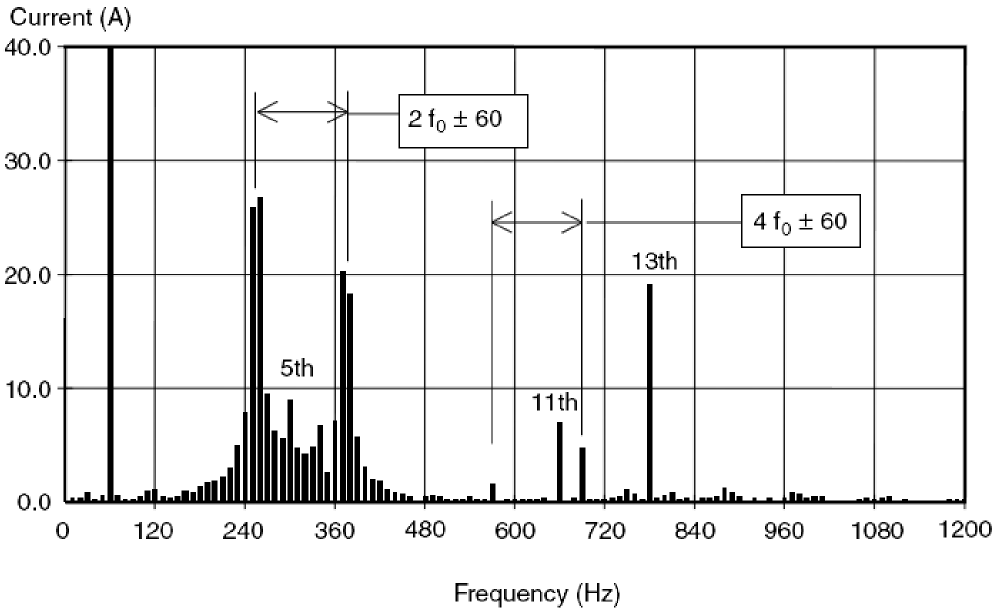


Figure 2.10 Inter current harmonic of induction furnace [1]

2.1.1.3 Voltage Harmonic

Current harmonics are sinusoidal currents with an integer multiplier frequency (150 Hz, 350 Hz, 180 Hz, 420 Hz) of the fundamental frequency (50 or 60 Hz). İn Equation 2.3. total harmonic distortion of voltage waveform is presented. V_1 is voltage value of fundamental frequency. V_{effn} is value of n. harmonic voltage. Voltage harmonics leads to the increase in iron losses and insulation stress. Pure sine waveform without harmonic distortion is practically absent. The distortion of the voltage waveform is even present at the production point. Distortion point in the production is very small, less than 1% [25].

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{effn}^2}}{V_{eff1}} = \sqrt{\left(\frac{V_2}{V_1}\right)^2 + \left(\frac{V_2}{V_1}\right)^2 + \cdots + \left(\frac{V_n}{V_1}\right)^2 +} \quad \textbf{(2.3)}$$

Harmonic currents are produced by loads. Harmonic currents are direct to the source so the disturbance in the current causes distortion in the voltage. The load current does not always cause distortion in voltage. Devices such as UPS (Uninterruptable Power Supply) have voltage distortion due to their operating nature. Even if the loads are linear, non-linear current is produced if the source is a nonlinear source. If one of the users using the common power line generates harmonic current, this will also affect other users [8].

At 95% of the weekly measurements, the harmonic distortion must be equal to or lower than the values in the Table 2.3 [22].

Table 2.3 Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of Un [25]

Odd harmonics				**Even Harmonics**	
Not multiples of 3		**Multiples of 3**			
Order h	**Relative voltage (%)**	**Order h**	**Relative voltage (%)**	**Order h**	**Relative 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				

2.1.1.3.1 Cause of Voltage Harmonic

2.1.1.3.1.1 Inverters

Inverters consisting of semiconductor circuit elements are network elements that convert DC to AC voltage pulse width modulation. PWM is the most effective method of using inverters for DC voltage convert to desired amplitude and frequency AC voltage. Inverters generate harmonics and noise due to semiconductor switching circuits. Depending on the type of converter used, the amount of harmonics in the output voltage varies [1].

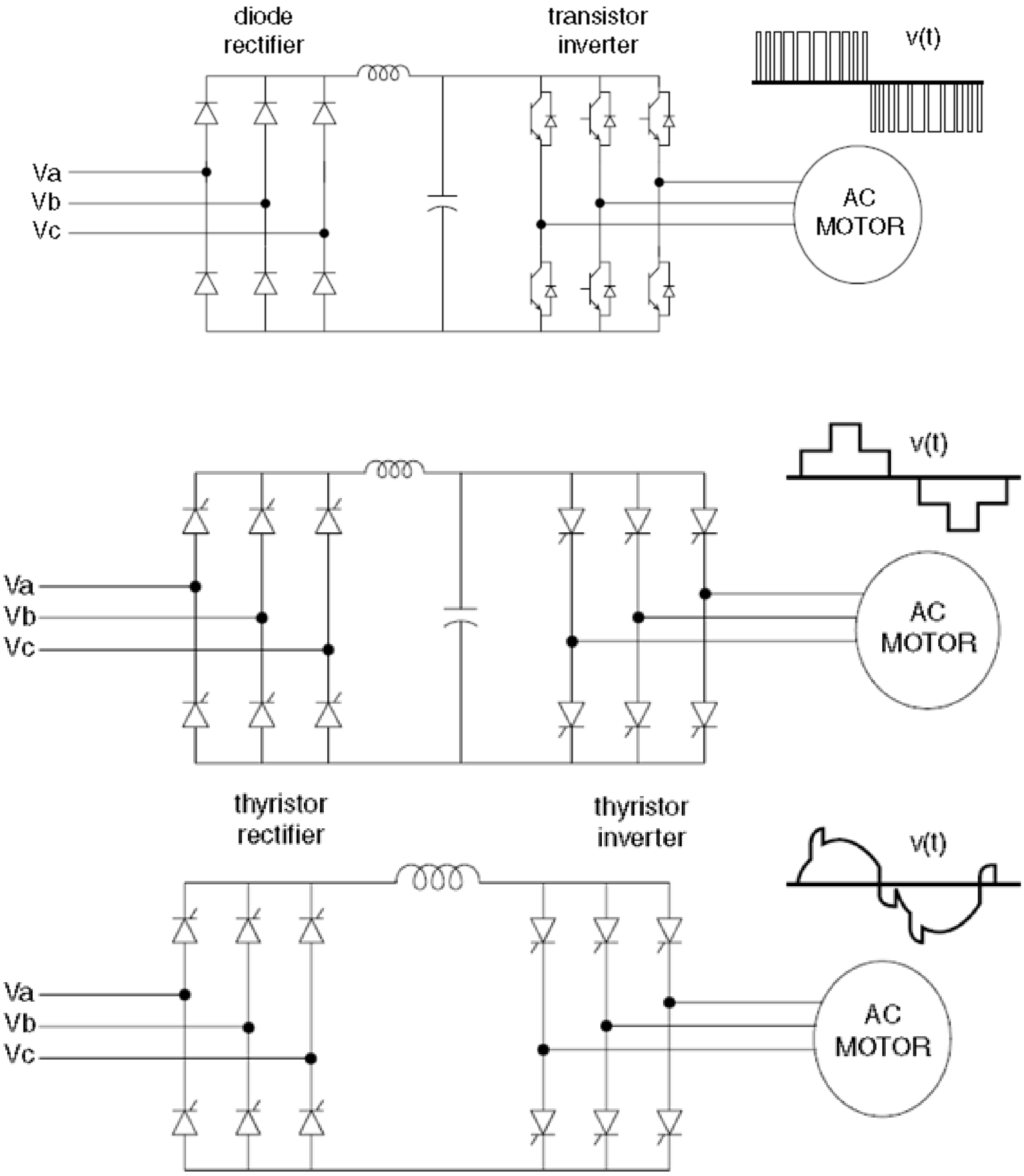


Figure 2.11 Various Inverter Output Voltage Waveform [1]

2.1.1.3.1.2 Static VAR Compensator

Thyristor controlled reactor (TCR) is widely used in power systems as a static shunt compensator. TCR applications are used to maintain voltage level, reduce voltage flicker, eliminate phase imbalances, and increase network stability. Harmonics are formed in the TCR output waveform due to the delays observed in the thyristor connections [32]. The RMS values of the harmonic components is shown in Equation 2.4.

$$I_h = \frac{4}{\pi}\frac{V}{X}\left[\frac{\sin(h+1)}{2(h+1)}\alpha + \frac{\sin(h-1)}{2(h-1)}\alpha - \cos(\alpha)\frac{sinh\alpha}{h}\right] \quad \textbf{(2.4)}$$

Where

h = 3, 5, 7 ….

V = line-to-line fundamental voltage

X = total inductive reactance of reactors in each phase

α = advance angle

2.1.1.4 Solution Methods of Harmonics

2.1.1.4.1 Passive Power Filter

Capacitors (C), inductors (L), resistors (R) are installed between the source and the receiver and destroy the components outside the fundamental frequency. It is necessary to set up a separate circuit for each harmonic in the passive filter. It is usually designed for the most effective harmonic component. The most important features separated from the active power filters are that they are not in a dynamic structure.

2.1.1.4.2 Series Passive Power Filter

The series power passive filters consist of resistance and inductance elements connected in series between the source and the harmonic generating element. This series impedance shows high impedance to the harmonic frequencies according to the formula X = 2 * pi * f * L, preventing their transition. It also shows low impedance at fundamental frequency. In Figure 2.12, Series passive power filter is demonstrated. Series power filters are used in front of AC motor drive circuits and high power AC / DC inverters. The difficulty of implementing the series filters is that the entire load current should pass through the filter, be insulated for full line voltages and even causing voltage drop [33].

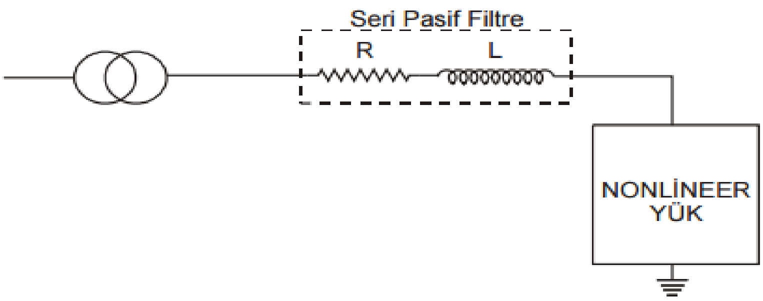


Figure 2.12 Series passive power filter [33]

Advantage of series passive power filter:

- Avoid the resonance owing to Tuned frequency
- Improve power factor

Disadvantages of series passive power filter

- Perform harmonic compensation for a single frequency.
- It is need the network that is being used is a stationary network and the all network information should be known

2.1.1.4.3 Parallel Passive Power Filter

Parallel (shunt) passive power filters are circuits in which a capacitor (C), inductance (L) and in some cases resistance (R) elements are connected in parallel between the harmonic source and the network. Separate resonance branches should be created for each harmonic frequency and these branches should be connected to the power system. However, this operation must be done for harmonic frequencies with high magnitude. Since it is not an optimum solution to create a separate resonance branches for each harmonic component, it is sufficient to create a resonance branches only for harmonic frequencies whose amplitude is high, and for a non-high harmonic frequency, it is sufficient to form a single resonance line that reduces their effectiveness. Parallel passive power filter is given in Figure 2.13.

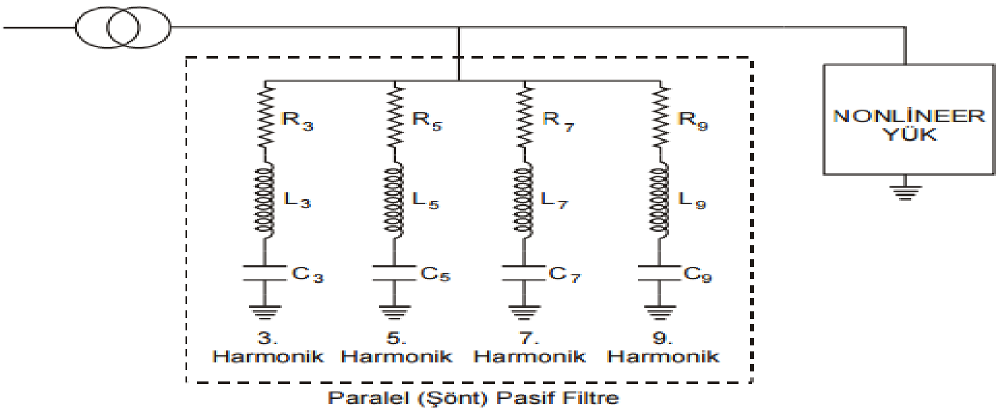


Figure 2.13 Parallel passive filter [33]

The main disadvantage of using shunt filter is that it can enter in parallel resonance with the power system. Therefore, a detailed analysis of the system is required before a passive filter is applied parallel to the power system. There are four types of parallel passive power filters [10].

2.1.1.4.3.1 Bandpass Filters

Single-tuned (bandpass) filters create a short-circuit path for a single frequency harmonic current, providing this current to be deflected. Single-tuned filters are formed the series R - L - C elements. In Figure 2.14 bandpass filter is given. The working principle of this filter is the resonance of the filter at the desired harmonic frequency by providing X_C = X_L condition. In this case the filter impedance Z_{ro} = R.

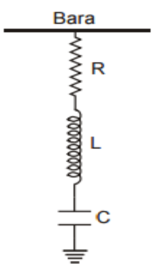


Figure 2.14 Bandpass Filter [33]

That is, the filter shows the minimum impedance value for the set frequency and this harmonic flows to the ground in this frequency. The frequency-impedance relationship of the bandpass filter is shown in Figure 2.15 [33].

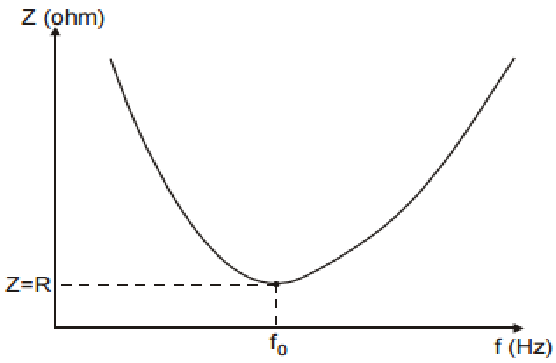


Figure 2.15 Frequency-Impedance relationship of bandpass filter

Advantages of bandpass filter:

- If there is no resistance added on demand, the losses are very small.
- Creates an impedance about zero to the harmonic current for the set harmonic frequency.
- Multiple filters can be used in parallel for multiple harmonic currents to be filtered

Disadvantages of bandpass filter:

- The filter is very sensitive to time-varying changes in the value of the elements that created the filter due to precise calculations
- Single-tuned filters can only be used on systems with nonlinear loads that have fixed power. Because capacitors in the filters are not variable, capacitors will remain on when the inductive loads in the system are deactivated, which can cause overcompensation in this case [33].

2.1.1.4.3.2 Double Tuned Filter

The equivalent impedance of the Double tuned filter is the same as the equivalent impedance of two single regulated filters. Double-tuned filter can eliminate two different harmonics. The most important feature of these filters is that the power loss of the fundamental frequency is small compared to the single-tuned filter. In Figure 2.16 Double-tuned filter is shown.

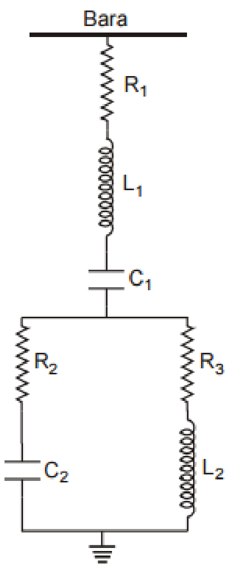


Figure 2.16 Double tuned filter

In Fıgure 2.17 Impedance-frequency relationship of double tuned filter is given. It can be seen from here that there are two different resonance points of the double-tuned filter.

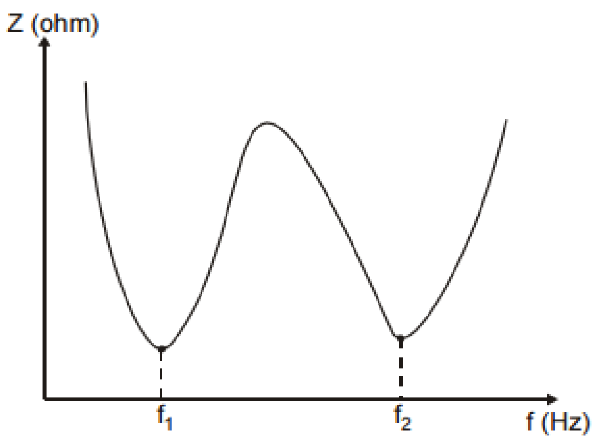


Figure 2.17 Impedance- frequency relatıonship of double tuned filter

2.1.1.4.3.3 Auto Tuned Filter

The adjustability of these filters ensures that both capacitor and inductance can be adjusted automatically. The limits of this setting are 5%. These filters consist of a control system which measures the reactive power and controls the L and C values according to the sign and magnitude of reactive power [33].

2.1.1.4.3.4 High Pass Filter

High-pass filters are filters with a low impedance above a certain frequency value. It is recommended that these filters be used with single-tuned filters. Single-tuned filters separate out low-harmonic frequencies with high amplitude values with different parallel branches for each harmonic, while high-pass filters separate out low harmonic frequencies of low amplitude with the help of a single parallel branches. There are four types of high pass filter. These are first order high pass filter, second order high pass filter, third order high pass filter and C type high pass filter. In Figure 2.18 shows type of high pass filter.

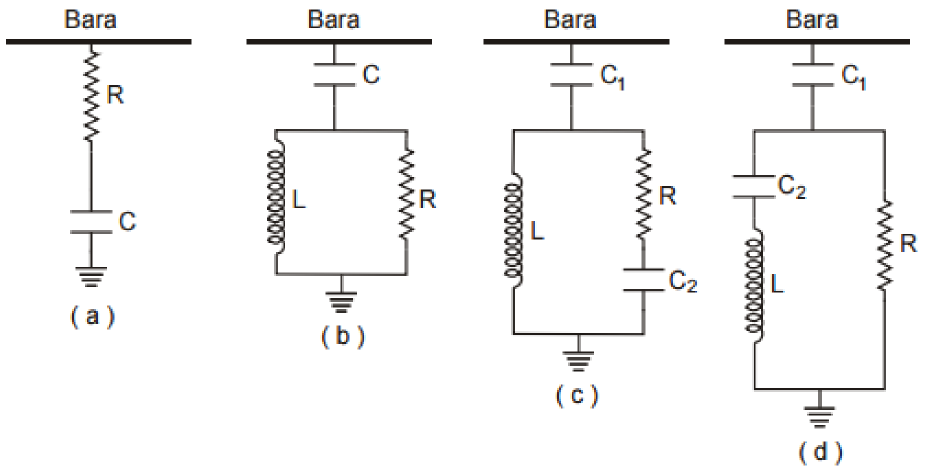


Figure 2.18 High pass filter a) first order b) second order c) third order d) C type [33]

In Figure 2.19 is given impedance-frequency relationship of high pass filter. It is seen from Figure 2.19 that the filter exhibits low impedance over a certain frequency, allowing high order harmonics to be removed from the system [33].

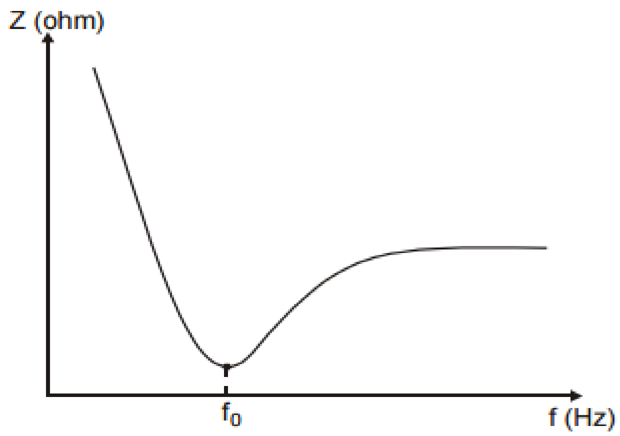


Figure 2.19 Impedance- frequency relatıonship of bandpass filter

2.1.1.4.4 Active Power Filter

Active filter reduces the harmonic current by injecting current in the exact opposite direction to the network harmonic components. These filters constantly update the signals they will produce in accordance with the amount of harmonics in the network by performing a continuous network monitoring. In addition, these filters do not resonance and can be easily integrated into the network. Parallel active filters can compensate harmonic load currents while series active filters can compensate the source harmonic voltages [33]. In Figure 2.20, block diagram of active power filter is demonstrated.

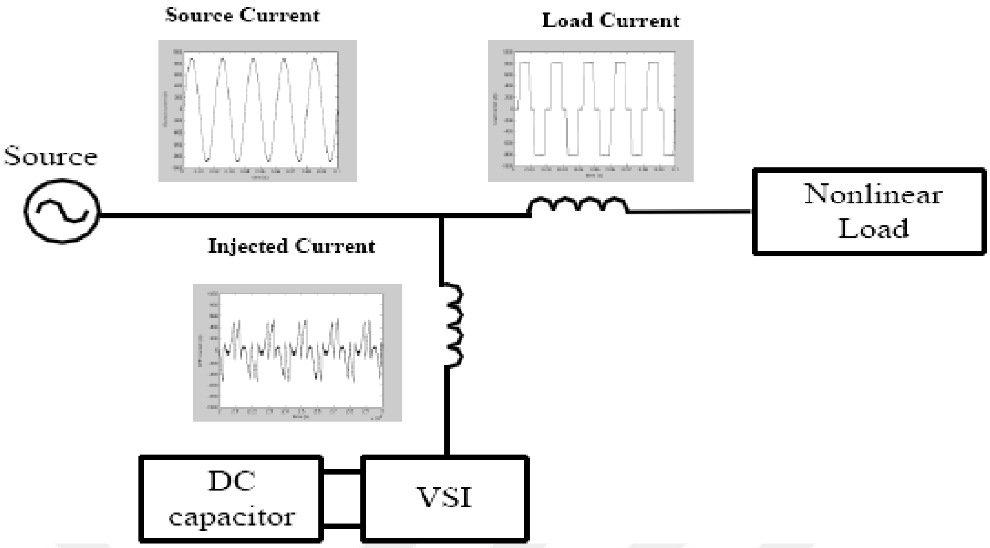


Figure 2.20 Active power filter block diagram [34]

2.1.1.4.2.1 Parallel Active Power Filter

The parallel active power filter works in parallel with the system. After identifying the harmonic currents that the load receives, it then injects currents of the same amplitude but reverse phase into the system. The parallel active filter is effective for nonlinear loads acting as a current source. The parallel active filter performs current-related compensation (reactive power compensation, current imbalances). The circuit diagram of the parallel active power filter is given in Figure 2.21

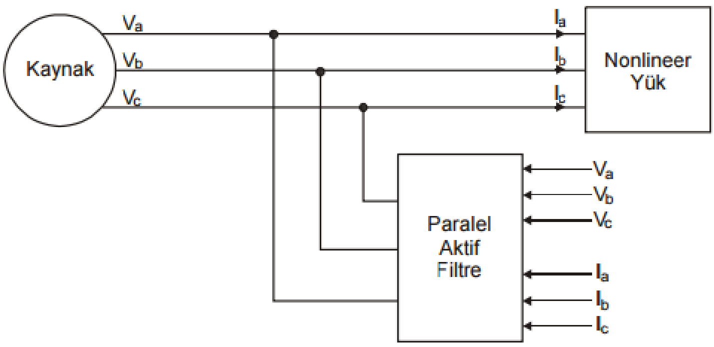


Figure 2.21 Block diagram of parallel active power filter [33]

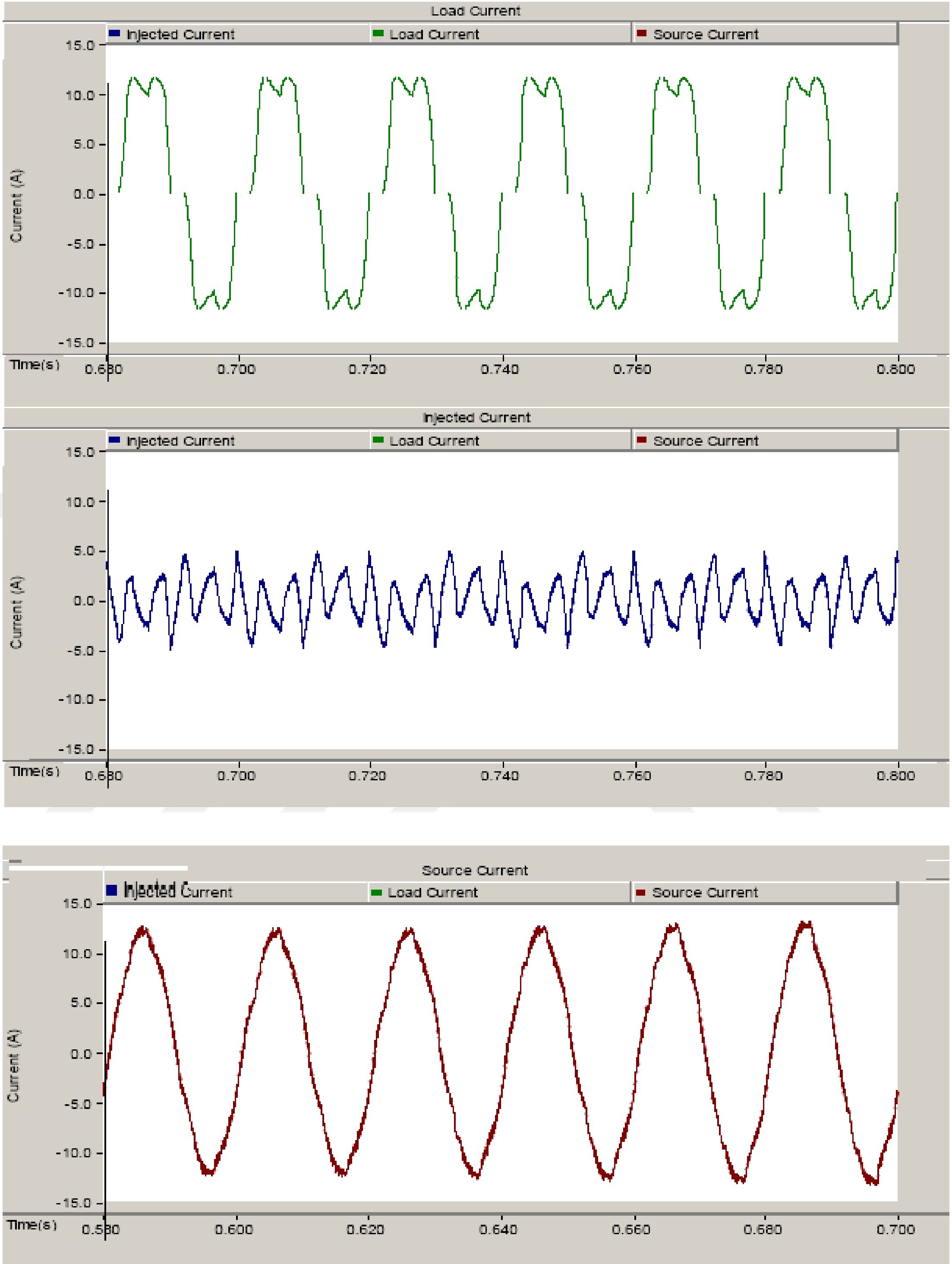


Figure 2.22 Load current, compensation current, Source current waveform [34]

In Figure 2.22, Load current, source current and compensation current waveform is presented. According to this figure, the harmonic current drawn by the load is filtered by the parallel active filter and the current drawn from the network does not contain harmonic current.

2.1.1.4.2.2 Series Active Power Filter

Series active power filters are connected to the system by a transformer. Voltage harmonics are eliminated with the series active power filter. It is effective for sources that act as a harmonic voltage source [33]. Figure 2.23 shows block diagram of series active power filter.

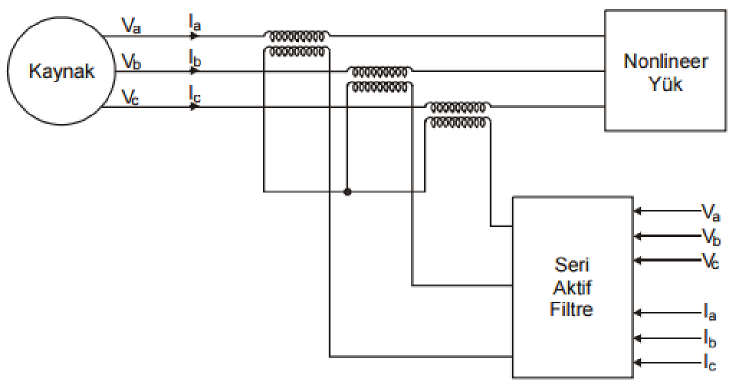


Figure 2.23 Block diagram of parallel active power filter [33]

In according Figure 2.24, if there is not active filter THD is high. When series active power filter is activated THD is decreased.

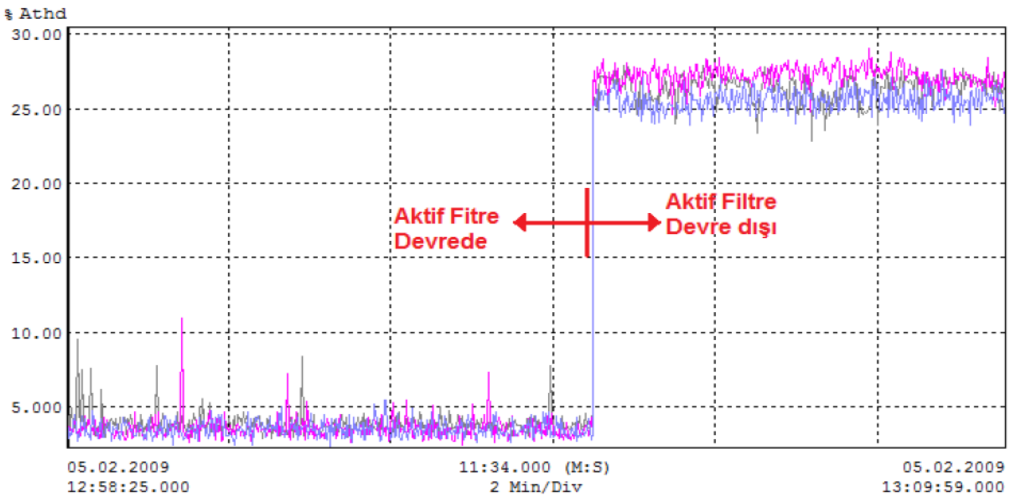


Figure 2.24 Change of Harmonic Disturbances in Phase Currents [35]

Advantages of active power filter:

- It can compensate harmonics from 2nd to 50th degree.
- The parallel active filter can be connected to the network very easily.
- The active filter has the ability to improve the power factor.

Disadvantages of active power filter:

- It is a very expensive application.
- Serious active filter needs to be adjusted to total power.

2.1.1.4.5 Comparison of Active Power Filter and Passive Power Filters

Table 2.4 shows comparison of active filter and passive filter in terms of various feature.

Table 2.4 Comparison of active filter and passive filter [33]

Subject	Passive Power Filter	Active Power Filter
Control of current harmonic	Requires a filter for each harmonic frequency.	It is possible to control many harmonic currents at the same time.
Effect of changing harmonic frequencies	Efficiency of the filter decreases	It has no effect.
Effect of the empadans modification	There is a risk of resonance.	It has no effect.
Risk of current rise	There is a risk of overloading and breakdown.	There is not a risk of overloading.
Adding new load to the system	Filter may need to be changed.	It does not cause any problems.
Change of the frequency of the fundamental wave in the system	Adjustment of filter is not possible. (it may need to be changed).	Possible by setting
Dimensions and Weights	very variable according to harmonic amplitude and degree	Small
Cost	Initial cost is low but maintenance is high	Initial cost is high but maintenance is low

2.2 RMS Disturbance

2.2.1 Short Duration Voltage Variation

According to IEEE 1159: 1995 short duration variations are defined as a change in the effective value of the amplitude of the voltage for a period of less than 1 minute in the range of 0-0.9 pu and 1.1-1.8 pu Short-term voltage variation can occur as large loads, which draw high starting currents, become active, and can also be caused by faults in the power system, such as disconnections in power conductors. Depending on the location of the fault and the system conditions, the fault may cause voltage sag, voltage swell or interruption [31]. In Figure 2.25 Short duration voltage variation waveform is demonstrated.

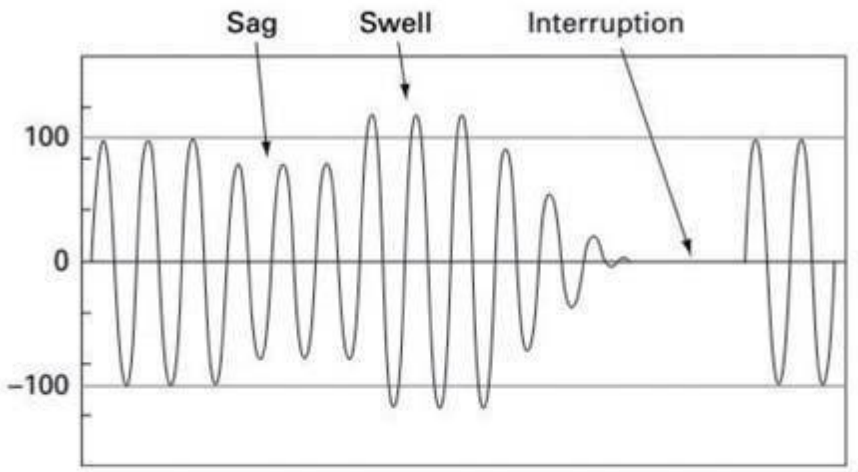


Figure 2.25 Short duration voltage variation waveform [36]

2.2.1.1 Voltage Swell

The swell according to IEEE 1159-1995 is defined as the increase in the effective value of the current or voltage for period from 0.5 cycle to 1 minutes. Typical amplitudes are between 1.1 pu and 1.8 pu. This classification is done with the "minimum value / total time" approach. This approach considers the lowest RMS voltage value seen in the three phases and the total duration of all three phases returning to normal operating conditions [9]. In Figure 2.26 voltage swell waveform is given.

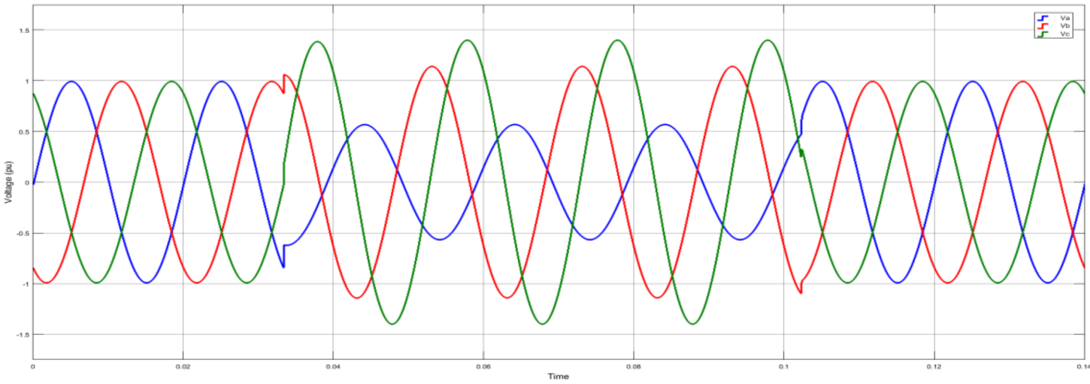


Figure 2.26 Voltage swell waveform

2.2.1.1.1 Cause of Voltage Swell

- **Capacitor energization**: Capacitor energization causes the voltage swell. Capacitors in the network are usually three-phase, so that the increase in the three-phase voltage is equal. In Figure 2.27, Voltage RMS waveform during capacitor energization is given.

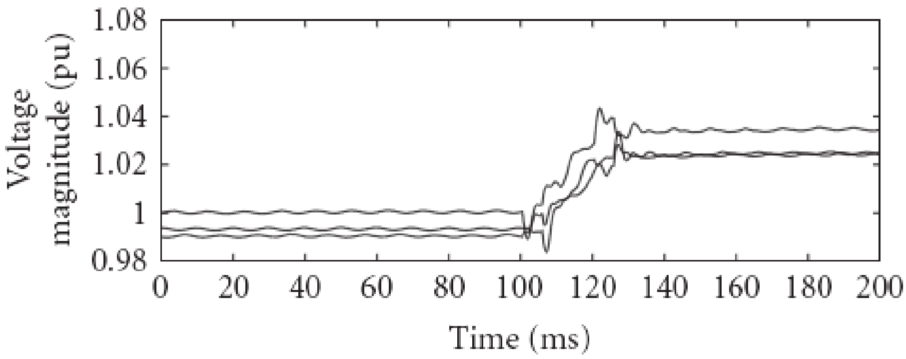


Figure 2.27 Voltage waveform during Capacitor energization [37]

- **Voltage swell due to ground fault**: Due to the ground fault, there may be voltage rise in two or three phases. Figure 2.28 shows the voltage waveform of the low-resistance grounding system. According to Figure 2.28, while voltage sag occurs in phase A voltage swell is occurs in phase B due to ground fault.

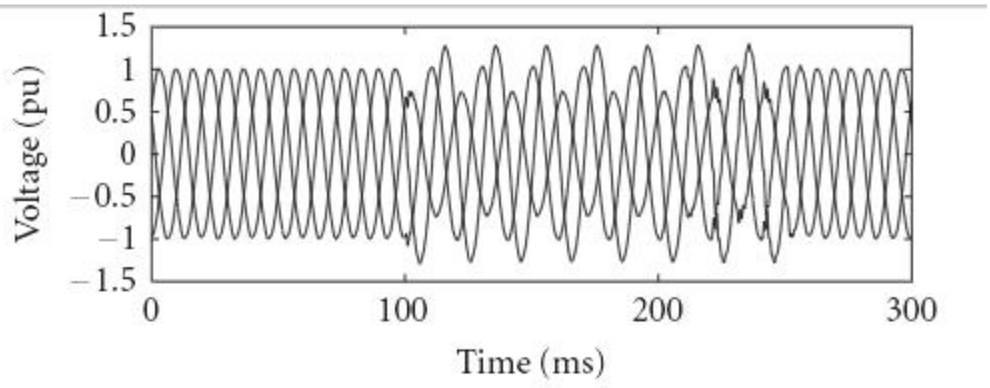


Figure 2.28 Voltage waveform due to ground fault [37]

2.2.1.1.2 Solution Methods of Voltage Swell

2.2.1.1.2.1 Static Synchronous Series Compensator

Static series compensators are controllable sources that can bring the load voltage connected in series on the network to the desired level [38]. static synchronous compensator acts as an extra voltage source to eliminate voltage imbalances, regulate load voltage, eliminate voltage sag and eliminate harmonic distortion at low harmonic degree depending on the type of controller installed in the electric networks. The method applied to bring the voltage level to the desired level in voltage sag is shown in Figure 2.29 on the phasor diagram. In Figure 2.30, circuit diagram of SSSC is present. In Figure 2.31, Source voltage, load voltage and voltage injected by SSSC is given.

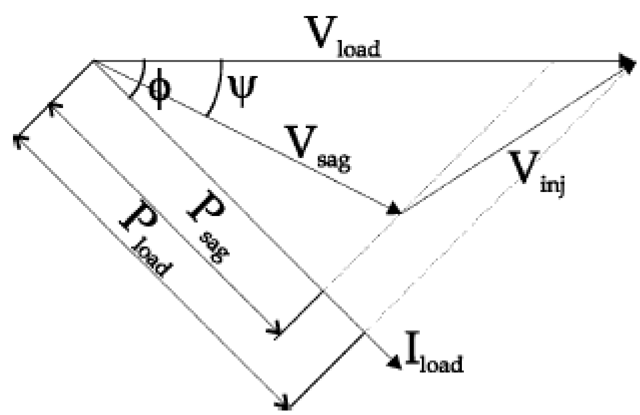


Figure 2.29 Phasor diagram of SSSC operation

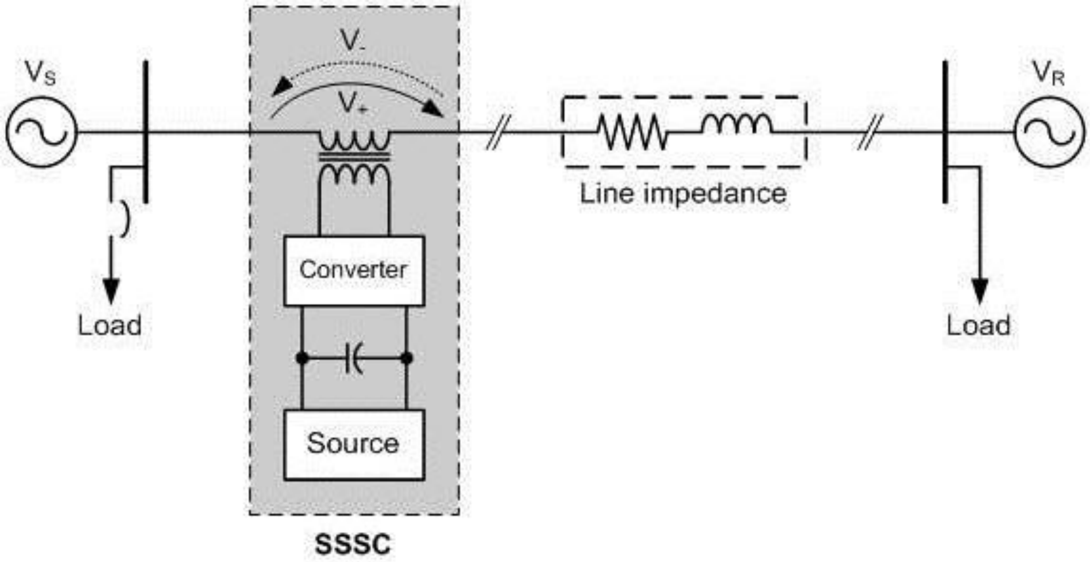


Figure 2.30 Circuit diagram of SSSC [40]

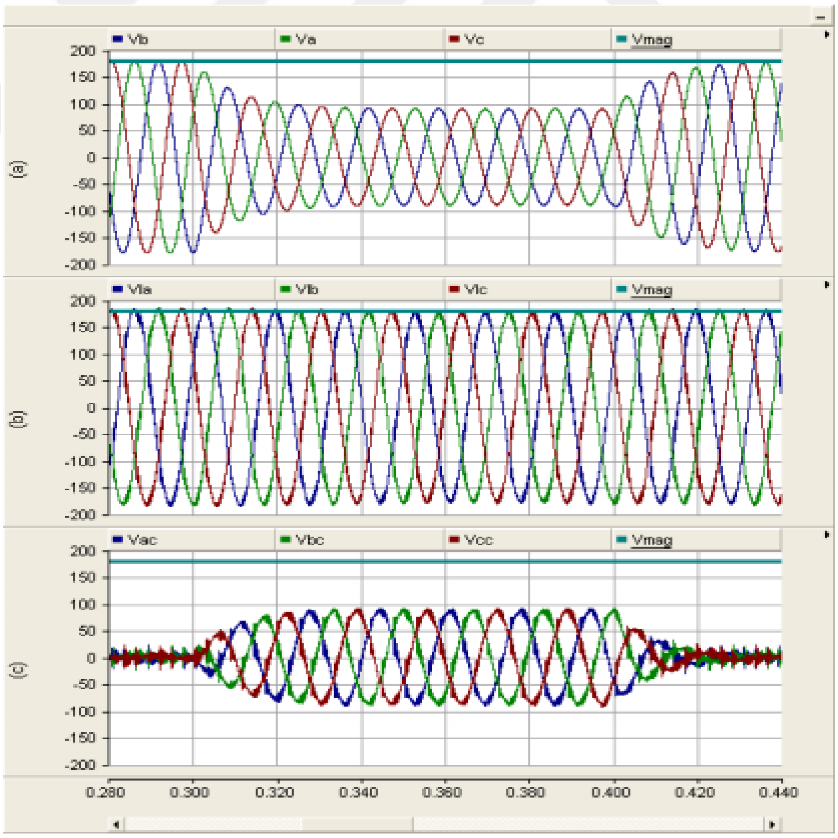


Figure 2.31 Source Voltage (b) Load Voltage (c) The voltage injected by the SSSC [41]

According to Figure 2.31, When voltage sag occurs in network DVR is activated and compensate low voltage.

2.2.1.1.2.2 Electronic Tap Changer

They are mounted at the inputs of transformers where sensitive loads are present. This technology ensures that the voltage value observed at the output of the transformer is set to the desired level. It is also known as SVR (Static Voltage Regulator). This equipment, which has several voltage stages, makes rapid transitions between stages to ensure that the voltage on the secondary side of the transformer remains constant in possible voltage oscillations. The transition period between these stages is approximately 10 ms. In Figure 2.32, electronic tap changer is demonstrated.

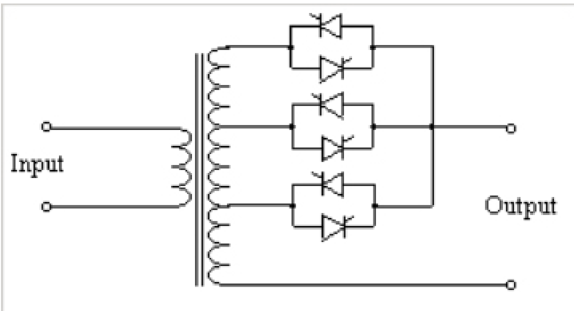


Figure 2.32 Electronic tap changer [42]

2.2.1.1.2.3 Dynamic Voltage Regulator

Dynamic Voltage Regulator is a low-cost electronic device used to regulate voltage imbalances in series or parallel-connected distribution networks. In Figure 2.33, General Structure of DVR is presented.

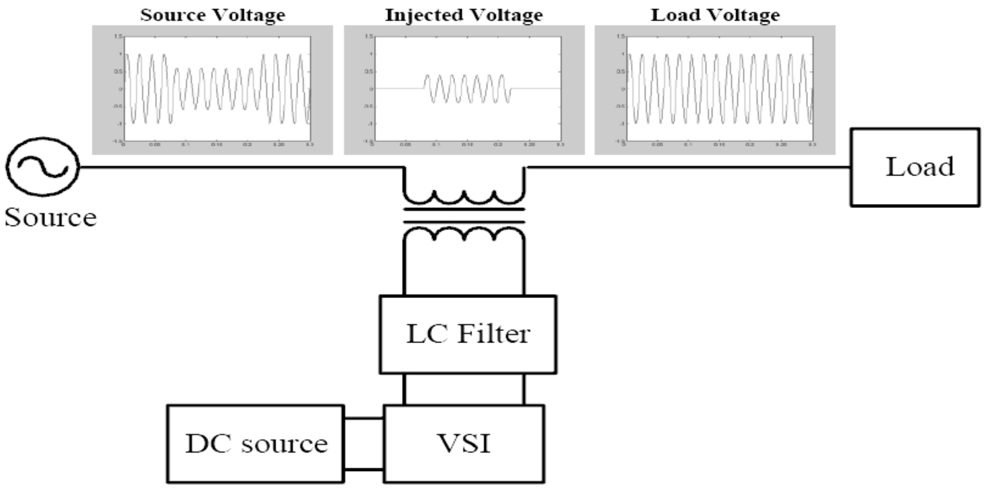


Figure 2.33 General structure of DVR [34]

The DVR consists of four main sections. These are Voltage source inverter, passive filter, injection transformer and storage unit. By calculating the voltage difference which occurs in case of any unbalance, it can provide the necessary voltage to eliminate this difference. In Figure 2.34, waveform of voltage sag is demonstrated.

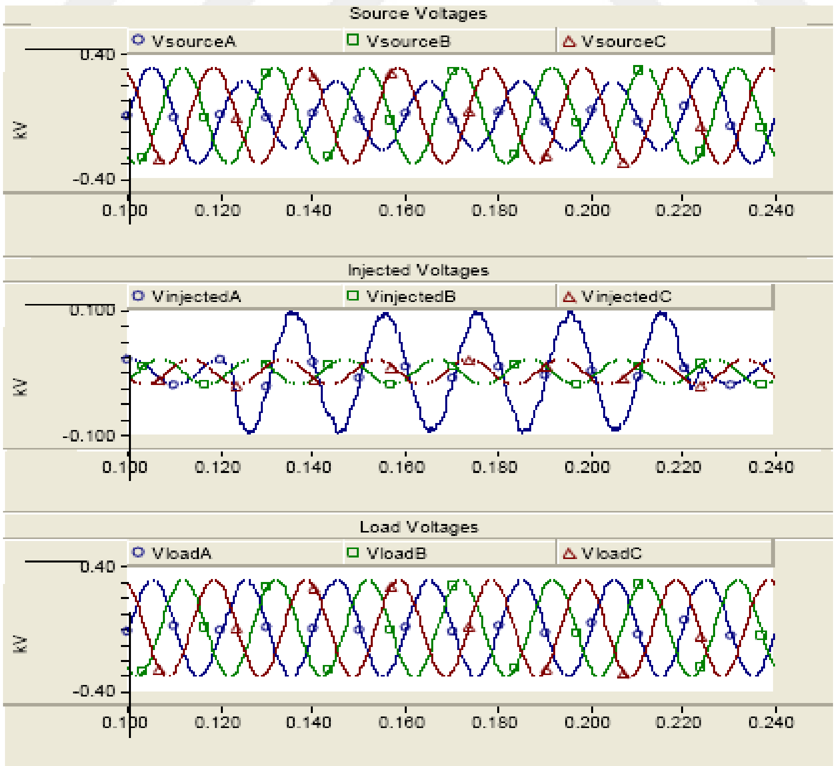


Figure 2.34 Source voltages, injected voltage, load voltage [34]

2.2.1.2 Voltage sag

A sag is a decrease in magnitude of voltage to among 0.1 pu and 0.9 pu for period from 0.5 cycles to 1 min. Voltage sag is generally defined as "two-dimensional" power quality events. This classification is done with the "minimum value / total time" approach. classifications are made with durations and voltage values. This approach considers the lowest RMS voltage value seen in three phases and the total duration of three phases returning to normal operating conditions [9].

2.2.1.2.1 Cause of Voltage Sag

- **Transformer energization:** It draw high current during energization of transformer. So voltage sag occurs in network. When the transformer is energized, firstly the three phase voltages fall at different ratios, then the voltage is recovered. An example is given in Figure 2.35.

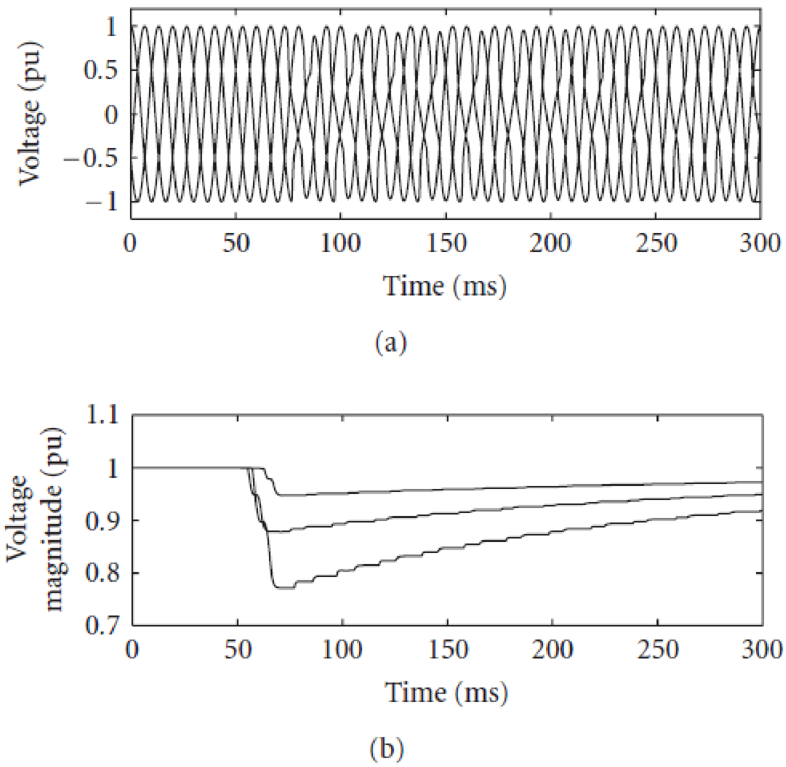


Figure 2.35 Voltage sag due to transformer energization a) voltage waveform b) voltage magnitude [37]

- **Voltage sag due to symmetric fault**: The most common cause of voltage sag in transmission and distribution systems is symmetrical and non-symmetrical faults. Faults with high current can cause voltage sag. In the case of symmetrical faults, the voltage drop in the three phases is the same. Voltage sag waveform and magnitude due to symmetrical fault are presented in Figure 2.36.

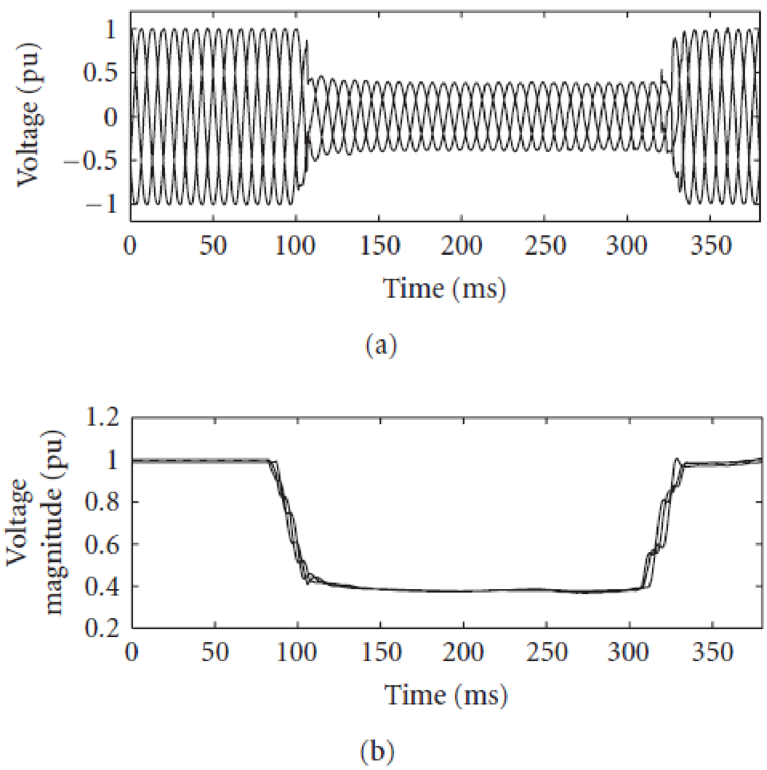


Figure 2.36 Voltage sag due to symmetrical fault a) Voltage waveform b) Voltage magnitude [37]

- **Voltage sag due to asymmetrical fault:** Differently from symmetrical faults, the voltage drop in each phase is different due to the fault occurring in one or two phases. An example is given Figure 2.37.

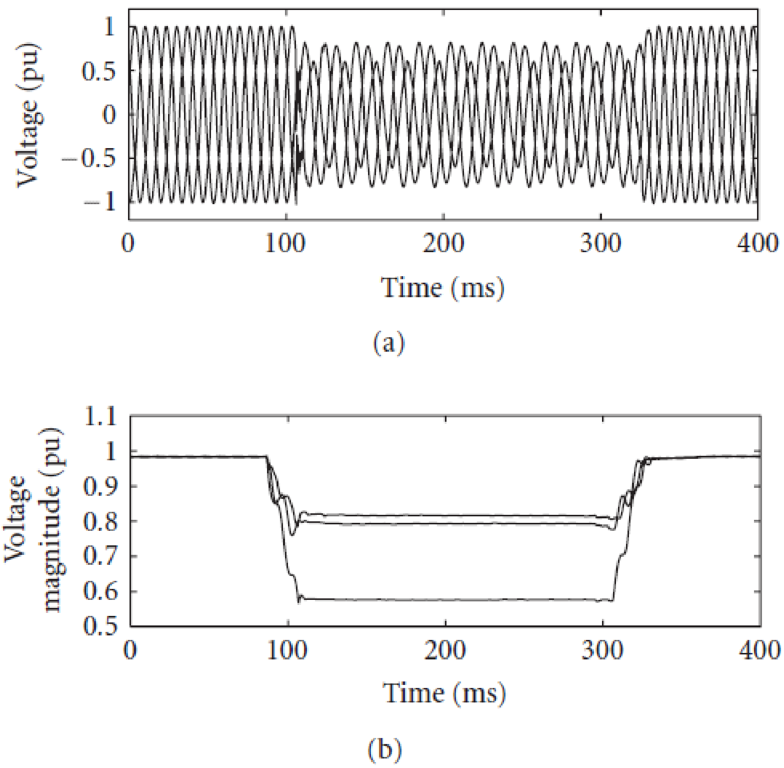


Figure 2.37 Voltage sag due to asymmetrical fault a) Voltage waveform b) Voltage magnitude [37]

- **Load Switching:** Switching of high power loads causes voltage drop. This drop in the voltage does not go back to its original state in a few seconds. As a result of disconnecting the load connection causing the voltage drop, the voltage level returns to its previous level. Example of voltage sag due to load switching is shown in Figure 2.38.

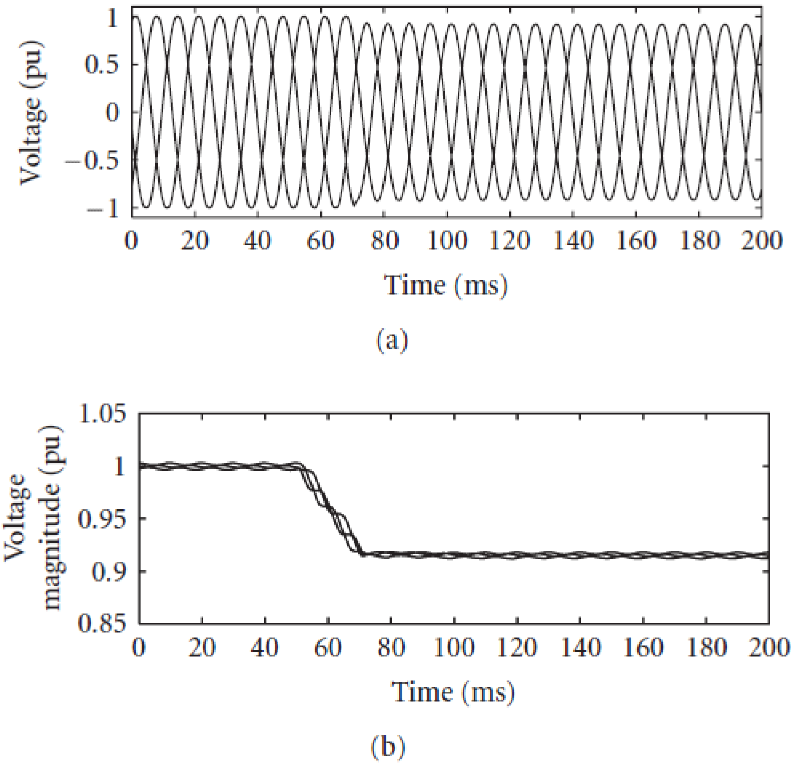


Figure 2.38 Voltage sag due to load switching a) voltage waveform b) voltage magnitude [37]

- **Induction motor starting:** The motors draw high current during starting. This high current initially causes the voltage drop. The motor current drops to the current value under normal operating conditions after the motor is driven. So gradual voltage recovery occurs in source voltage. Voltage magnitude and voltage waveform for voltage drop due to induction motor starting is demonstrated in Figure 2.39.

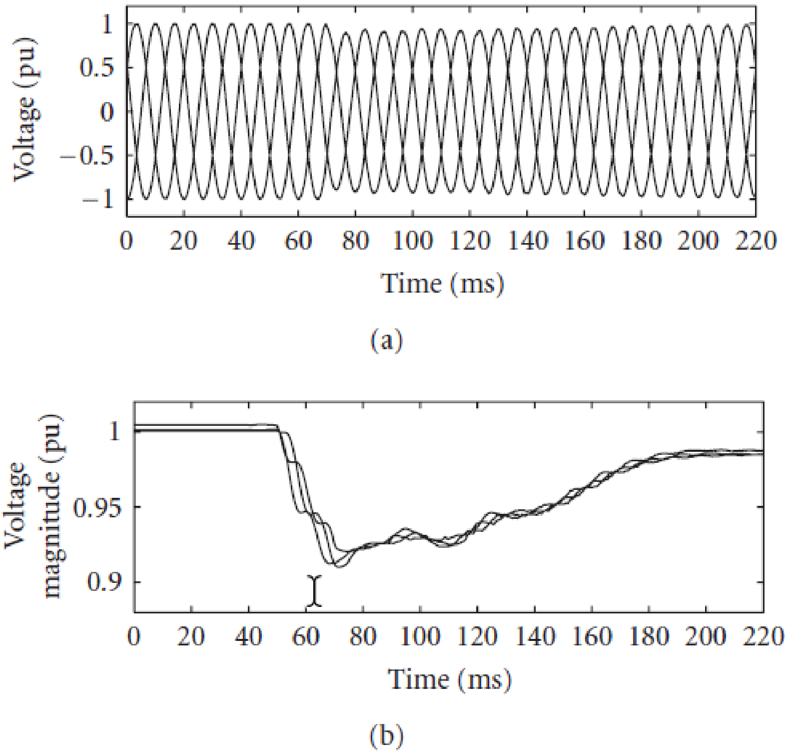
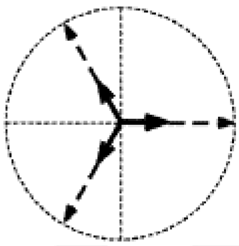
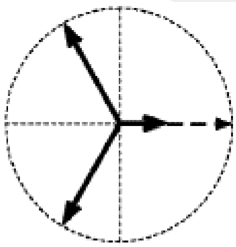
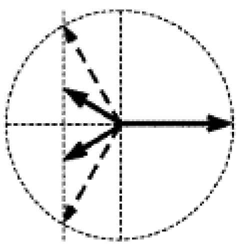
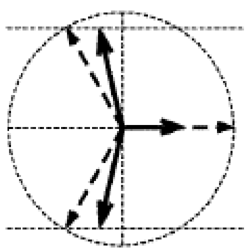
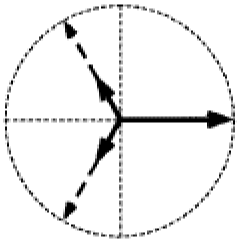
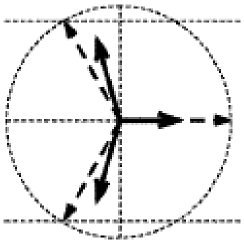
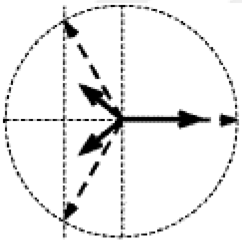


Figure 2.39 Voltage sag due to induction motor starting a) voltage waveform b) voltage magnitude [37]

Table 2.5 Reason and type of voltage sag [43]

TYPE OF VOLTAGE SAG	EXPLANATION OF VOLTAGE SAG	CAUSE OF VOLTAGE SAG
	The voltage value in the three phases is equal in magnitude and there is no phase shift	Three phase fault
	There is only one phase with a voltage sag, while the other phases are above the voltage sag limit and there is no phase shift at these phases.	Single phase fault
	There is a voltage sag across the two phases while they approach each other at the phase angles.	Two-Phase Fault or Single Phase Fault Propagation
	When there is a voltage sag across two phases, the two phase voltages are still large from the other phase and the phase angles move away from each other	Two-Phase Fault or Single Phase Fault Propagation

	While there is a voltage sag in two phase No phase difference is observed	Two phase ground Fault
	When there is a voltage sag across two phases, the two phase voltages are still large from the other phase and the phase angles move away from each other	Propagation of two phase ground fault
	There is a voltage sag across the three phases while they approach each other at the phase angles. İn two phase	Propagation of two phase ground fault

In Table 2.5, according to voltage magnitude and phase angle, reason and type of voltage sag is given [43]. This classification is based on voltage RMS values and phase angle.

2.2.1.2.2. Solution Method of Voltage Sag

- Static synchronous series compensator
- Static Transfer Switch
- Electronic Tap Changer
- Dynamic Voltage Regulator

- Uninterruptible Power Supply

- **Unified Power Quality Conditioner (UPQC):** The Unified power quality conditioner is a system in which the two voltage source inverter (VSI) are connected to a DC power storage capacitor. As shown in Figure 2.40, one of these VSI is connected in series to the network while the other is connected in parallel. It can perform both serial and parallel operations on the network.

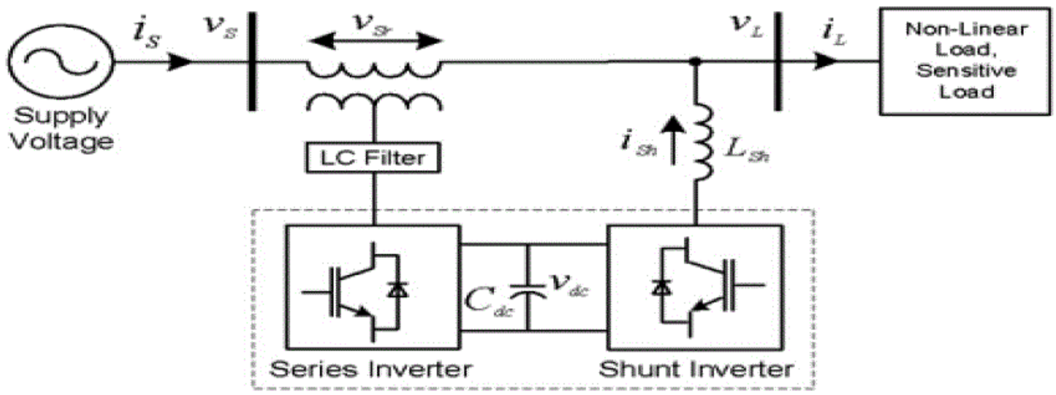


Figure 2.40 The system configuration of UPQC [44]

UPQC performs the voltage boost required by the network in voltage sag and voltage imbalances. At the same time, thanks to the parallel connection, current imbalances and harmonics can be eliminated. By using these two methods, it is possible to provide the desired amplitude and sinusoidal current and voltage for the loads. In Figure 2.41, load voltage waveform, source voltage waveform and voltage form injected by UPQS are shown.

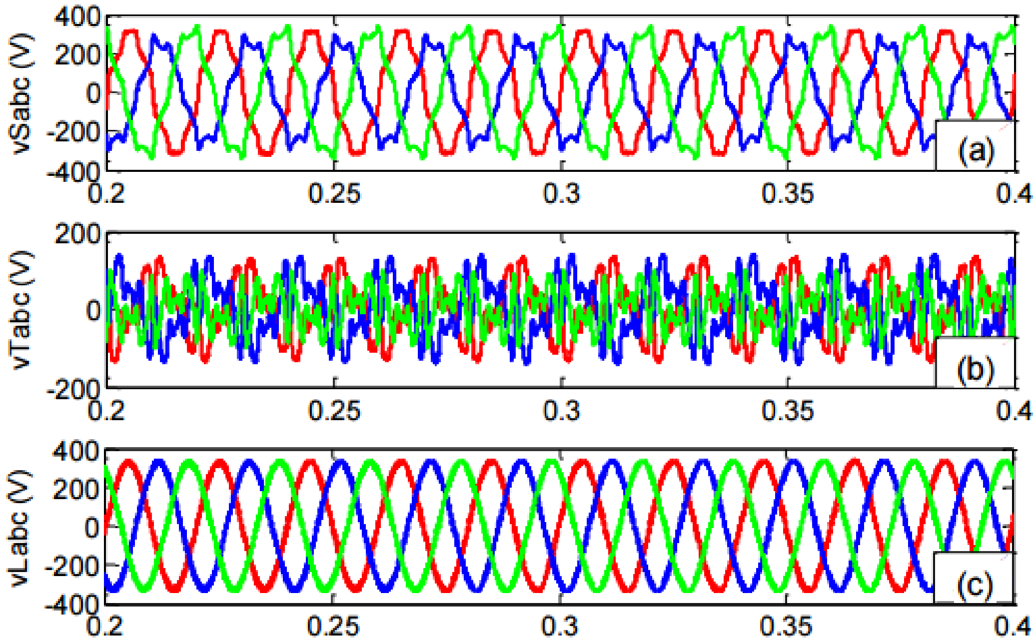


Figure 2.41 a) source voltage waveform B) voltage waveform injected by UPQS c) load Voltage waveform [34]

2.2.1.3 Voltage Interruption

Interruption is that the Source voltage declines below 0.1 pu for less than 1 minute. They are evaluated according to their duration, since the magnitude of the voltage generally falls below 10% of the nominal voltage [31]. Example of voltage interruption waveform is given Figure 2.42.

Figure 2.42 Waveform of voltage interruption [45]

2.2.1.3.1 Cause of Voltage Interruption

Interruptions due to network faults: An example of voltage interruption RMS value is demonstrated in Figure 2.43. According to Figure 2.43, there are four segment. After voltage level falls between 0.1-0.9 pu due to fault in first segment, it equal to zero pu in last segment.

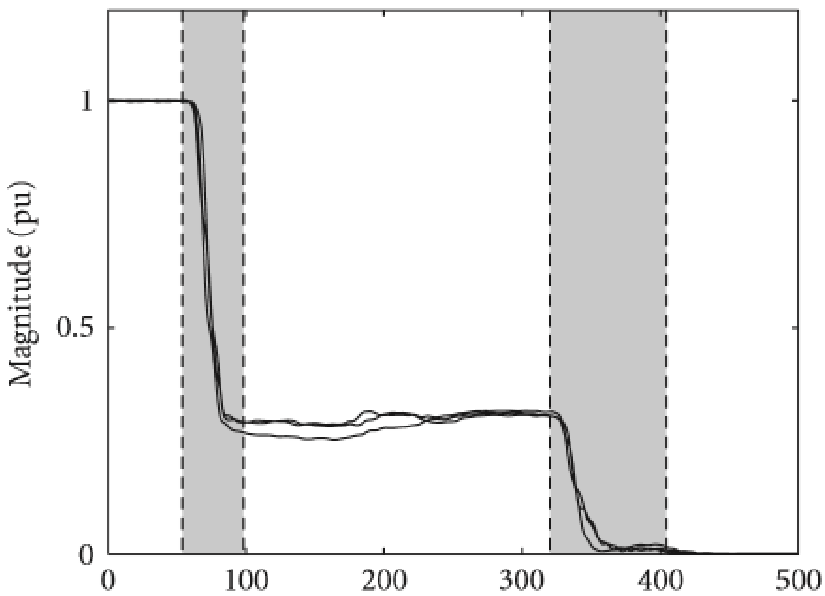


Figure 2.43 Voltage magnitude of interruption due to fault [37]

- **Planned Interruptions**: Voltage magnitude of interruption due to planned interruption is presented in Figure 2.44. According to Figure 2.44, there is one segment. In this stage, voltage magnitude decrease and finally equal to zero pu.

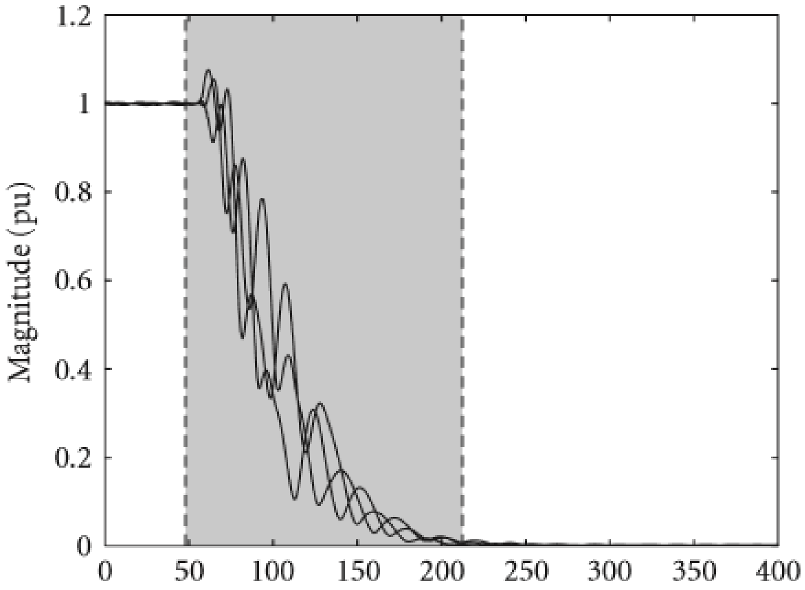


Figure 2.44 Voltage magnitude of planned interruption [37]

2.2.1.3.1.1 Solution Method of Voltage Interruption

2.2.1.3.1.1.1 Uninterruptible Power Supply

This technology, which can be summarized as an energy storage system connected to the network, provides energy the desired voltage level by activating in case of any voltage sags or interruptions in the network. In the event of a voltage sag or interruption, the source supplies the power supply at the desired voltage level for a period of minutes or hours in proportion to its capacity. This method, widely used for protecting small systems like computers, loses economic advantages for large systems. In Figure 2.45, Working principle of UPS is given.

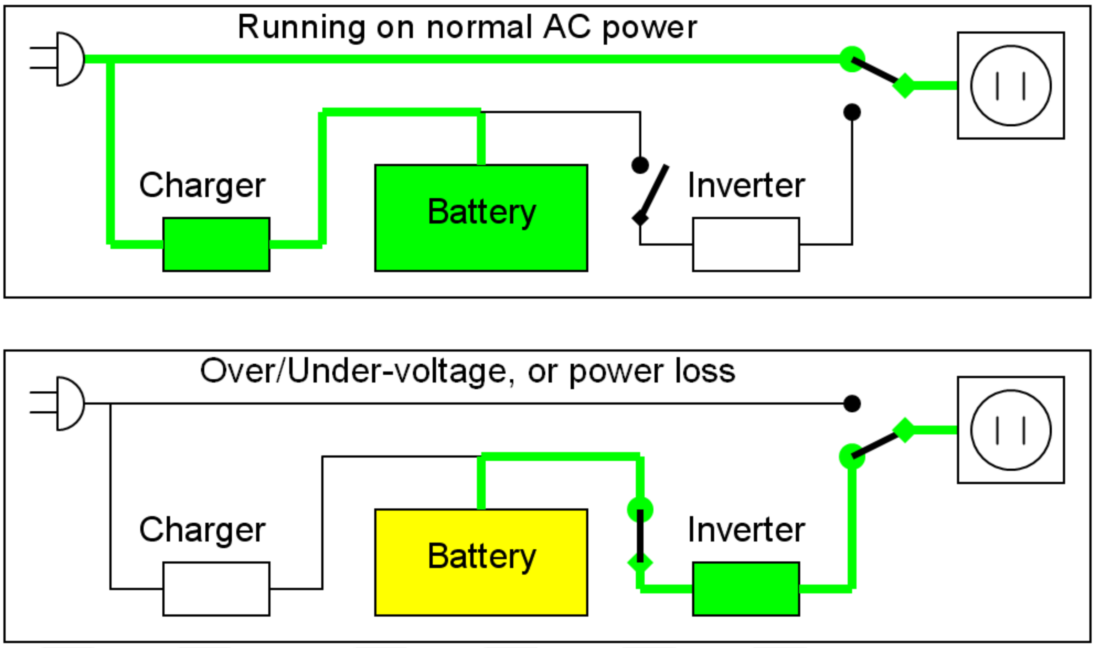


Figure 2.45 Workıng principles of UPS [46]

- **Static Series Switch**

2.2.2 Long Duration Voltage Variation

Load equipment problems are occurred by long duration voltage variation which continue higher than 1 minute. Overvoltage, Undervoltage and sustained interruptions are long duration voltage variation. Overvoltage and Undervoltage are not usually caused by system failures, but load changes and system switching operations cause them [31].

2.2.2.1 Overvoltage

The effective value of the voltage exceeds the value of 1.1 pu for more than 1 min. So failure can occur in electronic device due to overvoltage. Transformer or CTs or PTs cannot be easily affected by overvoltage, however sustained overvoltage can cause loss of equipment due to isolation problem. Solution methods of overvoltage are DVR, static series switching [9].

2.2.2.1.1 Cause of Overvoltage

It occurs as a result of disabling large loads or the activation of a capacitor group. In addition, the cause of the overvoltage is that the load in the system is reduced, the voltage controllers are inadequate and the transformer tap setting cannot be done correctly [9].

2.2.2.2 Undervoltage

The Undervoltage is that the effective value of the voltage decrease below 0.9 pu for longer than 1 min. Heating loss in motors enhances due to high current which is occurred by long duration Undervoltage. Solution methods of overvoltage are DVR, static series switching, UPQS [9].

2.2.2.2.1 Cause of Overvoltage

Switching events, such as activation of large loads or disabling capacitor groups, and overloaded circuits are among the causes of low voltage.

2.2.2.3 Sustained Interruption

The case where the supply voltage is less than 0.1 pu for more than 1 minute is defined as a sustained voltage interruption. When the voltage interruption is greater than one minute, it is mostly permanent, and human intervention is required to restore the system to its original state [31]. Voltage interruption limit for IEC, the supply voltage is less than 1% of the nominal voltage, less than 10% for IEEE. Voltage interruptions are often caused by triggered protection devices. Planned interruption by adjusted network operator can cause. Solutions method of sustained interruptions are UPS and static series switching.

2.2.2.4 Voltage Imbalance

Voltage unbalance is determined as proportion of amplitude of the negative sequence component to amplitude of positive sequence component, stated as a percentage. Generally, voltage unbalance in three phase system is lower than %3 [31]. Solutions method of voltage imbalance are SSSC, DVR and UPQC.

2.2.2.4.1 Cause of Voltage Imbalance

- Single / Two phase loads that have high power
- Unbalanced distribution of single / two phase loads on the network
- Single-phase or two-phase faults
- Blown fuses or overcurrent protective devices

2.2.2.5 Voltage fluctuation

Voltage fluctuations are rapid changes in voltage within the allowable range of 0.95-1.05 pu amplitude of nominal voltage. Rapid voltage fluctuations in power systems can cause a lot of harmful technical failures which can cause significant effects, such as the disruption of production processes where large investments are made [9]. Waveform of voltage fluctuation is shown in Figure 2.46. Solution methods of voltage fluctuations are SVC and D-STATCOM

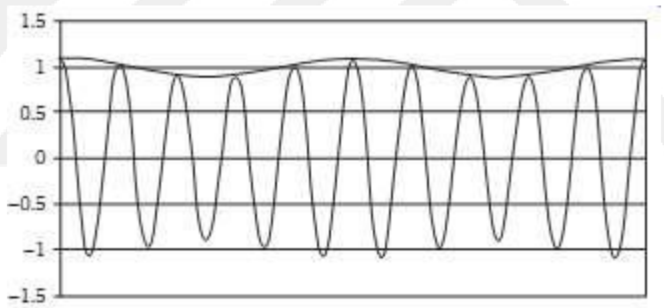


Figure 2.46 Waveform of voltage fluctuation [47]

2.2.2.5.1 Cause of Voltage fluctuation

- Arc furnace
- Drill
- Starting of induction motor
- Power regulator
- Welding machines
- Chainsaw
- Variation of production capacities of energy sources such as wind turbines

2.2.2.6 *Flicker*

Flicker term is originated from the effect of voltage fluctuation on light density. Flicker caused by variations in the loads is voltage fluctuations which cause flicker in light. The long term flicker severity index less than 1 (Plt ≤ 1) in 95% of the measurements. Long-term flicker severity index is calculated using Equation 2.5 with the short-term flicker severity index (Pst) measured at 10-minute intervals [31].

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} {P_{st}}^{3}} \qquad \textbf{(2.5)}$$

2.2.2.6.1 *Cause of Flicker*

Especially equipment, devices, or loads with sharp and continuous variable current in the reactive component cause the flicker observed in a network. Example of these loads are arc furnace, static frequency converter, direct frequency converters, rolling machine drives, starting of motors which have high power. Similarly, small power loads, such as welding machines, power regulators, heaters, and elevators, can produce flicker depending on where they are connected to the grid.

2.2.2.6.2 *Solution Method of Flicker*

2.2.2.6.2.1 *Static VAR Compensator*

The SVC assists in maintaining the voltage level on the network constant by performing reactive power generation and consumption. Absorbing the reactive power changes is the main reason why the network is used to solve flicker problems. In Figure 2.47 is shown configuration of SVC. In Figure 2.48, effect of the SVC established by ABB on the flicker is shown.

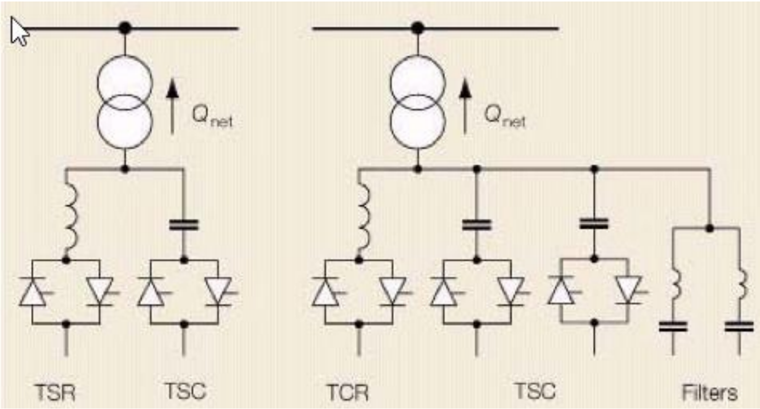


Figure 2.47 SVC configurations [48]

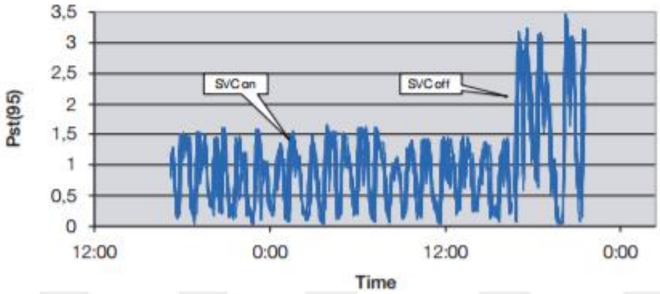


Figure 2.48 Effect of SVC on flicker [49]

2.2.2.6.2.2 D-STATCOM

This system can absorb both active and reactive power fluctuations. It also achieves flicker reduction by providing fast converter control through the use of voltage source converters (VSC) with pulse-width modulation (PWM). This concept emerges as the most appropriate method for reducing the flicker level today. Block diagram of D-STATCOM is demonstrated in Figure 2.49.

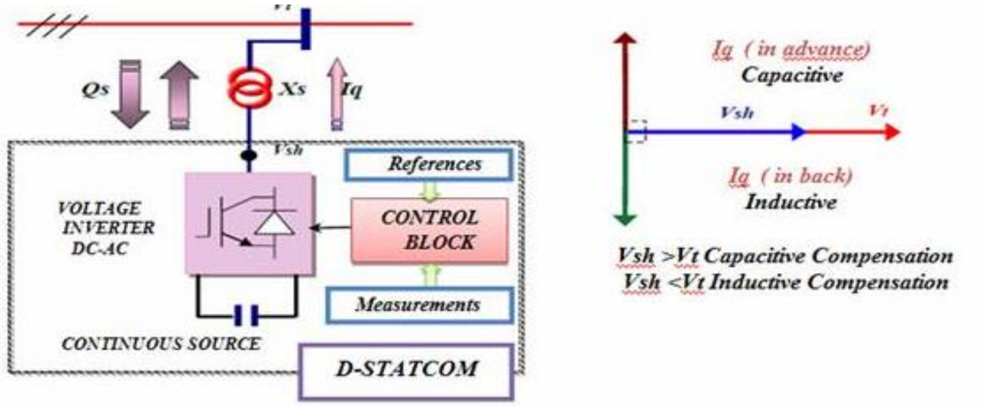


Figure 2.49 Block diagram of D-STATCOM [50]

incident angles near to 0°, the partial shading on back panel occurs and it cannot produce considerable amounts of power. This kind of partial shading occurs when the sunlight moves away from 0° vertically (in south-north direction).

2.2.2.7 Voltage Spike

Voltage spike is defined as a sudden increase in voltage that is less than 3 nanoseconds [51]. Causes of voltage spike are lightning, deactivation high-power loads. Active filter can be used to eliminate voltage spike.

2.3 Waveform Disturbance

2.3.1 Notching

Notch is periodic voltage distortion induced by normal operation power electronic equipment when current is transferred from one phase to another. Voltage notch is a periodic, harmonic content of it is high. So the notch can be considered as harmonic. However, it may not be easily defined with measurement device used generally harmonic analysis due to high frequency component of notching [31]. During the notching, Momentary short circuit occurs between two phase. This short circuit in equipment like as motor drives and three-phase rectifier cause notching. Example of voltage notching due to power electronic device is shown in Figure 2.50 Notch filter, isolation transformer and line reactor mitigate this disturbance.

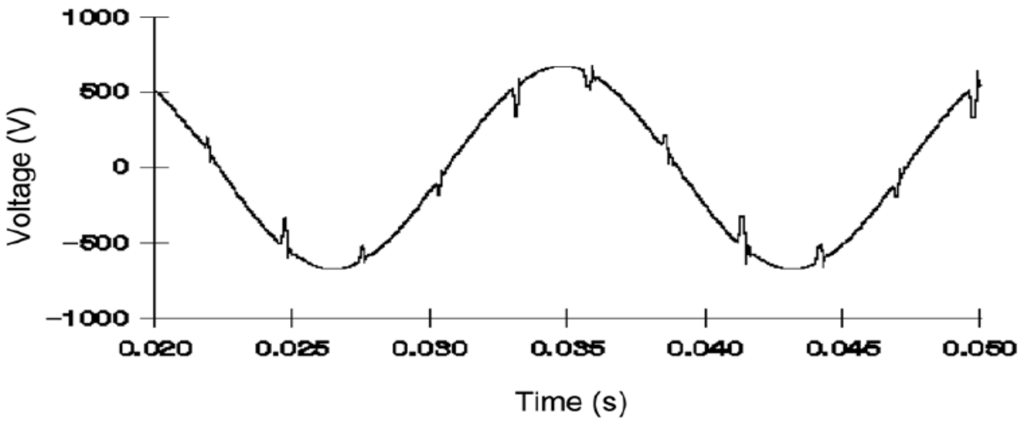


Figure 2.50 Example of voltage notching due to converter operation [31]

2.3.2 Noise

Noise is undesirable electrical signals with broadband spectral concept of less than 200 kHz added to current or voltage that can be carried over both phase conductors and neutral conductors. Incorrect grounding worsens generally noise problems. Power electronic devices, control circuit, arcing devices, switching power supply can cause noise problems. Filter and isolation transformer eliminate problems induced by noise [31]. In Figure 2.51, an example of noise in the sinusoidal waveform is given.

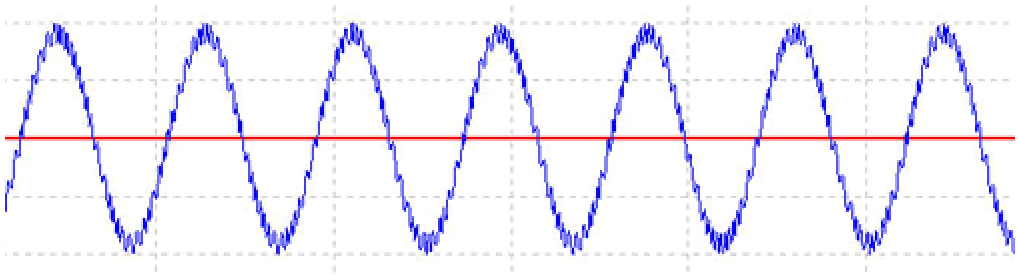


Figure 2.51 Noise in sinusoidal waveform [52]

2.3.3 DC offset

The presence of direct current or voltage in an alternative power system is called DC offset. Direct current generated in an AC network can cause saturation of an AC transformer in normal operating conditions. As a result, the transformer overheats and it shortens life of transformer. Half wave rectifier can cause DC offset in AC power network. High pass filter mitigate DC offset [9]. Sinusoidal waveform with direct DC offset is shown in Figure 2.52

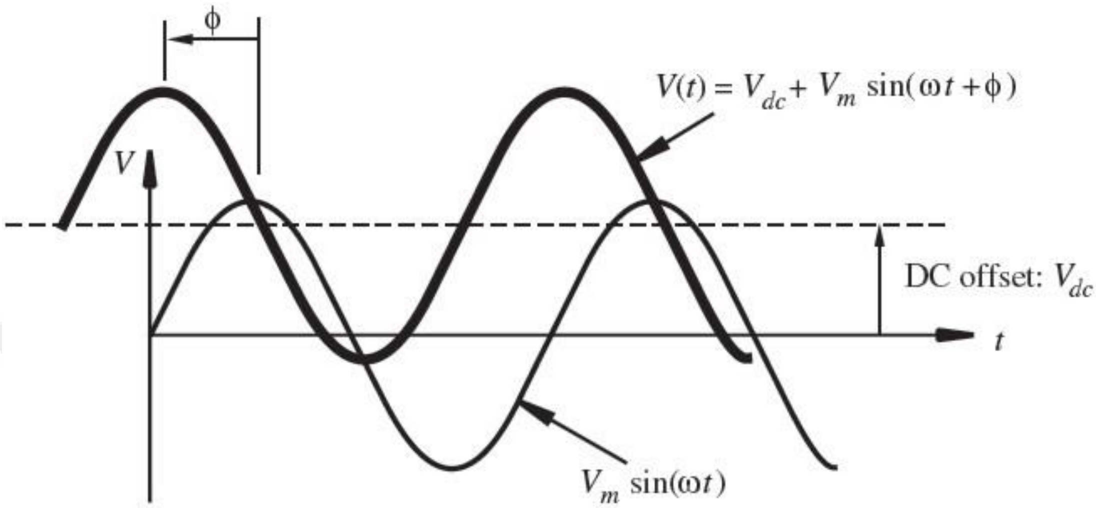


Figure 2.52 Sinusoidal waveform with DC offset [53]

2.3.4 Transient

The transient event is defined as unwanted short-time events in the analysis of power systems [54]. It is a sudden increase or decrease in the voltage or current that defines the transients by IEEE [31] In other words, transient events are changes that occur during the transition from a steady state to another of a system. Transient events are divided into two type as impulsive transient and oscillatory transient [31].

2.3.4.1 Impulsive Transient

Impulsive transients are either positive or negative (unidirectional) sudden changes in current, voltage, both magnitudes in steady state conditions. Impulsive transient events are usually defined by their rise and decay times. When impulsive transient is depicted like 1.2/50 μs, 1.2 shows rise time. 50 shows decay time [31]. Because frequency is high, voltage and current waveform rapidly. Therefore, currents and voltages may show different characteristics when viewed from different parts of the power system [9]. An example of current impulsive transient is shown in Figure

2.52. Lightning, electrostatic discharge causes impulsive transient. Surge Arrester protects from lightning that causes impulsive transient.

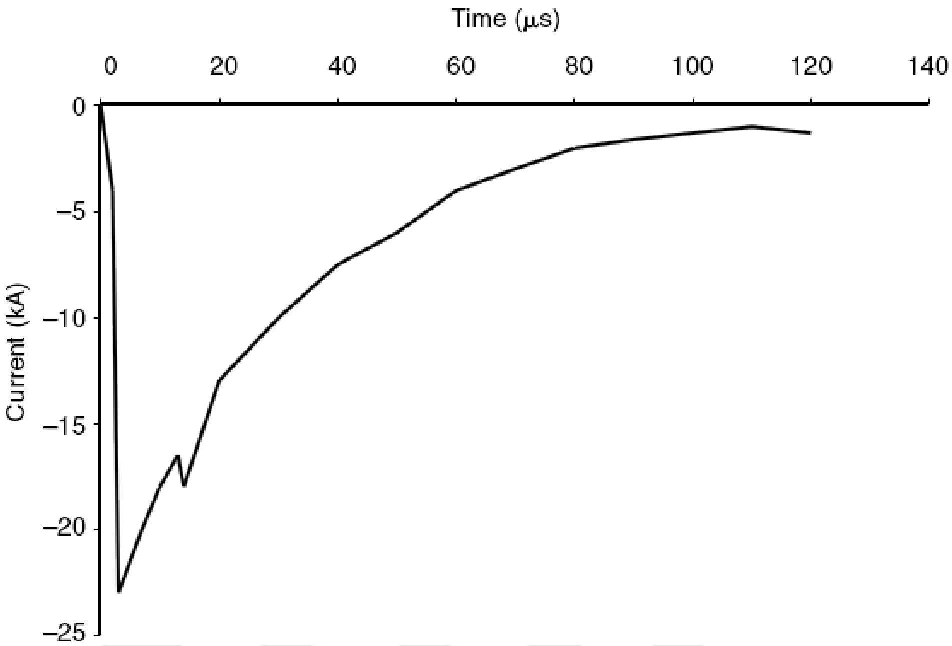


Figure 2.53 Current impulsive transient caused by lighting [31]

2.3.4.2 Oscillatory Transient

Impulsive transients are both positive and negative (bidirectional) sudden changes in current, voltage or both magnitudes in steady state conditions. Its amplitude, frequency, spectral content defines oscillatory transient. Oscillatory transient with fundamental frequency content higher than 500 kHz and continuance measured in microseconds is defined high frequency oscillatory transient. Some of switching event causes these transient. Fundamental frequency component between 5-500 kHz and continuance calculated in tens of microsecond is pondered medium frequency transient. Capacitor energization causes these transient. Fundamental frequency content lower than 5 kHz and a continuance from 0.3 ms to 50 ms is pondered low frequency transient [31]. Oscillatory transient caused by capacıtor energization is shown in Figure 2.54. In Figure 2.55, oscillatory transient due to Ferro resonance of transformer is given.

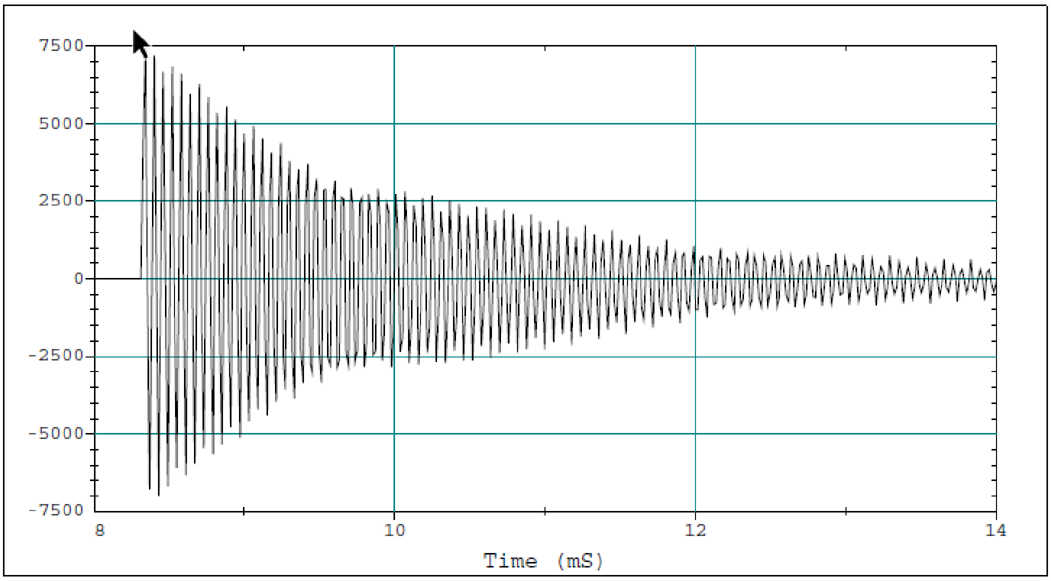


Figure 2.54 Oscillatory transient caused by capacitor energization [31]

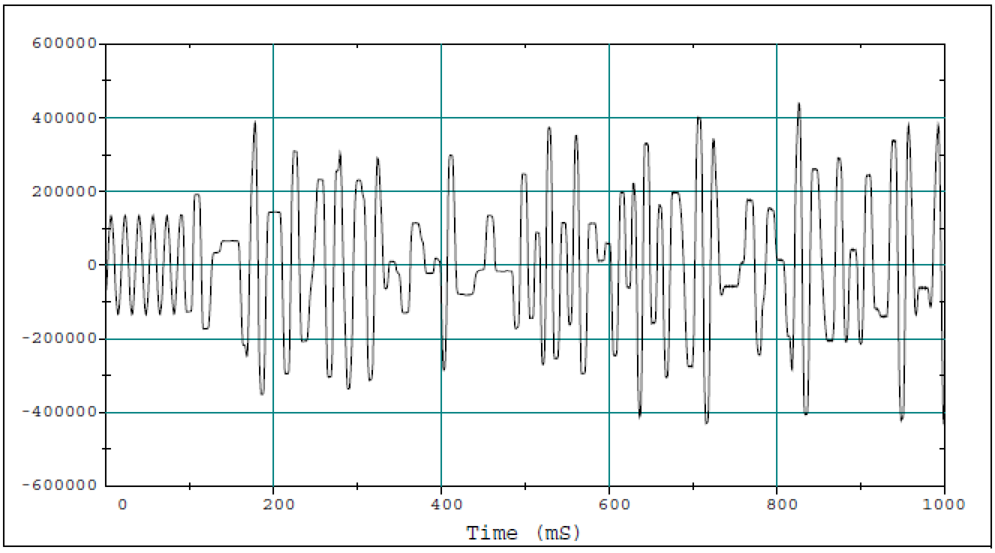


Figure 2.55 Oscillatory transient due to Ferro resonance of transformer [31]

CHAPTER 3

NATIONAL AND INTERNATIONAL POWER QUALITY STANDARDS

3.1 Regulation Quality Service for Electricity Distribution and Retail Sale [22]

3.1.1 Objective and Scope

This Regulation covers the principles and procedures to be followed by the distribution companies, the authorized procurement companies and the users in terms of the supply continuity, commercial and technical quality of the electrical energy.

3.1.2 Technical Terms and Calculations

- **Connection point:** Specifies the site or liaison point where users connect to the distribution system according to connection agreements.
- **Flicker**: Voltage swings below 50 Hz that occur due to over-current fluctuations and cause flicker in lighting armature.
- **Harmonic**: In an alternating current or voltage distorted by nonlinear loads or non-ideal generators with voltage waveforms, each of the sinusoidal components consisting of frequencies that are full multiples of the fundamental component frequency.
- **Steady state**: The system state in which the operating values can be assumed to be constant after the transient regime conditions are damped.
- **Maximum load current** (I_L): The effective value of the fundamental component of load current, calculated as the maximum of 15 or 30 minute average values.
- **Plt**: indicates the flicker intensity index calculated from the Pst values measured over the two-hour time interval (12 consecutive measurements) according to the Equation 3.1

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} {P_{st}}^{3}} \quad \textbf{(3.1)}$$

- **Pst**: indicates the flicker intensity index measured over 10 minute periods.
- **Total Harmonic Distortion**: The value calculated using Equation 3.2 formula and equal to the ratio of square root of sum of squares of voltage harmonic components' effective value over effective value of the main components expressing distortion of waveform as a percentage

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{40} V_{effn}^{2}}}{V_{eff1}} = \sqrt{\left(\frac{V_2}{V_1}\right)^2 + \left(\frac{V_2}{V_1}\right)^2 + \cdots + \left(\frac{V_n}{V_1}\right)^2 +} \quad \textbf{(3.2)}$$

- Total Demand Distortion (TDD): The value calculated using Equation 3.3 formula and equal to the ratio of square root of sum of squares of current harmonic components' effective value over maximum load current (IL) expressing distortion of waveform as a percentage.

$$TTD = \frac{\sqrt{\sum_{2}^{40} {I_h}^{2}}}{I_L} \text{ x } 100 \quad \textbf{(3.3)}$$

3.1.3 Network Technical Quality Requirements

In the operation of the distribution system, the voltage effective values in steady state and transient regime conditions must comply with the following values defined in TS EN 50160: 2011 in steady state:

- For Low voltage level; at least 95 % of 10-minutes-averages for voltage effective values during measurement period should change ±10 % of nominal effective voltage value at the maximum and total variation should be in +10 % -15 % interval of nominal effective voltage value at the maximum.
- 2- For MV level; at least 99% of the 10-minute average of the voltage active values measured during the measurement period (one week without a break) defined in TS EN 61000-4-30 [23] during the measurement period shall not

exceed + 10% of the declared effective voltage, at least 99% of these averages must not fall below 10% of the declared effective voltage value. None of the 10-minute averages of the measured voltage active values shall be outside the ± 15% limits of the declared effective voltage.

In the operation of the distribution system, the voltage imbalances in the steady state for the LV level must comply with the following values defined in TS EN 50160: 2011:

- 1-The ratio of at least 95% of positive 10-minute averages of the voltage negative component active values measured over the measurement period to the positive components should be at most 2%.
- 2- This rate can be up to 3% at the points where single-phase or two-phase loads are fed.

Distribution company is obliged to comply with the voltage harmonic limit values defined in TS EN 50160: 2011 standard and shown in Table 3.1. The values in Table 3.1 represent the proportional values of each voltage harmonic relative to the fundamental component. At least 95% of the 10-minute average of each voltage harmonic effective value measured during the measurement period must be less than or equal to the values given in Table 1. However, the THD value (including values up to the 40th harmonic) is applied as a maximum of 8%. The performance of the distribution company for voltage harmonics is measured mainly at the connection point for LV and MV level.

Table 3.1 Limit values for voltage harmonics

Odd harmonics				Even Harmonics	
Not multiples of 3		Multiples of 3			
Order h	**Relative voltage (%)**	**Order h**	**Relative voltage (%)**	**Order h**	**Relative 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				

Distribution system users subject to reactive energy fee are obliged to comply with the following harmonic limit values specified in IEEE Std. 519-1992 [31] or its revisions. Effective value of each current harmonic during measurement period and 3-second-averages of TDD proportional values to I_L should be lower than or equal to values shown in Table 3.2. The performance of the user in terms of current harmonics is measured mainly at the connection point for LV and MV level. However, if the distribution company needs it, the measurement can also be made at the point for billing. However, in this case, the current harmonics in transformer windings for MV users should be considered.

Table 3.2 Limit values for voltage harmonics

Single Harmonics						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤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
Double harmonics are restricted to 25 % of the value defined for the single harmonic after them.						

The distribution company ensures that the limit values in Table 3.3 of the network are not exceeded for the user's contribution to the network. The flicker intensity is measured by means of "Pst and Plt" indicators and by flicker meters according to TS EN 61000-4-15.

Table 3.3 Limit values for flicker severity

Flicker Severity Index	Limit Values
P_{st}	≤ 1.0
P_{lt}	≤ 0.8

3.2 EN 50160 Voltage Characteristic of Electricity Supplied by Public Distribution Systems

This European Standard defines and explains the main characteristics of the voltage supplied to electricity subscribers in LV and MV electricity distribution networks under normal operating conditions. This standard specifies the maximum or minimum limit voltage values that can be observed on the network, rather than the average operating conditions shown on the network. The limit values specified in this standard do not apply to the following abnormal operating conditions:

- Temporary supply in order to ensure that the users do not become electrically discharged as a result of interruption of electricity supply (malfunction, maintenance or repair) for any reason.
- Limit exceed resulting from network connections that do not comply with standards or technical conditions established by public authorities or distribution partners
- In exceptional situations (exceptional weather conditions and other natural disasters, third party interference, acts by public authorities, industrial actions (subject to legal requirements), force majeure, power shortages resulting from external events.)

Supply voltage characteristics described or defined in this European standard:

a. Frequency
b. Magnitude
c. Waveform
d. Symmetry of line voltage

These characteristics are subject to variations during the normal operation of a supply system because of load, disturbances produced by certain equipment and the existence of faults which are generally caused by external events [39].

3.2.1 Voltage Characteristics Limit Values [39]

3.2.1.1 Voltage Characteristics Limit Values in LV Network

The voltage characteristics of the LV network specified under EN 50160 standard are given in Table 3.5 in detail. The harmonic limit value in Table 3.4 is defined by the total harmonic distortion. At the same time, the harmonic value of each level must remain within certain limits. These harmonic limit values are given in Table 3.4.

Table 3.4 Limit value for voltage harmonic in LV

Odd harmonics				Even Harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative 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				

Table 3.5 Voltage Characteristic values in LV network

	Measurement time interval	Minimum Value	Maximum Value	Time of Employment
Power Frequency	10 sec	49.5 Hz	50.5 Hz	99.5% of the week
Power Frequency	10 sec	47 Hz	52 Hz	100%
Nominal Voltage Range	10 min R.M.S. value	0.9 Un	1.1 Un	95%
Flicker	2 hour	-	Plt ≤ 1	95% of the week
Voltage Sag	<1 sec	0.1 U	0.9 U	-
Short İnterruption	<3 min	-	0,1 U	-
Long İnterruption	>3 min	-	0,1 U	-
Voltage Swell	10 min R.M.S. value	1,1 U	1,5 kV	-
Voltage Swell	ms - µs	1,1 U	6 kV	-
Voltage Harmonics*	10 min R.M.S. value	-	THD > 8%	95% of the week
Communication signals (0.1 kHz- 100 kHz)**	-	1 Un	9 Un	-
Unbalance (Negative Component)	10 min R.M.S. value	0% of the positive component	2% of the positive component	95%
Unbalance (Negative Component) (If there is Single phase or two phase load)	10 min R.M.S. value	0% of the positive component	3% of the positive component	95%

* Detailed limit values are given in Table 5
** limit values depending on the frequency is given in Figure 3.1.

The communication signals in the distribution network are also limited to certain limits according to the frequency value. The maximum amplitude (relative to the value of Un) that these signals can take based on their frequency is shown in the graph in Figure 3.1.

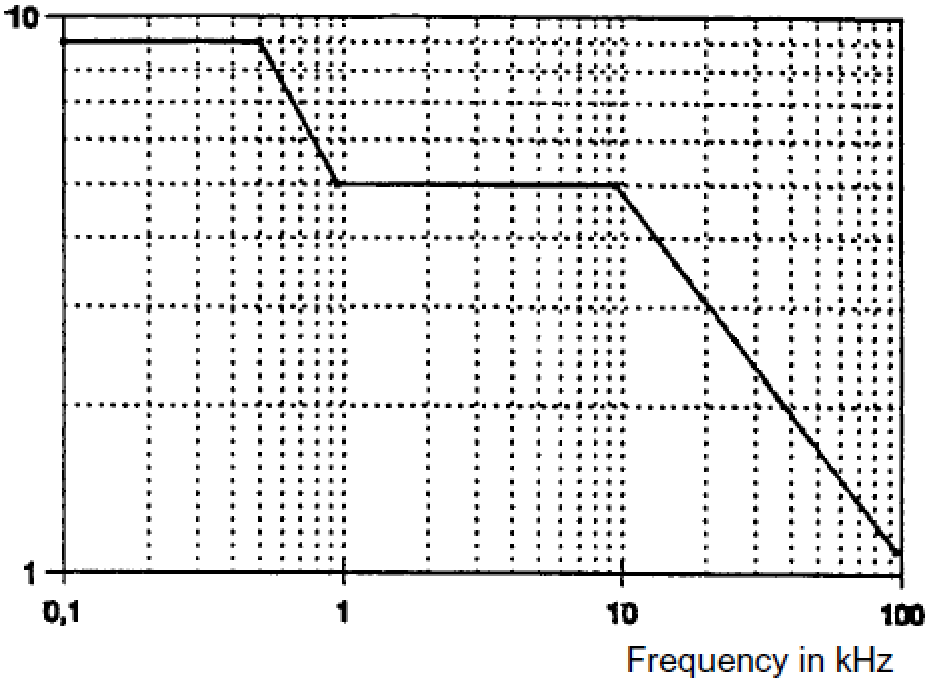


Figure 3.1 Voltage levels of signal frequencies in percent of U_c used in public LV networks

3.2.1.2 Voltage Characteristics Limit Values in MV Network

The voltage characteristics of the MV network according to the EN 50160 standard are given in Table 3.7 in detail.

Table 3.6 Limit value for voltage harmonic in MV network

Odd harmonics				Even Harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative 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				

Table 3.7 Voltage Characteristic values in MV network

	Measurement time interval	Minimum value	Maximum value	Time of Employ ment
Power Frequency	10 sec	49.5 Hz	50.5 Hz	99.5% of the week
Power Frequency	10 sec	47 Hz	52 Hz	100%
Nominal Voltage Range	10 min R.M.S. value	0.9 Un	1.1 U_n	95%
Flicker	2 hour	-	Plt ≤ 1	95% of the week
Voltage Sag	<1 sec	0.1 U	0.9 U	-
Short Interruption	<3 min	-	0,1 U	-
Long Interruption	>3 min	-	0,1 U	-
Voltage Swell	10 min R.M.S. value	1,1 U	1,7 U_c	-
Voltage Harmonics*	10 min R.M.S. value	-	THD > 8%	95% of the week
Communication Signals (0.1 kHz- 100 kHz)**	-	1 U_n	9 U_n	-
Unbalanced (Negative Component)	10 min R.M.S. value	0% of the positive component	2% of the positive component	95%
Unbalanced (Negative Component) (If there is a single phase or two phase load)	10 min R.M.S. value	0% of the positive component	3% of the positive component	95%

*Detailed limit values are given in Table 3.6
** limit values depending on the frequency is given in Figure 3.2

Similarly, the limit values for each harmonic grade are shown in Table 3.6 in the MV voltage characteristic values. The communication signals in the MV network also have similar limit values as in the LV network. The maximum amplitude (relative to Un) values of the communication signal to frequency are shown in the Figure 3.2.

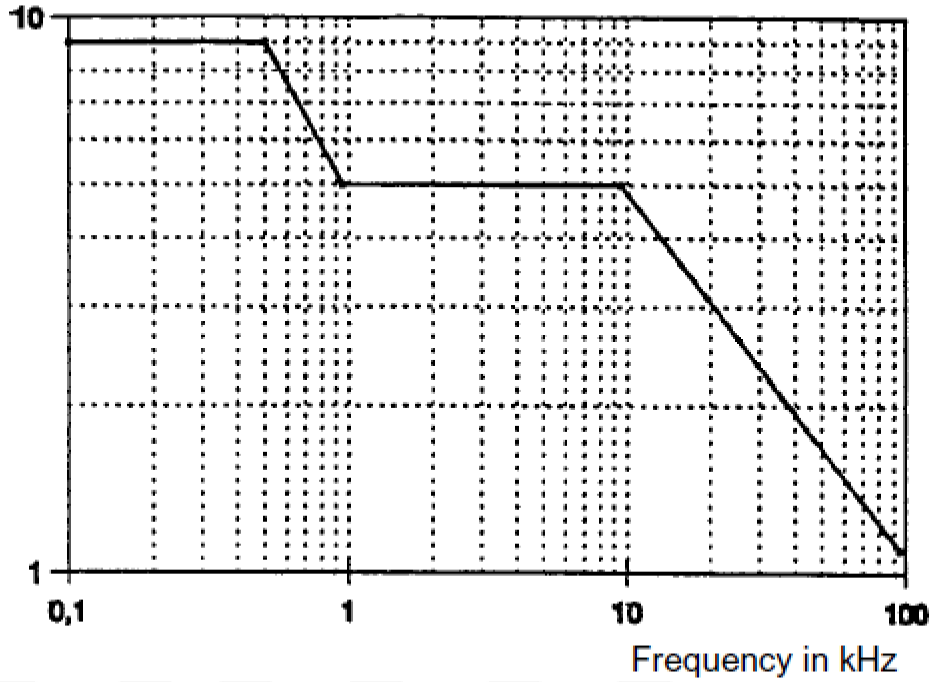


Figure 3.2 Voltage levels of signal frequencies in percent of U_c used in public LV networks

3.3 IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems [38]

3.3.1 Introduction

The electrical network includes nonlinear loads such as static power converters, arc discharge systems, saturated magnetic systems, and rotating machines, as well as harmonic generating systems or devices. Electrochemical power supplies, fixed speed drives and static power converters such as UPS are used for various purposes as the largest nonlinear loads. Such systems or devices perform ac / ac, ac / dc, dc / dc and dc / ac conversions.

Non-linear loads change the sinusoidal nature of the current signal. Hence, harmonic currents cause interference with communication circuits and other types of equipment. At the same time, these harmonic currents increase the technical losses and heating of various network equipment (ex. transformers, motors). In addition, reactive power compensation systems can generate Ferro resonance effects with harmonic currents, which can cause significant degradation of current and voltage signals.

Among the most known sources of harmonic currents in power systems are electronic converters, arc furnaces, static VAR systems, inverters for distributed generation, AC phase controllers, direct frequency converters and ac / dc converters for use in switch mode power supplies and PWM motor drivers. The harmonic currents produced by all these harmonic current sources do not vary with time, or the network characteristic, the state of the control device or other influences can vary quite.

3.3.2 Scope

This recommended practice sets goals for the design of electrical systems involving linear and non-linear loads. The interface between the sources and the loads is defined as the common coupling point, and compliance with the design goals will reduce the minimum interference between the electrical devices. This recommended practice addresses steady-state limitations. These limitations may be exceeded by transient conditions. This document specifies the quality of the power to be provided at the point of common coupling.

3.3.3 Objective

This recommended practice is intended as a guideline for the evaluation of the power quality situation in power systems where non-linear loads are present. The steady-state limit values indicate the worst possible operating conditions for the system. Transient conditions that exceed these limits can be observed. The limit values given in this document are only recommendations and should not be taken as limit values in each system condition.

This recommended practice should be applied at interface points between system owners or operators and users in the power system. This interface point (PCC) is defined as the closest point to the user of the network. Industrial users are often identified as the MV side of service transformer. In commercial users (shopping malls, offices, etc.) this point is designated as the LV side of the service transformer. The limit values determined in this application equally distribute the harmonic control responsibility to both the system operator and the user. The current harmonics generated by the users cause voltage distortions which cause other users to be affected. The total of harmonic voltage distortion supplied to other users is a function of the aggregate effects of the harmonic current generating loads of all users and the impedance characteristics of the supply system.

Requirements to keep the harmonic voltage distortion below the specified limit values:

- All users limit their harmonic current emissions to reasonable values, determined in an equitable manner based on the inherent ownership stake each user has in the supply system.
- The network operator should be able to take action to modifying the system impedance in order to reduce the voltage distortion level when it is necessary.

Users should not add passive equipment that impact the impedance characteristic in a way such that voltage disturbance are extend. In effect, such actions by a user could amount to generating immoderate voltage harmonic distortion.

3.3.4 Recommended Harmonic Voltage Limit Values

The phase voltage harmonics measured at the PCC should be limited by the network operator under the following conditions:

- Daily 99^{th} percentile very short time (3 s) values should be less than 1.5 times the values given in Table 3.8.
- Weekly 95^{th} percentile short time (10 min) values should be less than the values given in Table 3.8.

Table 3.8 Voltage harmonic limits

Bus voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortions (THD) (%)
V<= 1 kV	5	8
1kV< V <= 69 kV	3	5
69kV< V <= 161 kV	1.5	2
161 kV< V	1	1.5^{a}

a: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

3.3.5 Recommended Current Distortion Limits for Systems Nominally Rated 120 V through 69 kV

These limit values are determined for users whose voltage rating at the PCC point is between 120 V and 69 kV. Users shall limit their harmonic current values to the following conditions:

- Daily 99^{th} percentile very short time (3 s) harmonic currents should be less than 2 times the values given in Table 3.9.
- Weekly 99^{th} percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 3.9.
- Weekly 95^{th} percentile short time (10 min) harmonic currents should be less than the values given in Table 3.9.

Table 3.9 Current distortion limits for systems rated 120 V through 69 kV

Individual harmonic order (odd harmonics)						
I_{SC}/I_L	3≤ h <11	11≤ h < 17	17≤ h < 23	23 ≤ h < 35	35≤ h ≤50	TDD
< 20**	2,00	1,00	0,75	0,30	0,15	2,50
20-50	3,50	1,75	1,25	0,50	0,25	4,00
50-100	5,00	2,25	2,00	0,75	0,35	6,00
100-1000	6,00	2,75	2,50	1,00	0,50	7,50
>1000	7,50	3,50	3,00	1,25	0,70	10,00

The I_{SC} value in the table is the maximum short circuit current value in PCC and I_L is the maximum current demand value in PCC in normal operating conditions. Even harmonics are limited to 25% of the odd harmonic limits above. In these measurements, the DC component of the current signal is not included in the measurements.

3.3.6 Interharmonic Voltage Limits Based on Flicker

The inter harmonic components are not integer multiples of the power frequency, and the inter harmonic value shown in Figure 3 should remain below the limit values determined at 95% of the weekly measurements in short time measurements. As can be understood from Figure 3.3, the limit values vary depending on the voltage value observed in the PCC. Table 3.10 shows a detailed table of inter harmonic limit values for networks of less than 1 kV. These inter harmonic limit values are related to the 60 Hz short-time and flicker intensity (Pst) 1.0, and similar limit values can be obtained for 50 Hz systems. These limit values do not take into account the effects of other equipment on the network.

Table 3.10 Voltage inter harmonic limits corresponding to Figure 3.3 for PCC voltage less than 1 kV

Voltage Inter Harmonic in LV Network									
Frequency (Hz)	Limit (%)	Frequency (Hz)	Limit (%)	Frequency (Hz)	Limit (%)	Frequency (Hz)	Limit (%)	Frequency (Hz)	Limit (%)
16	5	35	1,05	54	0,29	73	0,34	92	1,64
17	4,5	36	0,95	55	0,35	74	0,38	93	1,78
18	3,9	37	0,85	56	0,4	75	0,43	94	1,9
19	3,45	38	0,81	57	0,58	76	0,48	95	2,03
20	3	39	0,78	58	0,77	77	0,5	96	2,15
21	2,77	40	0,71	59	0,95	78	0,57	97	2,3
22	2,53	41	0,64	60	1	79	0,64	98	2,53
23	2,3	42	0,57	61	0,95	80	0,71	99	2,77
24	2,15	43	0,5	62	0,77	81	0,78	100	3
25	2,03	44	0,48	63	0,58	82	0,81	101	3,45
26	1,9	45	0,43	64	0,4	83	0,85	102	3,9
27	1,78	46	0,38	65	0,35	84	0,95	103	4,5
28	1,64	47	0,34	66	0,29	85	1,05	104	5
29	1,54	48	0,31	67	0,27	86	1,13		
30	1,43	49	0,28	68	0,25	87	1,2		
31	1,33	50	0,25	69	0,23	88	1,26		
32	1,26	51	0,23	70	0,25	89	1,33		
33	1,2	52	0,25	71	0,28	90	1,43		
34	1,13	53	0,27	72	0,31	91	1,54		

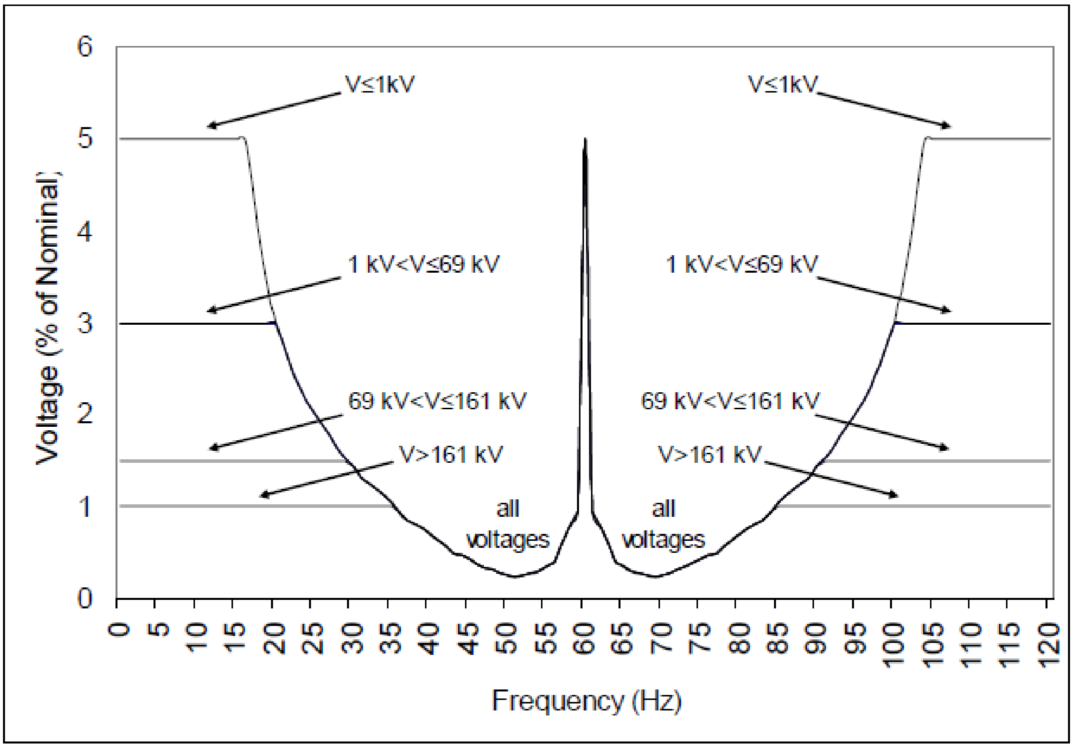


Figure 3.3 Interharmonic voltage limits based on flicker for frequencies up to 120 Hz for 60 Hz systems

3.4 Power Quality Standards in France

- For MV users it is necessary to keep ± 5% of the rated value of U_c in all voltage measurements.
- From December 2007, voltage variations in LV and MV networks should remain within ± 10% of the 10-minute RMS measurements.
- The threshold value between voltage sag and interruption is 8% of nominal voltage [56].

Table 3.11 shows power quality limit value in France.

Table 3.11 Power quality limit values in France

Quality parameters	**EdF's annual electricity quality obligation**	**Customer's electricity quality obligation**
Planned interruptions (work on the net)	Number<2 Duration<4 hours	No
Long interruptions (>3 min) (Number)	<10,000 inhabitants: 6 10,000-100,000 inhabitants: 3 >100,000 inhabitants (except cities): 3 Cities>100,000 and Paris Suburbs: 2	No
Short interruptions(1 s- 3 min) (Number)	<10,000 inhabitants: 30 10,000-100,000 inhabitants: 10 >100,000 inhabitants (except cities): 3 Cities>100,000 and Paris suburbs: 2	No
Voltage variations (RMS)	Voltage is ± %5 of contractual voltage and U_c is ± %5 of nominal voltage	No
Voltage fluctuations and flicker	Plt <= 1 (measured according to IEC 1000-4-15)	Voltage changes in stages: <5% of contractual voltage.(Measured according to IEC 61000-2-2)
Unbalance	<= 2%	<=1% if short circuit power> 40MVA
Frequency	50 Hz ±1% 50Hz ± 4% and -6% (island systems)	No
Harmonics (temporary clause)	Harmonics: 10 minute values according to EN-50160 and IEC 61000-2-2)	Levels are defined as a function of the order number, according to agreement
Customer adjusted agreements. Short interruptions (1s-3min) Voltage sags	Customer-Adjusted values Not take in account are Duration < 600ms Residual voltage>70%	No

3.5 Power Quality Standards in Hungary

- In the LV networks, the 10-minute RMS values should be within ± 7.5% band of U_N value at 95% of weekly measurements or ± 10% at 100% of weekly measurements.
- In LV networks, the voltage value for 1 minute RMS values should be between ± 15% of the U_N value [56].

3.6 Power Quality Standards in Portugal

- In HV networks, U_c value should be within ± 7% of U_N value. Under normal operating conditions, 95% of the 10-minute RMS voltage measurements should be within ± 5% of the U_c value [56].

3.7 Power Quality Standards in Netherlands

- In LV and MV networks, 95% of the weekly values of the supply voltage must be within ± 10% of the UN value. Interconnected areas and measurements on long lines should be at 100% - 15% and + 10% band spacing [56].

3.8 Power Quality Standards in Italy

The Organizing Committee for Electricity and Gas Markets in Italy (AEEG) implements a system in which incentives and penalties are imposed in order to improve the quality and sustainability of energy supply. This practice is similar to the practice of leakage loss in Turkey. In the 230 geographical regions divided by the Organizing Committee according to population density, limit values were determined considering the performances in the past years. The more the network operator can improve the value of these limits, the more incentive they are able to afford, and if they cannot provide the limit values, they have to pay the penalty [56].

3.9 Power Quality Standards in Spain

- In LV and MV networks, the supply voltage at the PCC point should be within ± 7% of the U_c at 95% of the measurements.
- For distributors who supply over 1-36 kV network, the above value can be reduced to 80%.

3.10 Power Quality Standards in China

China Network Manager issued the regulations which name is "Technical requirements and limitations on network power quality" in 1998 and "Technical requirements and limitations on power quality and reactive power for China power network" in 2004. National standards are generally published in accordance with IEC measurement methodologies standards [56]. Power quality standards in china is shown Table 3.12.

Table 3.12 Power quality standards in china

Supply voltage characteristic	**Statistical Evaluation**	**Compliance limit**	**vs. EN 50160**
Power frequency	100% of the time	50 Hz ± 1%	Harder
Supply voltage variations	100% of the time	U_c ± 10%	Same
Rapid voltage changes	<= 1000/hour Other	4% 2%	Harder Harder
Flicker	95% of the time 100% of the time	Pst<= 1 Plt<= 0.8	Harder Harder
Supply voltage dips	None given	None given	Same
Short interruptions	1 year	None given	Same
Long interruptions	1 year	None given	Same
Temporary overvoltages	1 year	$\sqrt{3}$ per unit	Harder
Supply voltage unbalance	95% of the time	<4%	Easier
Harmonic voltage	Mean value for 10 minutes Mean value for 10 minutes	Odd < 2.4% Even < 1.2% THD > 3%	Harder Harder Harder
Mains signaling voltage	None given	None given	Easier

Compared to Chinese standards and EN 50160 standard:

- Chinese standards have more stringent limit values than EN 50160 for frequency, rapid voltage variations, flicker, transient over voltages and low-level harmonic voltages
- The Chinese standards accept the same limit values like as the EN 50160 standard for voltage swell, sag and interruptions.
- The scope of the standards has been expanded to include 500 kV networks.
- Stable status parameters in Chinese standards are obliged to comply with 100% of measured values. (Except communication signals)
- Chinese standards have higher limit values than EN 50160 for high-grade harmonic voltages.
- Voltage imbalance limits in Chinese standards are given at wider intervals [56].

3.11 Power Quality Standards in Norway

The Norwegian Regulatory agencies has constituted its new regulation on the quality of supply on 1 January 2005. This regulation, revised twice in 2006 and 2007, sets the optimal limit values for the quality of electricity supply in the continuously expanding electricity network. The limit values in this regard have been prepared considering the national and special interests [56]. The table of the Norwegian regulation, which contains considerably different variations from EN 50160 standards, is shown in Table 3.13.

Table 3.13 Comparison of Norwegian Grid Regulation and EN 50160 Standard

COMPARISON BETWEEN EN 50160 AND NORWEGIAN REGULATIONS ON VOLTAGE QUALITY PARAMETERS						
Quality aspects	**EN 50160**			**The Norwegian regulations on quality of supply**		
Voltage level	[0, 1] kV	<1,35> kV	[35, ∞] kV	[0, 1] kV	<1,35> kV	[35, ∞) kV
Supply Voltage variations	230 ± 10%(10 min mean 95% of the week) 230 ±10/ -15% (all 10 min mean values)	U_c ±10% (10 min mean of the of the week)	None	230 ± 10% (all 1 min mean values)	None	None
Rapid voltage changes (RVC)	Indicative: Generally <5% up to 10%	Indicative: Generally <4% up to 6%	None	Maximum 24 per 24 hour $\Delta U_{steady\ state}$ >=3% ΔU_{max}>=5% Exception for some causes	Same as LV	Maximum 12 per 24 hour $\Delta U_{steady\ state}$ >=3% ΔU_{max}>=5% Exception for some causes
Voltage swells	Indicative: < 1.5 Kv (phase to earth)	Generally < 1.7 U_c (earthed) Generally < 2.0 x U_c (Isol/resonant.)	None	Same as RVC	Same as LV	Same as RVC
Voltage dips	Indicative: A Few tens of to thousand	Same as LV	None	Same as RVC	Same as LV	Same as RVC

Flicker	Plt<= 1 (95% of the week)	Same as LV	None	Pst<= 1.2 (95% of the week) Plt <= 1 (100 % of the time)	Same as LV	Pst<= 1 (95% of the week) Plt <= 0.8 (100 % of the time)
Voltage unbalance	<=2% (10 min mean 95% week) <= 3% occur in some areas	Same as LV	None	<=2% (all 10 min mean values)	Same as LV	Same as LV
Harmonic voltage, THD	THD<= 8% (10 min mean 95% of the week)	Same as LV	None	THD<= 8% (all 10 min mean values) THD <= 5% (all mean week values)	Same as LV	<35, 230] kV: THD<= 3% (all 10 min mean values) , <230, ∞>: THD <= 2% (all mean week values)
Harmonic voltage individual	EN 50160 table 1 (10 min mean 95% of the week)	Same as LV	None	Same as table 1 In the 50160 but for 100% of the time. Plus general limits above 25^{th} order (all 10 min mean values)	Same as LV	Limits for all harmonic orders. Generally limits above 25^{th} order (all 10 min mean values)

3.12 Power Quality Standards in USA

In the United States, standards are established by IEEE, ANSI, and some equipment manufacturing organizations (NEMA). American National Standard (ANSI C84.1) published for distribution networks of 10 kV and above contains voltage nominal values and tolerances. In summary, according to ANSI C84.1, Network input voltage should be within ± 5% of the rated voltage and the output voltage should be within the range of + 6% to -13% of the rated voltage. According to the same standard, the voltage imbalance value limit is defined as 3% of the ratio of the negative sequence voltage value to the positive sequence voltage. Voltage imbalance greater than this value causes serious overheating on the motors connected to network [56].

3.13 Comparison of Power Quality Parameters in Different Country

Various regulatory agencies and network operators around the world are trying to identify power quality limitations that best fit their private networks with new approaches. In Norway, Spain, Italy and other countries, standards-optimized with new approaches are used [55]. European regulatory agencies emphasize both power quality and reliability by issuing various guidelines and requirements. Some countries have begun to provide various incentives for momentary interruptions, considering the events of voltage sag may arise in the future. In this section, some of the example power quality trends in Europe will be mentioned.

EN 50160 sets limits within a certain percentage of the range over a few voltage disturbance or long-term measurements in the network under normal operating conditions.

- Supply voltage variations (within 95% of 10-minute RMS values should be between the limit values)
- Flicker (95% of 2-hour data should be between the limit values)
- Harmonic distortion of voltage waveform (95% of 10 minute RMS values should be between the limit values)
- Mains signaling voltage (99% of 3 second RMS values should be between the limit values)

National regulators in some countries have adopted power quality limit values different from EN 50160. Table 3.14 gives a list of countries with different power quality limit values from EN 50160 [56].

Table 3.14 National Power Quality Standards Different from EN 50160 Standards

NATIONAL VOLTAGE QUALITY REGULATIONS OR STANDARDS THAT ARE DİFFERENT FROM EN 50160	
Voltage characteristics in EN50160	**Countries with a different regulation or standard**
Supply voltage variations	Spain, France, Hungary, Norway (only for LV customers) Portugal (only for EHV-HV customers)
Flicker	Norway (requirements for both P_{st} and P_{lt}) Portugal (only for EHV-HV customer) Netherlands (maximum limit for P_{lt})
Voltage dips	Norway, France (Customised engagement on request only for MV and HV customers)
Voltage swells	Norway, France
Transient overvoltage	France
Voltage unbalance	France, Norway, Netherlands
Harmonic voltage	France, Norway, Portugal (only for EHC-HV customers) Netherlands (maximum limit for THD 5^{th} and 7^{th} harmonic)
Interharmonic Voltage	none
Mains signaling voltage	none
Single rapid voltage changes	NO

(*) In France, power quality limit values are determined according to the agreement between the user and the network operator. Regulatory agencies will review this agreement, but does not determine its limits

Table 3.15 shows the supply voltage limit values for each country. Table 3.16 shows flicker limit values of different countries.

Table 3.15 Supply voltage limit for different countries

Period	**Time**	**Limit**	**Country (voltage level)**
10min	95%	+/- 7.5%of Un	HUNGARY(LV)
10min	100%	+/- 10%of Un	HUNGARY (LV) SWEDEN (HV,MV,LV)
1 min	100%	+15% /- 20%of Un	HUNGARY(LV)
10min	95%	+/- 5%of Un	PORTUGAL (HV)
10min	95%	+/- 7%of Un	SPAIN (,MV,LV)
1 min	100%	+/- 10% of Un	NORWAY(LV)
10min	95%	+/- 10% of Un	NETHERLANDS(MV)
10min	100%	+10 /- 15% of Un	NETHERLANDS(MV)
10min	99.9%	+/- 10% of Un	NETHERLANDS(HV)
10min	95%	+6 /- 10 % of Un	ITALY(LV)
10min	95% (for LV level) 99%(for MV level)	+10 % -15 % of Un (for LV level) ±15 %.of Un (for MV level)	TURKEY
Continuously One week (TSEN 61000-4-30)	99%	+/- 10 % of Un (for MV level)	TURKEY

Table 3.16 Flicker limit for different countries

INDICATOR	TIME	LIMIT	COUNTRY
Pst	95%	≤ 0.35	CYPRUS(HV,MV,LV)
Plt	95%	≤0.35	CYPRUS(HV,MV,LV)
Pst	95%	≤0.8	CZECH REPUBLIC (HV,MV,LV)
Plt	95%	≤0.6	CZECH REPUBLIC (HV,MV,LV)
Pst	100%	≤0.85(planning level)	ITALY (HV)
Plt	100%	≤0.62(planning level)	ITALY (HV)
Pst	95%	≤1.2	NORWAY (MV,LV)
Pst	95%	≤1	NORWAY(HV)
Plt	100%	≤1	NORWAY (MV, LV) POLAND(HV)
Plt	100%	≤0.8	NORWAY(HV)
Pst	100%	≤1	PORTUGAL
Plt	100%	≤5	NETHERLANDS(HV,MV,LV)
Pst/Plt(TS EN 61000-4-15)	95%	For Pst≤1 For Plt≤0.8	TURKEY

The limit values of voltage imbalance among European countries also change. The limit values and the compliance rates differ from each other while all countries perform their measurements over the 10-minute RMS values.

Table 3.17 shows voltage imbalance limit values of different countries.

Table 3.17 Voltage imbalance limit for different countries

INDICATOR	PERIOD	TIME	LIMIT	COUNTRY
V_{un}	10 min	95%	≤ 2%	EN 50160
V_{un}	10min	95%	≤ 1%	ITALY (HV)
V_{un}	10min	100%	≤ 2%	NORWAY (HV, MV, LV) SWEDEN(HV, MV, LV)
V_{un}	10min	100%	≤3%	NETHERLANDS(MV, LV)
V_{un}	10min	99.9%	≤ 1%	NETHERLANDS(HV)
V_{un}	10min	95%	≤ 2%	TURKEY

Table 3.18 shows harmonic limit values of different countries. In the harmonic limitations shown in Table 3.18, the measurement periods are usually performed over RMS values of 10 minutes. Only the Norwegian boundary values are defined over one-week measurement period.

Table 3.18 Harmonic limit for different countries

INDICATOR	PERIOD	TIME	LIMIT	COUNTRY
THD	10 min	95%	≤ 8%	EN 50160
THD	10min	100%	≤ 3%	ITALY(HV)
THD	10min	100%	≤ 8% 0,23 ≤ U ≤ 35 kV ≤ 3% 35 < U ≤ 245 kV	NORWAY(HV,MV,LV)
THD	1 week	100%	≤ 5%	NORWAY(MV,LV)
INDIVIDUAL	10min	95%	Table	PORTUGAL(HV)
INDIVIDUAL	10min	100%	Table	NORWAY(HV,MV,LV)
INDIVIDUAL	10min	100%	Table as in EN5160	SWEDEN(HV,MV,LV)
THD	10min	95%	≤ 8% U ≤ 35 kV ≤ 6% 35 < U ≤ 150 kV	NETHERLANDS
INDIVIDUAL	10min	99.9%	Table U < 35 kV	NETHERLANDS
THD	10min	99.9%	≤ 12% U < 35 kV ≤ 7% 35 ≤ U < 150kV	NETHERLANDS
THD	10min	95%	8%	TURKEY

In relation to time, voltage limit values have not been defined in many countries including EN 50160 standards. But Norway, Sweden and the Czech Republic are shown as exceptions to this issue. Table 3.19 shows time dependent sudden voltage variation limit values for Sweden, Norway and Czech Republic Network, while time dependent voltage swell and sag limit values for Sweden network are shown Figure 3.5 and Figure 3.6

Table 3.19 Sudden voltage variation limit for different countries

Voltage Variations	Index	Limit	Country / (Voltage level)
Voltage sag	Voltage sag table is divided into areas A, B and C. (Figure and Figure)		Sweden (HV, MV, LV)
Voltage swell	Voltage swell table is divided into areas A, B and C.		Sweden (HV, MV, LV)
Rapid Voltage Change	Number of voltage changes in the 24 hour period	ΔVss ≥3% ≤24 0.23 ≤ U ≤ 35 kV ≤12 35 kV < U ΔVmax ≥5% ≤24 0.23 ≤ U ≤ 35 kV ≤12 35 kV < U	Norway (HV, MV, LV) Sweden (HV, MV, LV)
	Number of voltage changes in the 24 hour period	<1 ΔVmax=3 [1-10] ΔVmax=2.5 [10-100] ΔVmax=1.5 [100-1000] ΔVmax=1	Czech Republic HV

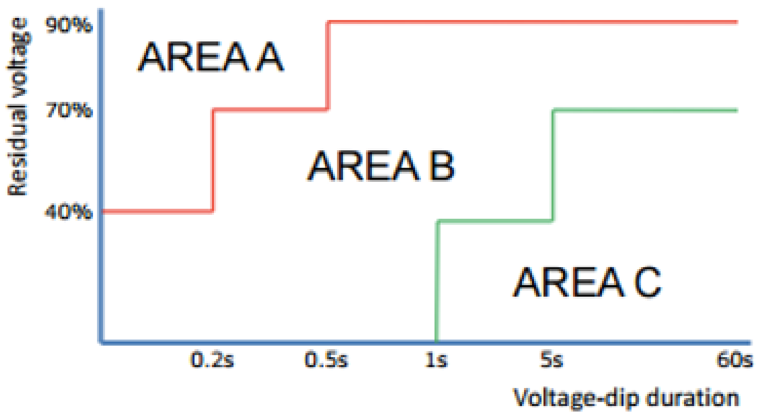


Figure 3.4 Voltage Crash Limit Values for the Swedish Electric Network 1[5]

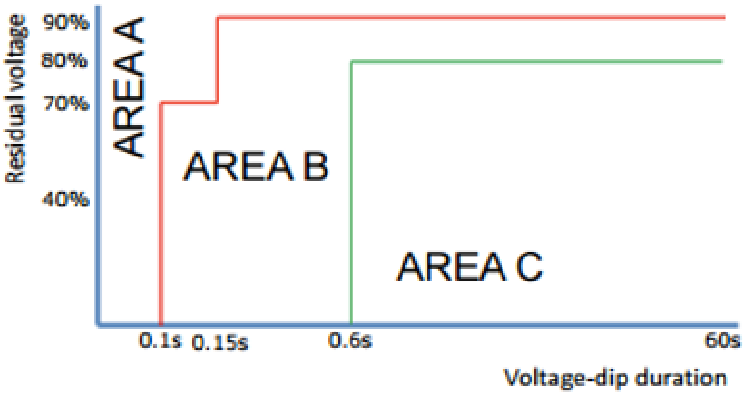


Figure 3. 5 Voltage Crash Limit Values for the Swedish Electric Network 2 [55]

CHAPTER 4

IDENTIFICATION OF VOLTAGE SAGS

Voltage sag is a consequence of Ohm law: V= I x R. The voltage sag is due to the voltage drop that the overcurrent caused by fault or load create across the all system impedance. Referring to Figure 4.1, Vs is supply voltage that have theoretical zero-impedance AC source. R correspond to total resistance between AC source and customer loads, represented as a motor in Figure 4.1. Motor draw excessive current at starting. This current causes a voltage drop across all system impedance. Voltage applied to load is calculated by subtracting the voltage drop from source voltage. Depending on the magnitude of this current value and the magnitude of the system impedance, if load voltage decreases between 0.1 pu and 0.9 pu voltage sag occurs [57].

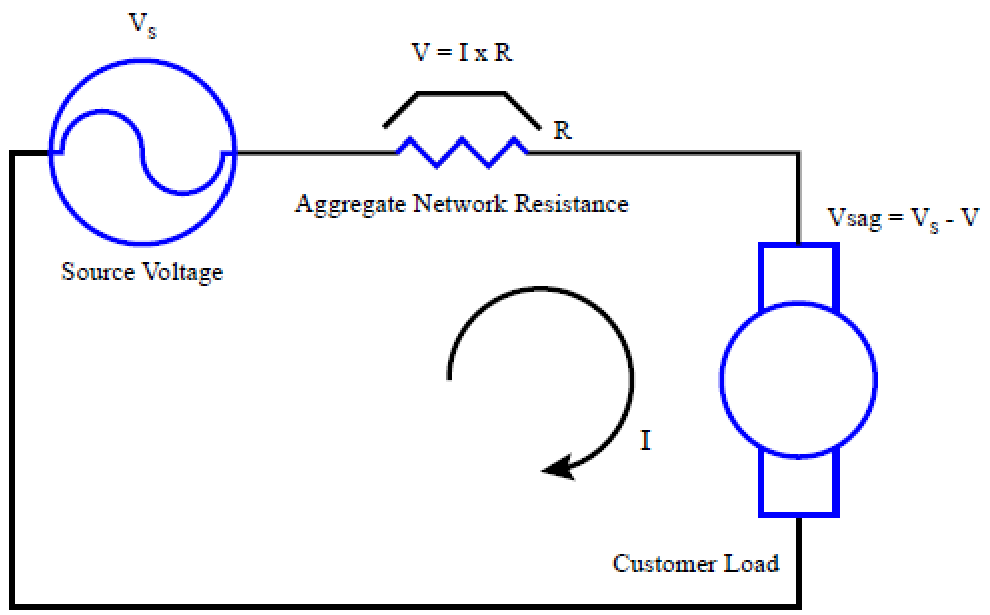


Figure 4.1 Simple voltage sag model [57]

Example of two-customer is shown Figure 4.2. Total current produced by Vs is I_1+I_2.Voltage drop due to total current occurs across common impedance (Z_1).

Further drop created by I_2 forms across Z_2.Both Customer 1 and Customer 2 see drop but Voltage drop of Customer 2 is greater than customer 1 due to Z_2 impedance. All load downstream of that fault point will be effected because they are electrically in parallel. If voltage sag causes disturbance in customer 2 and PQ analyzer is at customer 2' service entrance, Recorded voltage at customer 2 have depth and frequency any sag. Customer 2 current help deciding to whether sag is caused by load 2 or upstream. Because customer 1 may cause that disturbance. Between relationship voltage and current help determine voltage sag location [57]. Upstream denotes the direction of a disturbance in the bus about the result of fault that occurred in the transmission line or transformer center located above fault location (the fault current does not pass over the power analyzer.). In the case of upstream, Fault current is not present in PQ analyzer recording. Downstream denotes the direction of a disturbance in the bus about the result of fault that occurred in the load or transformer center located below fault location. Fault current is present in PQ analyzer recording.

- **Case 1:** PQ analyzer is at service entrance of customer 1. if there is a fault in customer 1, fault current is recorded by PQ analyzer. Thus, voltage sag occurs in bus of customer 1. Event direction is downstream.
- **Case 2:** PQ analyzer is at service entrance of customer 2. if there is a fault in customer 1, fault current is not recorded by PQ analyzer. Thus, voltage sag occurs in bus of customer 2. Event direction is upstream.
- **Case 3:** PQ analyzer is at service entrance of customer 1. if there is a fault in customer 2, fault current is not recorded by PQ analyzer. Thus, voltage sag occurs in bus of customer 1. Event direction is upstream.
- **Case 4:** PQ analyzer is at service entrance of customer 2. if there is a fault in customer 2, fault current is recorded by PQ analyzer. Thus, voltage sag occurs in bus of customer 2. Event direction is downstream.
- **Case 5**: PQ analyzer is at service entrance of customer 1 and customer. if there is a fault in customer 1, fault current is recorded by PQ analyzer of customer 1. Thus, voltage sag occurs in bus of customer 1 and customer 2. Event direction of customer 1 is downstream, while event direction of customer 2 is upstream.

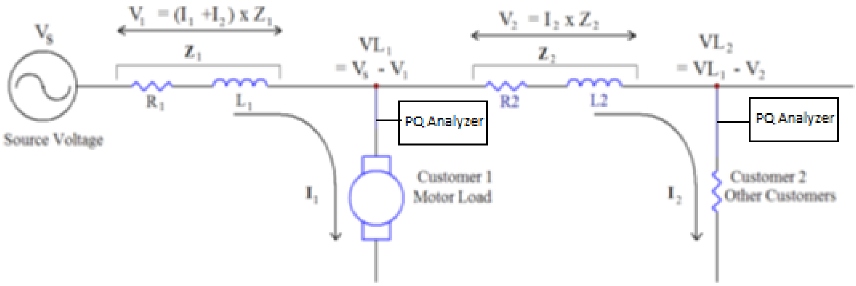


Figure 4.2 More complex sag model with two load [57]

Example of RMS voltage sags caused by current spikes is given figure 4.3. In according to Figure 4.3, voltage sag happens at same time with current spike. Event location of this disturbance is downstream Because current spike recorded in PQ analyzer. Amplitude of voltage sag directly depend on amplitude of current and rely on load and system impedance.

Figure 4.3 RMS voltage sags caused by current spikes [57]

Another example is given in Figure 4.4. Small motor draw 19 A pending motor start. That causes small voltage drop in system. But there is a deeper sag at same time in the system. Load producing deeper sag is upstream. If high current causes voltage sag, direction of sag is downstream [57].

As a consequence, the clue to locating voltage sag sources in power quality data is the relationship between sag voltage and current. It can be determined voltage sag location by examining this relationship. These clues are given following:

- High current, either from a system fault or excessive momentary load current is the root cause of a voltage sag
- If the undesirable source causing the sag is downstream of the power quality monitor, its high current will be contained in the data along with all other downstream loads.
- If PQ analyzer records high current and this high current causes voltage sag, direction of event is downstream.
- If there is a voltage sag in distribution system and PQ analyzer is not record high current, direction of event upstream.
- If the undesirable source is upstream, the voltage sag will be present, but the monitored current will only show other loads reacting to the sag, not the extreme spike causing the sag. These load responses may be small increases or decreases in current.
- Comparing a current of a load that causes a suspicious voltage sag with other similar current spikes and corresponding voltage changes may help to reveal whether an increase in current is the cause or effect of a sag [57].

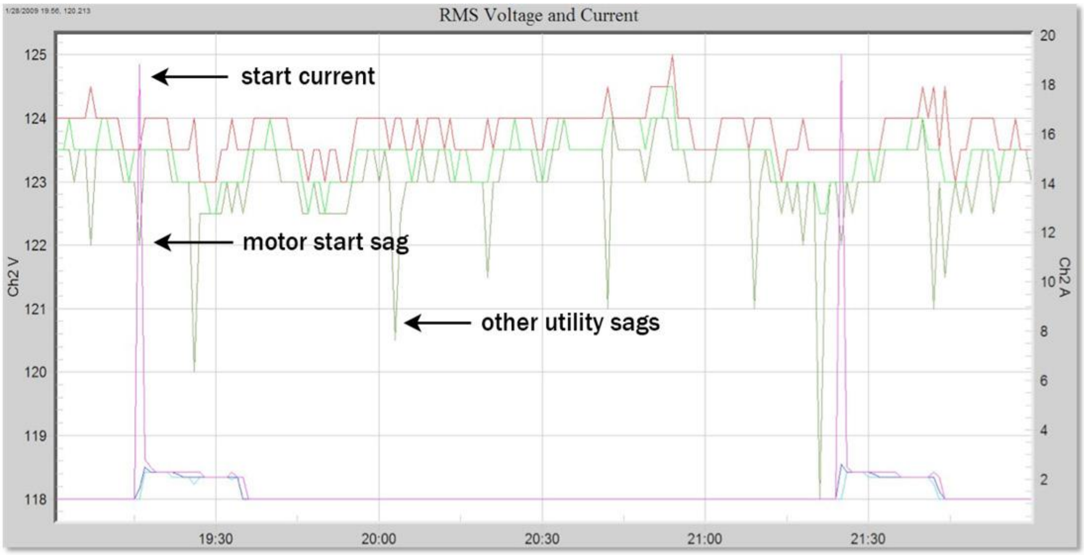


Figure 4.4 An insignificant sag caused by a load, with larger sags incoming from upstream [57]

4.1 Simulation Study

Simulation study is realized to extract features of current and voltage waveform occurring during the voltage sag. Figure 4.5 depicts the single line diagram of simulated system, which is 20 km transmission line. The transformation ratio is 154/34.5 kV. Total resistance of 3/0 transmission line is 6 Ω. Total reactance of 3/0 transmission line is 125.66 Ω. Load is 10 MVA and power factor is 0.95.

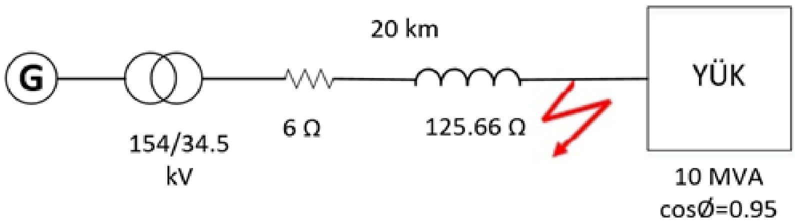


Figure 4.5 Simulation model

The main event that causes voltage sag in the electricity distribution network are faults. The current and voltage waveforms during fault help us identify the type of fault. In the literature, faults are generally divided into 4 classes. These are single phase ground fault, two phase ground fault, three phase ground fault and two phase faults. For each of these fault types, the current and voltage waveforms during fault are obtained by simulating them in the MATLAB / SIMULINK. The fault types simulated are single phase ground fault (AG, BG, CG), two phase ground fault (ABG, ACG, BCG), three phase ground fault (ABCG) and two phase faults (AB, AC, BC).

4.1.1 Simulation Study for Single Phase Ground Fault

A single phase ground fault occurs when one of the phases contact with the ground. Voltage waveform and current waveform for AG is given respectively Figure 4.6 and Figure 4.7. In this fault, while voltage value of A phase contacted with ground decreases current value of A phase increases. Voltage waveform and current waveform for BG and CG is given respectively Figure 4.8, Figure 4.9, Figure 4.10 and Figure 4.11.

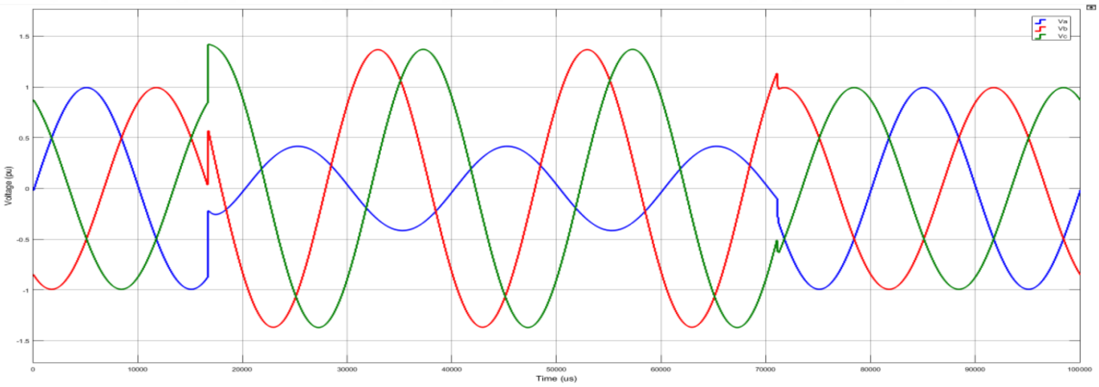


Figure 4.6 Voltage waveform for AG

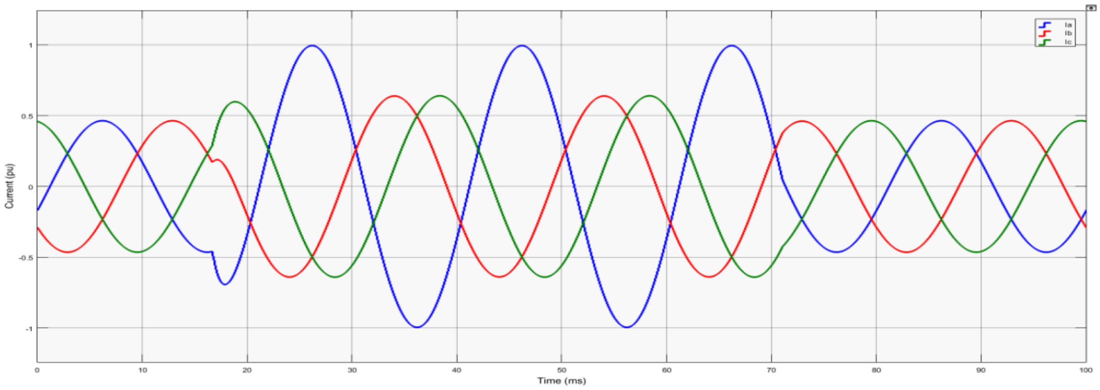


Figure 4.7 Current waveform for AG

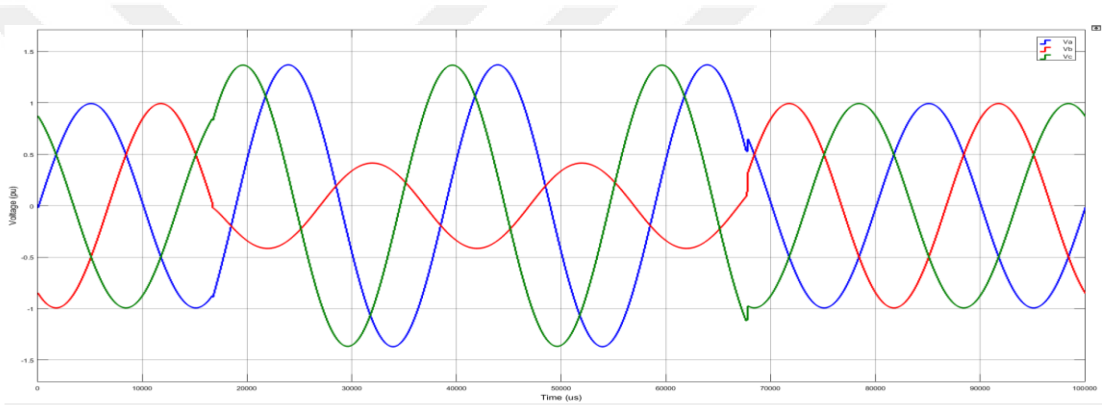


Figure 4.8 Voltage waveform for BG

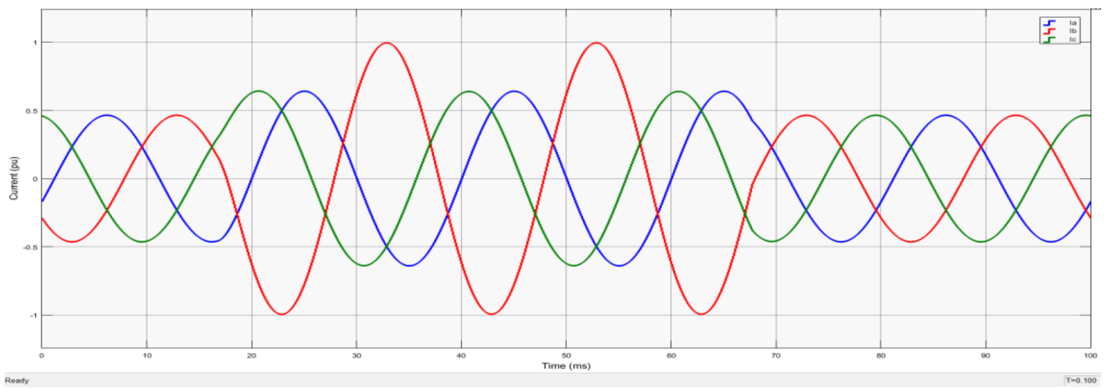


Figure 4.9 Current waveform for BG

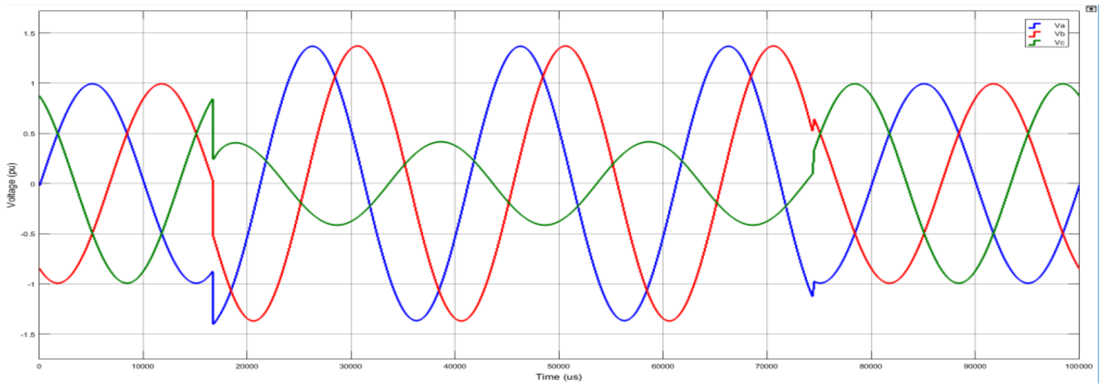


Figure 4.10 Voltage waveform for CG

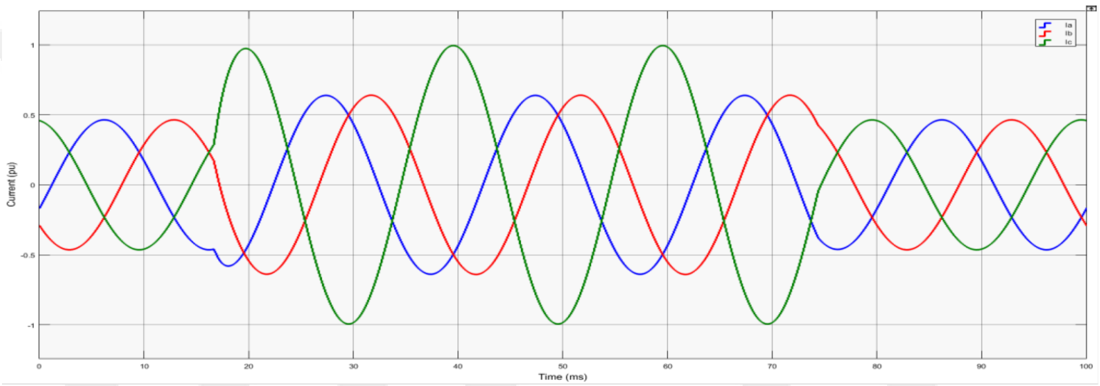


Figure 4.11 Current waveform for CG

4.1.2 Simulation Study for Two Phase Ground Fault

A two phase ground fault occurs when two of the phases contacts with the ground. Voltage waveform and current waveform for ABG is given respectively Figure 4.12 and Figure 4.13. In this fault, while voltage sag occurs in A and B phase, current value of A and B phase increase. Voltage waveform and current waveform for BCG and ACG is given respectively Figure 4.14, Figure 4.15, Figure 4.16 and Figure 4.17.

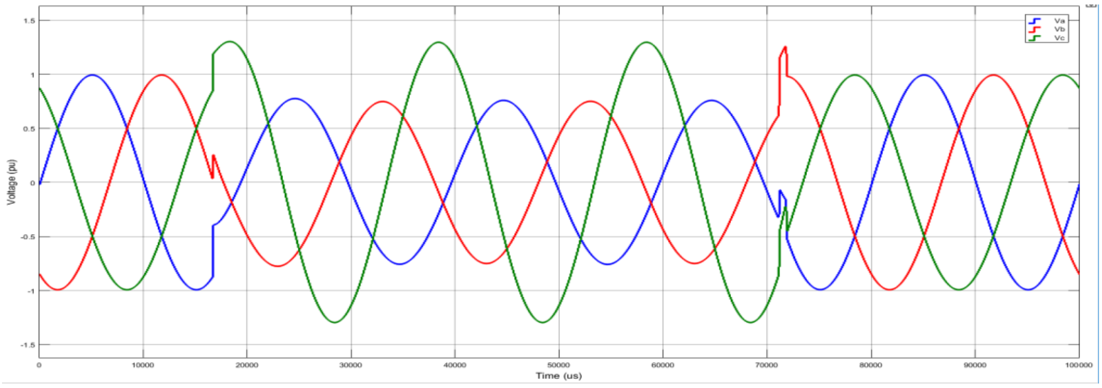


Figure 4.12 Voltage waveform for ABG

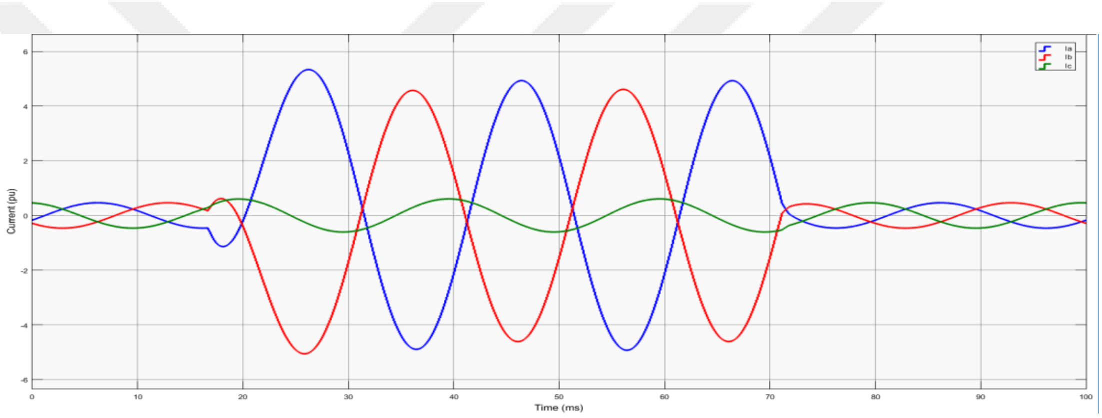


Figure 4.13 Current waveform for ABG

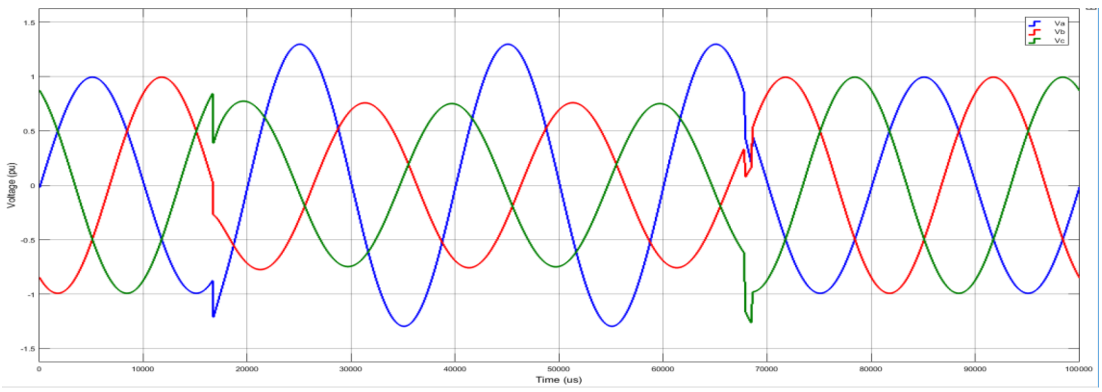


Figure 4.14 Voltage waveform for BCG

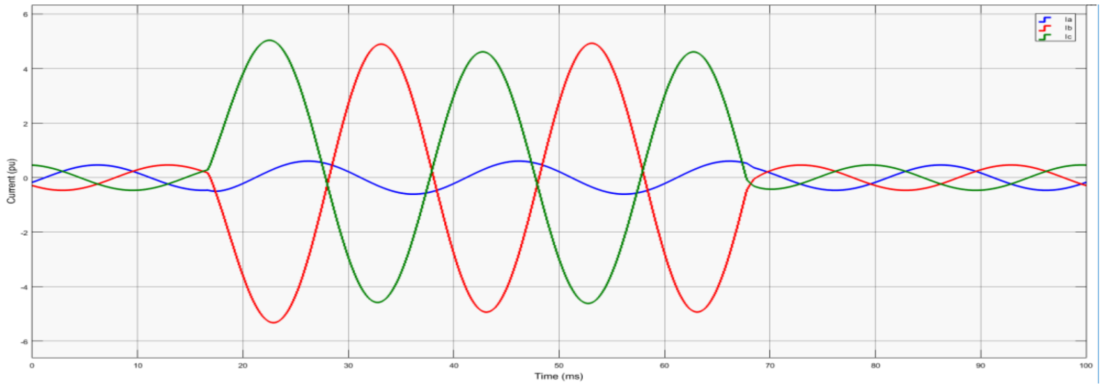


Figure 4.15 Current waveform for BCG

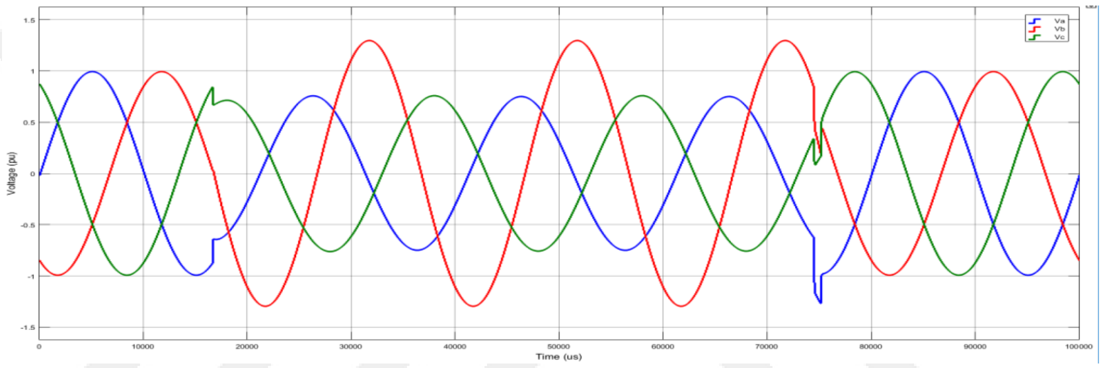


Figure 4.16 Voltage waveform for ACG

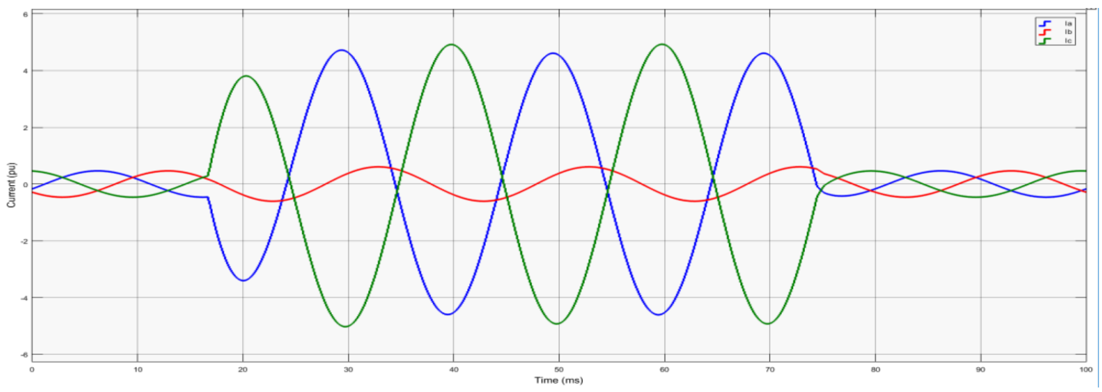


Figure 4.17 Current waveform for AG

4.1.3 Simulation Study for Three Phase Ground Fault

A three phase ground fault occurs when all phases contact with the ground. Voltage waveform and current waveform for ABCG is given respectively Figure 4.18 and Figure 4.19. In this fault, while voltage sag occurs in all phases, current value of all phases increase.

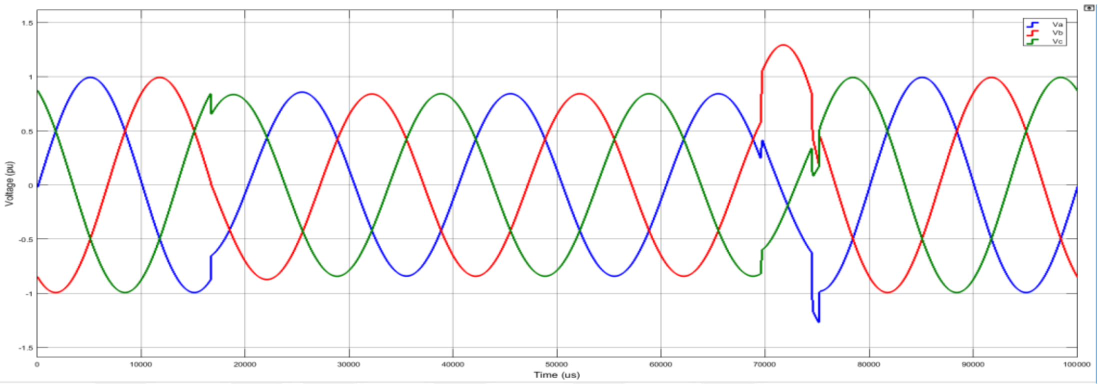


Figure 4.18 Voltage waveform for ABCG

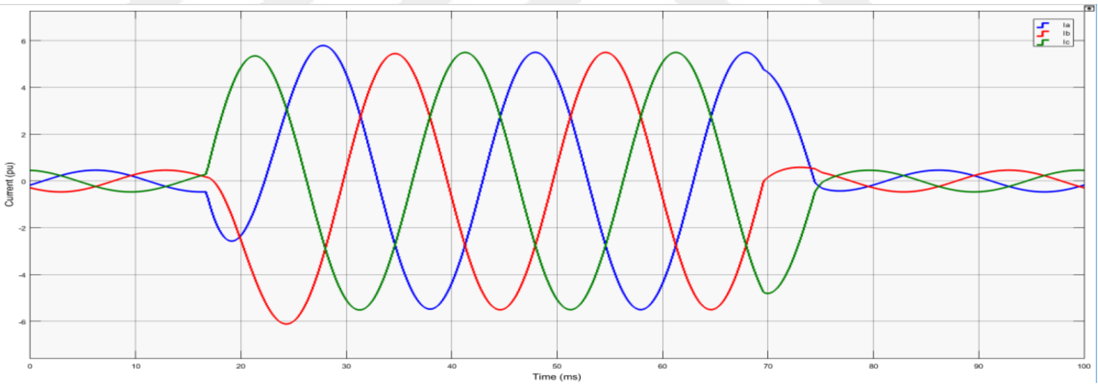


Figure 4.19 Current waveform for ABCG

4.1.4 Simulation Study for Two Phase Fault

A two phase fault occurs when two phase contacts with the ground. Voltage waveform and current waveform for AB is given respectively Figure 4.20 and Figure 4.21. In this fault, while voltage sag occurs in two phase, current value of this two phases increase. Voltage value of other phase is within limit value. Voltage waveform and current waveform for BC and AC is given respectively Figure 4.22, Figure 4.23, Figure 4.24 and Figure 4.25

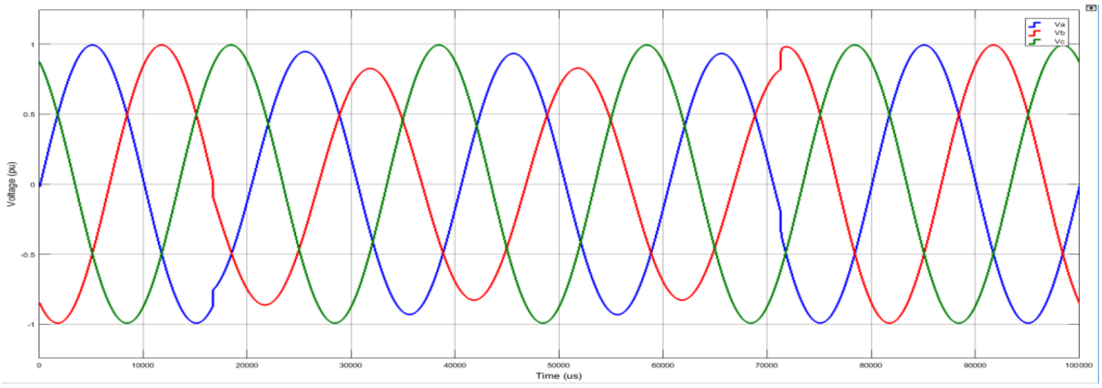


Figure 4.20 Voltage waveform for AB

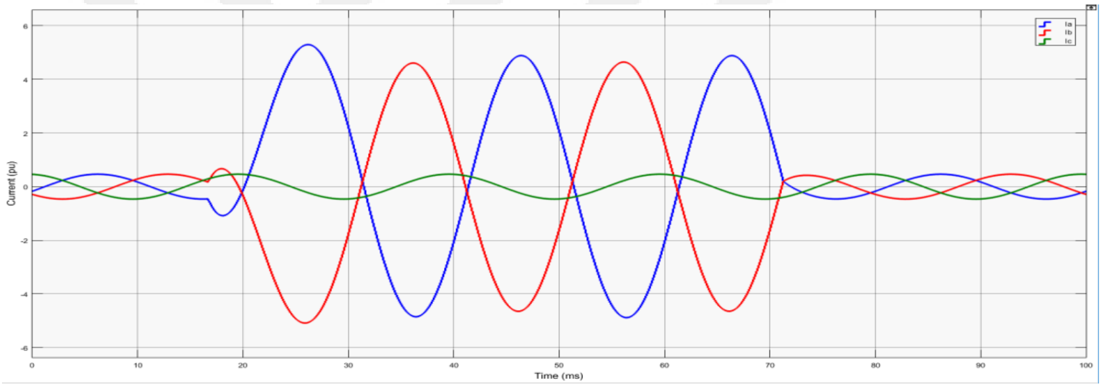


Figure 4.21 Current waveform for AB

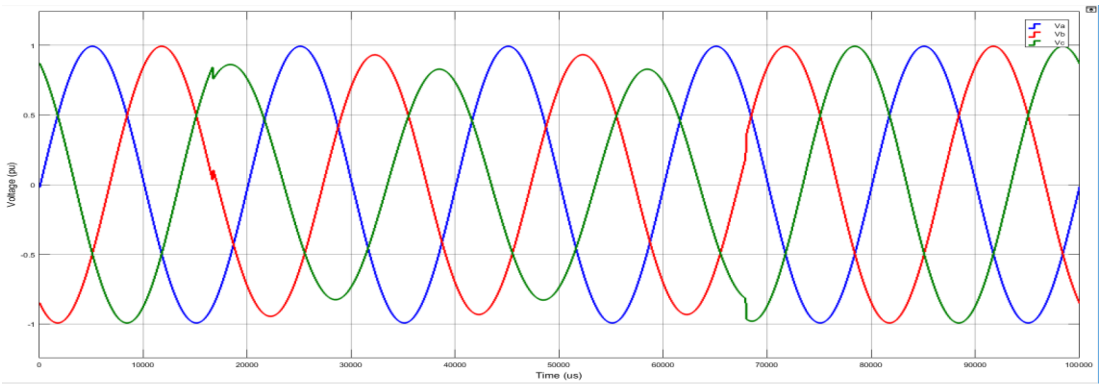


Figure 4.22 Voltage waveform for BC

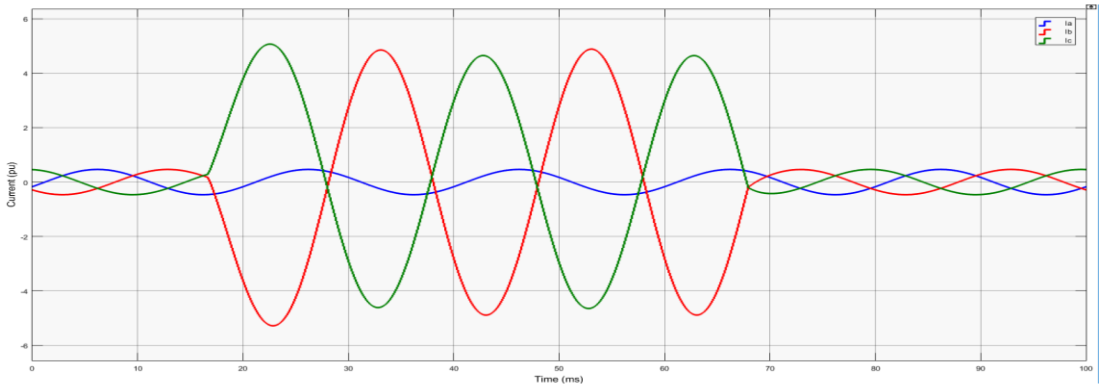


Figure 4.23 Current waveform for BC

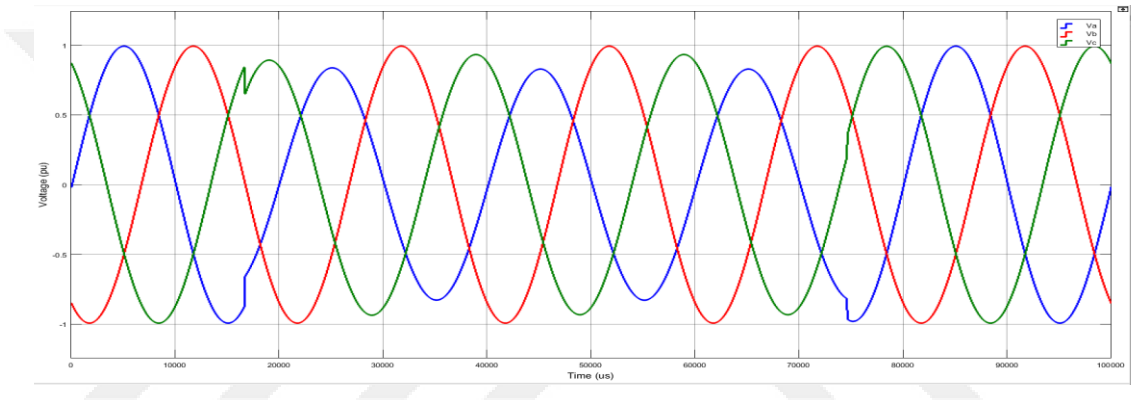


Figure 4.24 Voltage waveform for AC

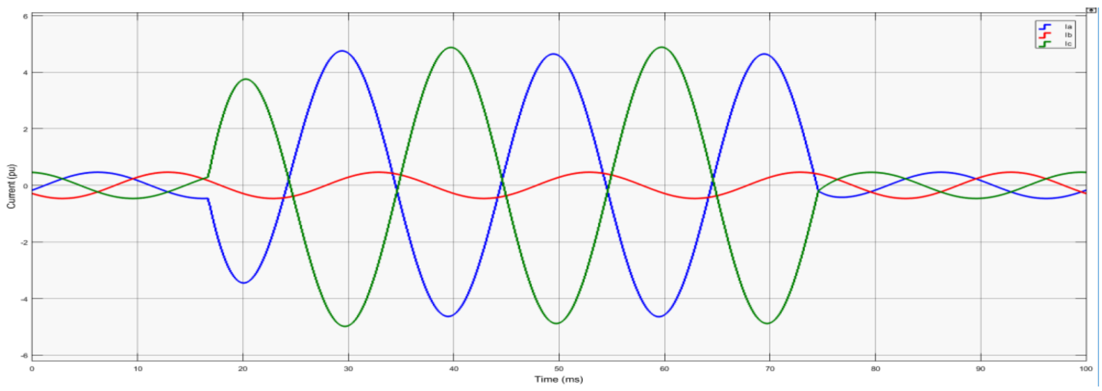


Figure 4.25 Current waveform for AC

CHAPTER 5

INAVITAS SOFTWARE AND REPORTING SYSTEM

Inavitas is basically a central monitoring, analysis and management system software for smart grid, smart buildings and renewable energy sources. Name of Inavitas consists of bringing together the words "innovatio" and "navitas" which means "innovation" and "energy" in Latin. The product family "Inavitas" developed for "decision makers" at all level provides monitoring, analysis and make a decision for investment, operation and maintenance aims from generation up to single end-customer. Basic benefits of Inavitas software:

- Produce meaningful and usable information using big data
- Combining multiple data sources on a single platform.
- Raise system performance and productivity
- Help you to make right decision
- Accomplish various needs on single platform
- Allow to access your device data from anyplace at any time

Inavitas can basically perform the network monitoring and management actions required for smart network solutions. At the same time, it can analyze the load information obtained over the network and transform them into the data that the users can understand. Smart grid solutions from Inavitas:

- Remote and real-time monitoring of devices with communication capability in the electricity transmission and distribution network
- Practical and economical solutions for devices without communication capability
- Hardware and software development for managing bi-directional power flow
- Development of optimization tools to reduce technical losses [58].

- Data management from single platform with integration third-part systems like as OSOS, CBS, SCADA.

User can get various report with power quality value from Inavıtas according to value measured in network. Inavitas used by 19 distribution company creates various power quality reports using the data received from the devices on the grid in accordance with the power quality limitations specified in the "Regulation on service quality in electricity distribution and retail sale " published by EMRA. The EMRA report shows that the power quality at the point where measurements are taken according to the data received from the power quality analyzers located in the network, how far compliance with the limit conditions specified in the regulation. Table 5.1 shows that for 9 different power quality devices, how many weeks exceeds the limit values in the 51-week measurement period. The numbers indicated below the voltage imbalance, total harmonic distortion, harmonic voltages and long term flicker, voltage sag columns indicate how many weeks the power analyzer value exceeds power quality limit relating to column. According to table 5.1 while HB 1 network analyzer exceeded the long-term flicker limit for 6 weeks in a 35-week measurement, 265 voltage sag events were observed in the 51 week measurements taken from HC network analyzer.

Table 5.1 Example of 51-Week EMRA Report from Inavitas

ROW NUMBER	NAME OF SUBSTATION	DEFINITION OF MEASUREMENT POINT	NUMBER OF MEASUREMENT PERIOD	NUMBER OF WEEKS EXCEEDING LIMIT VALUES					
				VOLTAGE MAGNITUDE VARIATION	VOLTAGE UNBALANCE	VOLTAGE SAG	TOTAL HARMONIC DISTORTION	VOLTAGE HARMONIC	LONG TERM FLICKER
1	KAYSERİ-3 TM xxx	KD	51	0	0	222	0	2	2
2	KAYSERİ-3 TM xxx	KC	51	0	0	225	0	1	1
3	KAYSERİ-3 TM xxx	HA 1	51	0	0	231	1	1	8
4	KAYSERİ-3 TM xxx	HB 1	35	0	0	171	0	0	6
5	KAYSERİ-2 TM xxx	HD	51	0	1	271	1	1	1
6	KAYSERİ-2 TM xxx	HC	51	0	0	265	0	1	2
7	KAYSERİ-2 TM xxx	HA 2	34	0	0	435	0	0	24
8	KAYSERİ-2 TM xxx	HB 2	34	0	0	437	0	0	23
9	KAYSERİ-2 TM xxx	KE	34	0	0	103	0	0	2

Inavitas creates the EMRA report with weekly power quality reports. They are basically obtained by evaluating the measurements taken from the network weekly based on the limit values shown in Table 5.2.

Table 5.2 Inavitas power quality limit values compliance with EMRA regulation

POWER QUALITY PARAMETER	ACCEPTABLE LIMIT VALUES	MEASUREMENT PERIOD	MONITORING PERIOD	ACCEPTED LEVEL
Voltage Variaton (LV)	± %10	10 min	1 week	95%
	± %10 with - %15	10 min	1 week	100%
Voltage Variaton (MV)	<+%10	10 min	1 week	99%
	>-%10	10 min	1 week	99%
	± %15	10 min	1 week	100%
Voltage Unbalance- (LV) for single phase and two phase load	3%	10 min	1 week	95%
Voltage Unbalance- (LV) for three phase load	2%	10 min	1 week	95%
Voltage Unbalance - (MV)	2%	10 min	1 week	95%
Total Harmonic Distortion	8%	10 min	1 week	95%
Voltage Harmonic	Regulations Table- 10	10 min	1 week	95%
Long Term Flicker (Plt)	<=1	2 hour = 12 Pst	1 week	95%
Voltage Sag		10 ms	x	%95 -%100

Weekly reports are generated as a result of evaluation of measurement results. Example of weekly report is given in Table 5.3. The table 5.3 shows the number of measurements taken regarding the power quality problems identified by the relevant regulation and how many of these measurements exceed the limit values. These measures exceeding the limit values also violate the acceptance levels specified in the relevant regulation, and then the measurements for that week will be "FAİL" for this power quality.

Table 5.3 Weekly report created by Inavitas

EVALUATION CHART					
STANDARD VALUES	RESULTS OF THE MEASUREMENT			ASSESSMENT RESULTS	
POWER QUALITY PARAMETERS	NUMBER OF MEASUREMENT THAT PARAMETERS ARE APPROPRIATE	NUMBER OF MEASUREMENT THAT PARAMETERS ARE NOT APPROPRIATE	TOTAL MEASURMENT NUMBER	MEASURMENT RATE PROVIDED BY STANDARD(%)	RESULT
Voltage Variation - A Phase % 10	1014	0	1014	100	PASS
Voltage Variation- B Phase % 10	1014	0	1014	100	PASS
Voltage Variation - C Phase % 10	1014	0	1014	100	PASS
Voltage Variation - A Phase % 15	1013	1	1014	99,9	FAIL
Voltage Variation - B Phase % 15	1013	1	1014	99,9	FAIL
Voltage Variation - C Phase % 15	1013	1	1014	99,9	FAIL
Voltage Unbalance	1014	0	1014	100	PASS
Total Harmonic Distortion -A Phase	1014	0	1014	100	PASS
Total Harmonic Distortion -B Phase	1014	0	1014	100	PASS
Total Harmonic Distortion -C Phase	1014	0	1014	100	PASS
Voltage Harmonics A Phase	1014	0	1014	100	PASS
Voltage Harmonics B Phase	1014	0	1014	100	PASS
Voltage Harmonics C Phase	1014	0	1014	100	PASS
Long Term Flicker - A Phase	80	4	84	95,24	PASS
Long Term Flicker - B Phase	79	5	84	94,05	FAIL
Long Term Flicker - C Phase	81	3	84	96,43	PASS
Voltage Sag- A Phase	6				
Voltage Sag- B Phase	6				
Voltage Sag- C Phase	7				

A detailed report can be generated for each power quality event included in the weekly report. A list of these power quality reports that can be received via Inavitas is shown in Figure 5.1. When the flicker report in this list is analyzed as a sample report, the flicker values from the power quality analyzer are seen in Table 5.4. Threshold value of flicker is given in the column of limit value in Table 5.4. Table 5.5 shows that how many measurement values are taken and how many of them exceed the limit value. Since the flicker measurements of each phases exceeding the threshold value are not more than 5% of the total measurements, these measured values are considered "PASS" from the flicker problem.

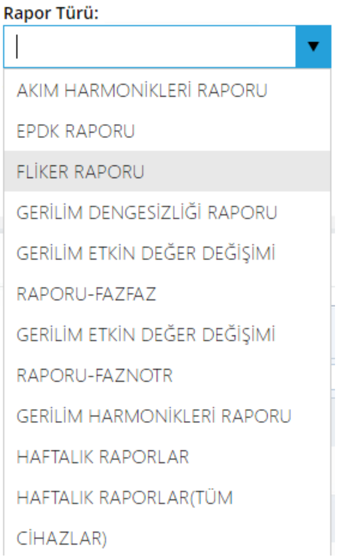


Figure 5.1 Power Quality Reports from Inavitas

Table 5.4 Flicker measurement values taken from Inavitas

FLIKER

06.01.2018 / 13.01.2018

Create Date	Pst A	Pst B	Pst C	Pst LIMIT	Plt A	Plt B	Plt C	Plt LIMIT
06-01-2018 13:40:00	0,115	0,131	0,16		0,146	0,157	0,178	1
06-01-2018 13:50:00	0,136	0,142	0,15		0,146	0,157	0,178	1
06-01-2018 14:00:00	0,133	0,132	0,145		0,141	0,151	0,176	1
06-01-2018 14:10:00	0,134	0,153	0,185		0,141	0,151	0,176	1
06-01-2018 14:20:00	0,103	0,166	0,167		0,141	0,151	0,176	1
06-01-2018 14:30:00	0,141	0,14	0,155		0,141	0,151	0,176	1
06-01-2018 14:40:00	0,155	0,163	0,2		0,141	0,151	0,176	1
06-01-2018 14:50:00	0,129	0,128	0,129		0,141	0,151	0,176	1
06-01-2018 15:00:00	0,117	0,13	0,165		0,141	0,151	0,176	1
06-01-2018 15:10:00	0,131	0,148	0,168		0,141	0,151	0,176	1
06-01-2018 15:20:00	0,142	0,154	0,171		0,141	0,151	0,176	1
06-01-2018 15:30:00	0,11	0,124	0,148		0,141	0,151	0,176	1
06-01-2018 15:40:00	0,137	0,156	0,194		0,141	0,151	0,176	1
06-01-2018 15:50:00	0,138	0,142	0,16		0,141	0,151	0,176	1
06-01-2018 16:00:00	0,144	0,162	0,193		0,133	0,148	0,172	1

Table 5.5 Weekly flicker report

ASSESMENT OF FLICKER inavitas T&D

06.01.2018 / 13.01.2018

Conditions	Sample Number	Fail	Percentage	Result
	741	0	0	PASS
	741	0	0	PASS
	741	0	0	PASS
	741	0	0	PASS
	741	0	0	PASS
	741	0	0	PASS

In addition to reports conforming to EN 50160 standards from Inavitas software, raw measurement data from energy analyzers can also be obtained. This data can be obtained on a graph if desired, or downloaded from the software in .csv or .xlsx format. A graph of three voltage values for the E07-TR1 transformer in the KCETAŞ distribution network is shown in Figure 5.2. A graph of three current values for the E07-TR1 transformer on the KCETAŞ power distribution network is demonstrated in Figure 5.3. Three Phase Current and Voltage Values of E07-TR1 Transformer in xlsx file format is shown in Figure 5.4.

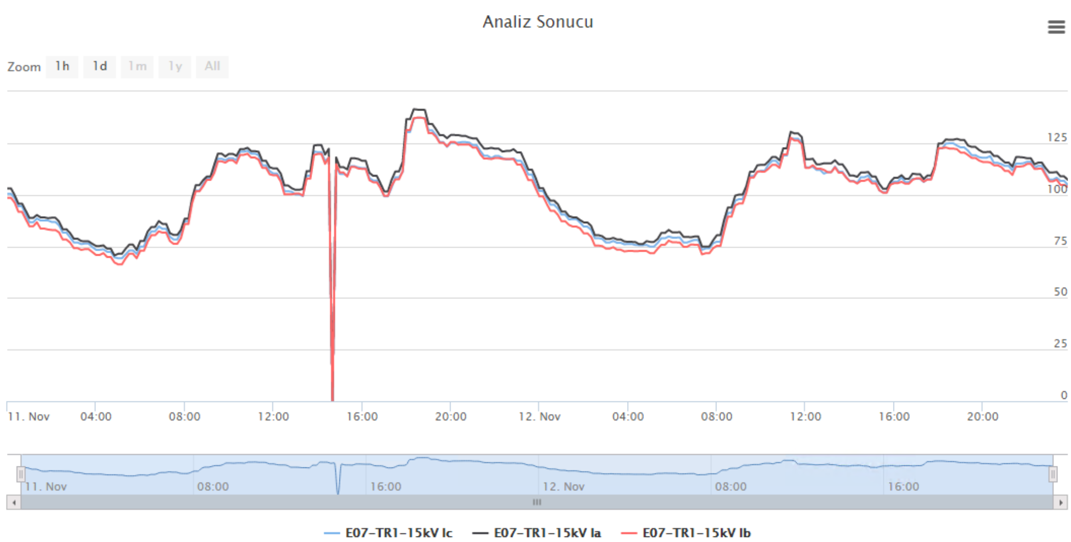


Figure 5.2 Three phase voltage graph for E07-TR1 transformer in Inavitas Software

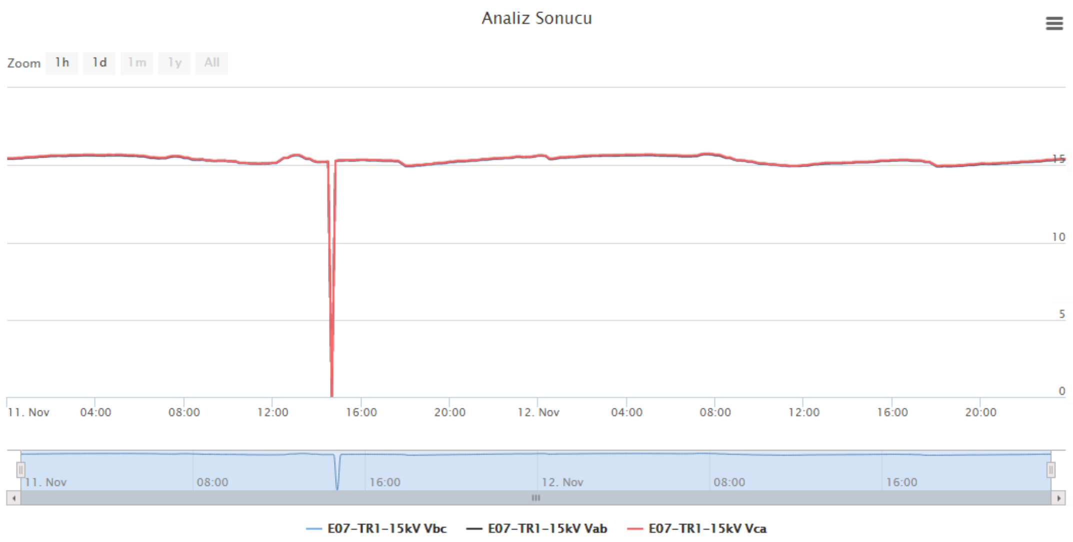


Figure 5.3 Three Phase Current Graph for E07-TR1 Transformer in Inavitas Software

CREATED_AT	E07-TR1-15kV Ic	E07-TR1-15kV Ia	E07-TR1-15kV Vbc	E07-TR1-15kV Vab	E07-TR1-15kV Vca	E07-TR1-15kV Ib
11.11.2016 00:00	100,448	103,063	15,391	15,416	15,455	98,48
11.11.2016 00:10	100,448	103,063	15,391	15,416	15,455	98,48
11.11.2016 00:20	98,324	99,714	15,396	15,419	15,456	96,149
11.11.2016 00:30	94,368	95,666	15,424	15,446	15,49	91,713
11.11.2016 00:40	94,368	95,666	15,424	15,446	15,49	91,713
11.11.2016 00:50	90,248	92,207	15,462	15,485	15,526	88,08
11.11.2016 01:00	86,679	88,739	15,477	15,502	15,542	84,664
11.11.2016 01:10	86,679	88,739	15,477	15,502	15,542	84,664
11.11.2016 01:20	88,499	90,181	15,494	15,522	15,561	86,673
11.11.2016 01:30	87,493	89,027	15,532	15,548	15,592	83,596
11.11.2016 01:40	87,493	89,027	15,532	15,548	15,592	83,596
11.11.2016 01:50	87,54	88,638	15,551	15,572	15,616	83,148
11.11.2016 02:00	86,822	88,848	15,576	15,595	15,642	82,921
11.11.2016 02:10	86,822	88,848	15,576	15,595	15,642	82,921
11.11.2016 02:20	85,144	87,004	15,578	15,602	15,646	81,745
11.11.2016 02:30	81,669	83,298	15,57	15,594	15,642	78,291
11.11.2016 02:40	81,669	83,298	15,57	15,594	15,642	78,291
11.11.2016 02:50	79,314	81,398	15,587	15,617	15,666	76,791
11.11.2016 03:00	76,881	78,701	15,598	15,629	15,675	74,126
11.11.2016 03:10	76,881	78,701	15,598	15,629	15,675	74,126
11.11.2016 03:20	76,078	77,569	15,601	15,629	15,673	73,259
11.11.2016 03:30	76,343	77,413	15,615	15,647	15,686	73,641
11.11.2016 03:40	76,343	77,413	15,615	15,647	15,686	73,641
11.11.2016 03:50	74,643	76,226	15,609	15,638	15,681	72,244
11.11.2016 04:00	73,322	75,183	15,607	15,631	15,68	70,813
11.11.2016 04:10	73,322	75,183	15,607	15,631	15,68	70,813
11.11.2016 04:20	73,555	75,458	15,582	15,615	15,662	71,698
11.11.2016 04:30	72,353	73,862	15,607	15,637	15,681	69,869
11.11.2016 04:40	72,353	73,862	15,607	15,637	15,681	69,869
11.11.2016 04:50	69,649	70,569	15,606	15,638	15,678	67,184
11.11.2016 05:00	69,221	71,382	15,618	15,641	15,688	66,231
11.11.2016 05:10	69,221	71,382	15,618	15,641	15,688	66,231
11.11.2016 05:20	71,051	73,79	15,593	15,619	15,668	69,107
11.11.2016 05:30	73,044	75,812	15,577	15,605	15,653	71,428
11.11.2016 05:40	73,044	75,812	15,577	15,605	15,653	71,428
11.11.2016 05:50	71,381	73,283	15,571	15,6	15,643	69,21
11.11.2016 06:00	74,931	77,623	15,544	15,573	15,621	72,891
11.11.2016 06:10	74,931	77,623	15,544	15,573	15,621	72,891
11.11.2016 06:20	79,729	82,184	15,494	15,522	15,569	77,324

Figure 5.4 Three Phase Current and Voltage Values of E07-TR1 Transformer in xlsx file format

CHAPTER 6

PROPOSED ALGORITHM FOR EVENT DIRECTION AND FAULT TYPE

6.1 Introduction

ION7650 (PQ analyzer) intelligent metering and control equipment supply revenue-accurate, true RMS measurements of voltage, power, energy and current. Extensive I/O capabilities, detailed logging, and advanced power quality measurement and compliance verification functions complement ION7650 intelligent device. It can have combined with IO software or other energy management, Supervisory Control and Data Acquisition (SCADA), automation and invoicing systems, which uses multiple industry-standard communication channels and protocols. ION7650 meters comply with the EN50160 including Flicker (with ordering option only) and IEC 61000-4-30 Class A Edition 2. COMTRADE permits you to save waveform data in COMmon Format for TRAnsient Data Exchange (COMTRADE) format, available for download via FTP. Parameters measured by ION 7650 PQ analyzer is given following:

- Energy: kWh, kVARh, kVAh net, kWh delivered and received, kWh, kVARh, kVAh total, kVARh, kVAh delivered and received, Volt-hours and amp-hours
- Voltage and current, active and reactive power, apparent power, power factor, frequency, voltage and current unbalance (Instantaneous)
- Harmonics: individual harmonics, total even harmonics, total odd harmonics, K-factor, Crest factor.
- Max-Min recording: Voltage and current min/max, kW, kVAR, and kVA min/max, power factor, frequency, voltage unbalance.
- Power Quality: Sag/swell, Transient [59]

While we design this algorithm, we use voltage and current min/max data record by ION 7650 PQ analyzer during voltage sag and voltage swell. The basic clue in determining the direction of events such as voltage swell and voltage sag is the relationship between voltage and current. According to this relationship, the direction of the event can be determined. There are many studies in the literature about direction of event. A new algorithm is proposed by examining these studies. Voltage and current information of the phases is taken from the database. These are V_{1max}, V_{1min}, V_{2max}, V_{2min}, V_{3max}, V_{3min}, I_{1max}, I_{1min}, I_{2max}, I_{2min}, I_{3max}, I_{3min}.

6.2 General Flow Diagram of Algorithm

In Figure 6.1, flow diagram of algorithm is given. According to the algorithm, it is defined as undefined data if V_{1max}=V_{1min}, V_{2max} =V_{2min}, and V_{3max}= V_{3min} are equal during the event in three phases. Since the value of $V_{max}$and V_{min} is equal, it is an unreasonable condition, so event data is defined as measurement error 1 and is excluded from evaluation. Then, if the V_{max}value for one phase is greater than 1.1 pu and the V_{min}value for the same phase is less than 0.9 pu, the event data is determined as measurement error 2. Because at the same time in one phase neither the voltage sag nor the voltage swell can occur. Since the limit of the voltage sag are between 0.1pu and 0.9pu, if the values of the minimum voltages of all phases fall below the value of 0.1pu, they are classified as interruption. Therefore, if V_{1min} and V_{2min} and V_{3min}, values are lower than 0.1 pu, it is defined as interruption. For some power quality analyzer only the voltage probe is connected and the current probes are not connected. In this case, the event data is determined as undefined data 4 to attract the attention of the user. the direction of the voltage sag is determined according to the total score value calculated according to current and voltage information. The total score is the sum of the scores calculated according to whether the event data provided the conditions. According to this score, the direction of the event is determined. If the total score is less than 6, the event direction is determined as upstream, while if the total score is greater than 6, it is determined as downstream. For downstream events, root cause of the event is determined. In summary, firstly following conditions are checked. Then event type or direction is determined according to whether the event data is provided by these conditions. if the event direction is downstream, the root cause of the event is determined.

- If (V_{1min}= V_{1max} and V_{2min}= V_{2max} and V_{3min}= V_{3max}) then undefined data 1
- If ((V_{1min}<=0.9 ve V_{1max}>=1.1) or (V_{2max}>=1.1 ve $V_{2min} <= 0.9$) ve (V_{3max} >=1.1 ve V_{3min}<=0.9)) then undefined data 2
- If (current probe is not connected) then undefined data 4
- If (V_{1min}= 0 ve V_{2min}= 0 ve V_{3min}= 0) then interruption
- If (S_T<6) then upstream
- If (S_T>6) then downstream

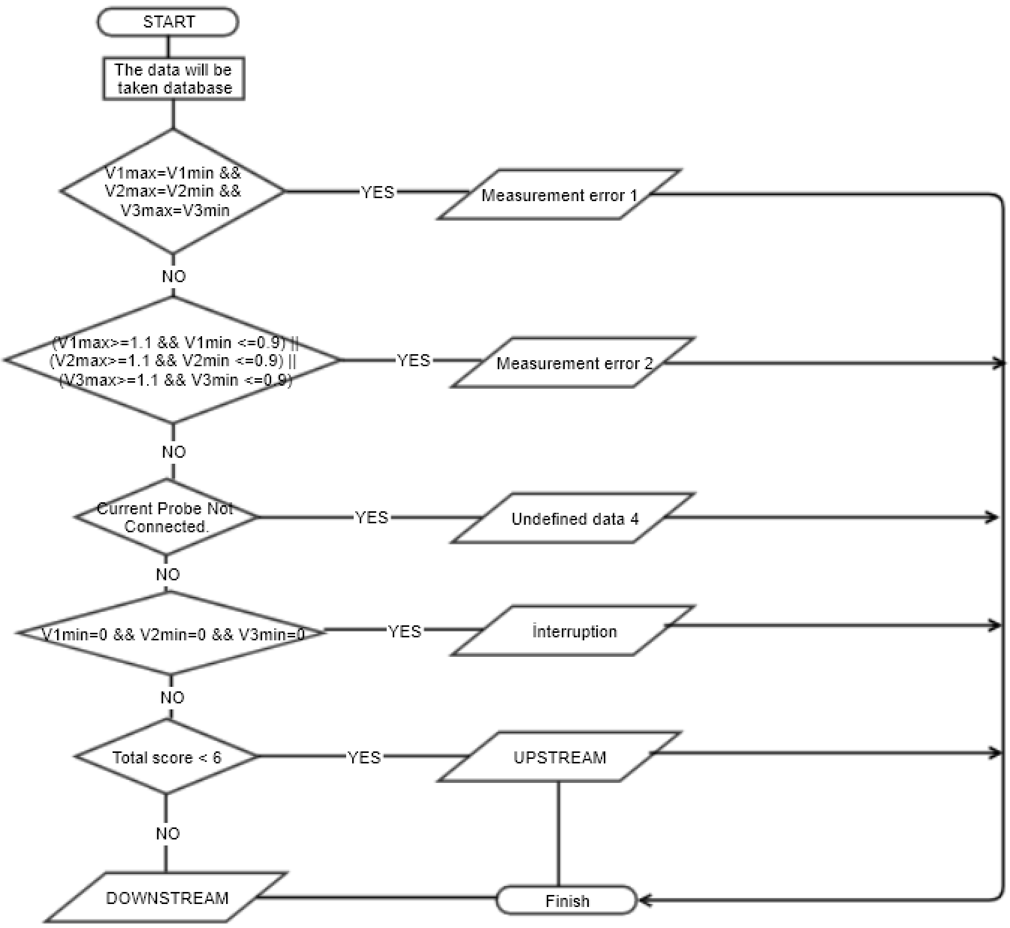


Figure 6.1 Flowchart of proposed algorithm

6.3 Scoring by Voltage Value

In Figure 6.2, the flow chart for the total score part is shown. V_{1max}, V_{1min}, V_{2max}, V_{2min}, V_{3max}, V_{3min}, I_{1max}, I_{1min}, I_{2max}, I_{2min}, I_{3max}, I_{3min} data about the events are firstly taken from the database according to the flow chart in Figure-6.1. Using this data, a total score is calculated. The direction of the event is determined by the total score value.

K_i=f $(V_1, V_2, V_3, I_1, I_2, I_3)$

K_i=f $(V_{1max}, V_{1min}, V_{2max}, V_{2min}, V_{3max}, V_{3min}, I_{1max}, I_{1min}, I_{2max}, I_{2min}, I_{3max}, I_{3min})$ i =1,2,3 …… 37

S_i= f(K_i) U f$(V_1, V_2, V_3, I_1, I_2, I_3)$

$S_T = \sum_{i=1}^{36} S_i$

$C_1 = \frac{I_{1max}}{I_{1min}}$ $C_2 = \frac{I_{2max}}{I_{2min}}$ $C_3 = \frac{I_{3max}}{I_{3min}}$

$\mathrm{MC}_1 = \frac{I_{1max}}{I_{2max}}$ $\mathrm{MC}_2 = \frac{I_{1max}}{I_{3max}}$ $\mathrm{MC}_3 = \frac{I_{2max}}{I_{1max}}$ $\mathrm{MC}_4 = \frac{I_{2max}}{I_{3max}}$ $\mathrm{MC}_5 = \frac{I_{3max}}{I_{1max}}$ $\mathrm{MC}_6 = \frac{I_{3max}}{I_{2max}}$

MV_1= max$(V_{1max}, V_{2max}, V_{3max})$
MV_2= min $(V_{1min}, V_{2min}, V_{3min})$,
MV= $MV_1 - MV_2$

K_i is the result of the i-th conditional function depending on the voltage and current values. If the condition is satisfied, the value of K_i is 1, otherwise the value of K_i is zero. S_i is score value of the event that provides i-th conditional. The S_i value is calculated if i-th condition is satisfied. S_T is the sum of S_i. The data recorded during the event is controlled separately for each condition and the score is calculated for the provided condition. The scores from each condition are summed and the total score (S_T) is calculated. During the event, the max / min current ratios for the phases are denoted by C while the max / max current ratios are denoted by MC. All condition is shown Table 6.1.

Table 6.1 Conditions related to event

K_i \ f	Conditions
K_1	if (V_{1min}<=0.9 and V_{2max}>=1.1 and $V_{3min} > 0.9$ and V_{3max} <1.1)
K_2	İf (V_{1min}<=0.9 and V_{2max}<1.1 ve $V_{2min} > 0.9$ and V_{3max} >=1.1)
K_3	İf (V_{1min}>0.9 ve V_{1max}<1.1 and $V_{2min} <= 0.9$ and V_{3max} >=1.1)
K_4	İf (V_{1min}>0.9 and V_{1max}<1.1 and $V_{2max} >= 1.1$ and V_{3min} <=0.9)
K_5	İf (V_{1max}>=1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ and V_{3max} <1.1)
K_6	İf (V_{1max}>=1.1 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <0.9)
K_7	İf (V_{1min}<=0.9 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1)
K_8	İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ ve V_{3max} <1.1)
K_9	İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}>0.9 and $V_{2max} < 1.1$ ve V_{3min} <=0.9)
K_{10}	İf (V_{1min}<=0.9 and V_{2max}>=1.1 and V_{3max} >=1.1)
K_{11}	İf (V_{1max}>=1.1 and V_{2min}<=0.9 and V_{3max} >=1.1)
K_{12}	İf (V_{1max}>=1.1 and V_{2max}>=1.1 and V_{3min} <=0.9)
K_{13}	İf (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3max} < 1.1$ and V_{3min} >0.9)
K_{14}	İf (V_{1min}<=0.9 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <=0.9)
K_{15}	İf (V_{1min}>0.9 and V_{1maz}<1.1 and $V_{2min} <= 0.9$ and V_{3min} <=0.9)
K_{16}	İf (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3max} >= 1.1$)
K_{17}	İf (V_{1min}<=0.9 and $V_{2max} >= 1.1$ and V_{3min} <=0.9)
K_{18}	İf (V_{1maz}>=1.1 and $V_{2min} <= 0.9$ and V_{3min} <=0.9)
K_{19}	İf (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3min} <= 0.9$)
K_{20}	İf ($C_1 > 5$ and $C_2 > 5$ ve $C_3 > 5$)
K_{21}	İf ($C_1 > 1.3$ and $C_2 > 1.3$ and $C_3 < 1.3$)
K_{22}	İf ($C_1 > 1.3$ and $C_2 > 1.3$ and $C_3 > 1.3$)
K_{23}	İf ($C_1 > 1.3$ and $C_2 < 1.3$ and$C_3 > 1.3$)
K_{24}	İf ($C_1 < 1.3$ and $C_2 > 1.3$ and $C_3 > 1.3$)
K_{25}	İf ($C_1 > 1.3$ and $C_2 < 1.3$ and $C_3 < 1.3$)
K_{26}	İf ($C_1 < 1.3$ and $C_2 > 1.3$ and $C_3 < 1.3$)
K_{27}	İf ($C_1 < 1.3$ and $C_2 < 1.3$ and$C_3 > 1.3$)
K_{28}	İf (V_{1max}>=1.1 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1)
K_{29}	İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1)
K_{30}	İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ ve V_{3max} >=1.1)
K_{31}	İf (V_{1max}>=1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1)
K_{32}	İf (V_{1max}>=1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ ve V_{3max} >=1.1)
K_{33}	İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 ve V_{3max} >=1.1)
K_{34}	İf (V_{1max}>=1.1 and V_{2max}>=1.1 ve V_{3max} >=1.1)
K_{35}	İf ($MC_1 > 1.3$ $veya$ $MC_2 > 1.3$ $veya$ $MC_3 > 1.3$ $veya$ $MC_4 > 1.3$ $veya$ $MC_5 > 1.3$ $veya$ $MC_6 > 1.3$
K_{36}	İf (($V_{1max} - V_{1min}$<=0.02) and ($V_{2max} - V_{2min}$<=0.02) and ($V_{3max} -$

	V_{3min}<=0.02))
K_{37}	İf ((MV>0.5) or (0.5>MV>0.4) or (0.4>MV>0.3) or (0.3>MV>0.2))

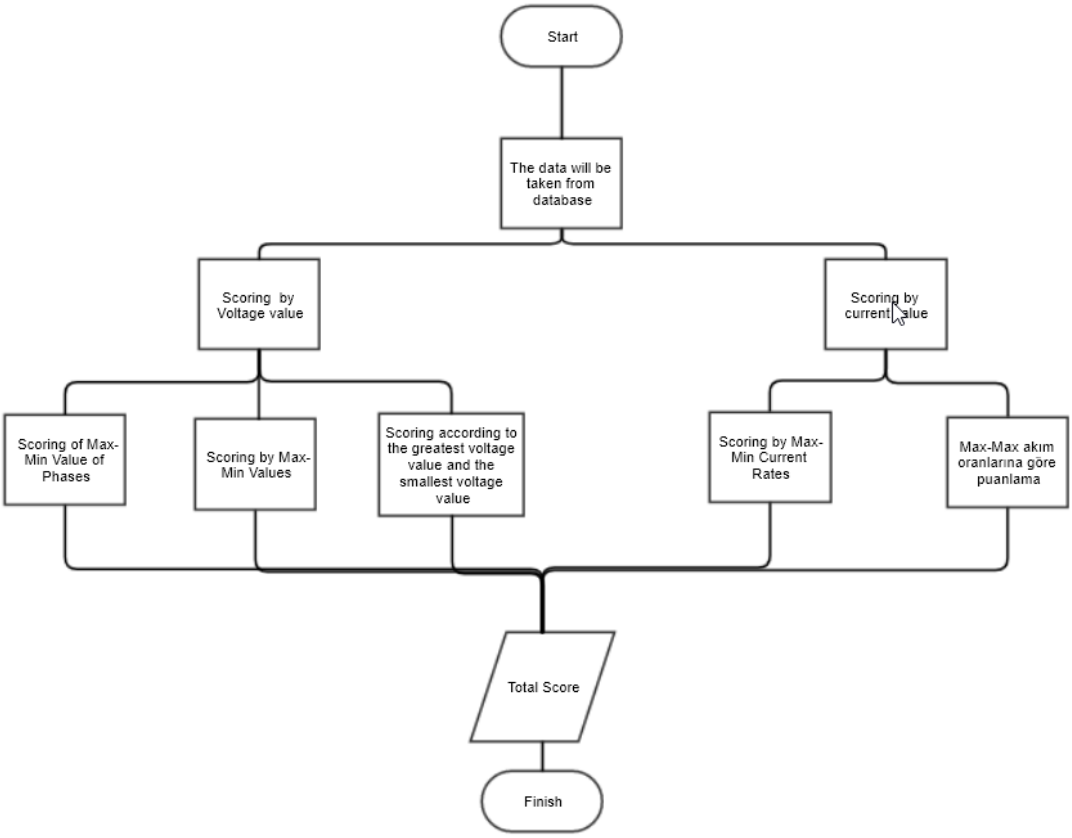


Figure 6.2 Scoring flowchart

6.3.1 Scoring by Max-Min Values of Voltage

Firstly, in the Scoring block according to the Max-Min values, a score is calculated according to the maximum and minimum voltage value during the event. Different calculation methods are applied for different situations in this score calculation. These methods are given in the following rules. D is difference value.

Rule 1: if (V_{1min}<=0.9 and V_{2max}>=1.1 and $V_{3min} > 0.9$ and V_{3max} <1.1), then $D_1 = V_{3min} - V_{1min}$ $D_2 = V_{2max} - V_{3max}$

Rule 2: if (V_{1min}<=0.9 and V_{2max}<1.1 ve $V_{2min} > 0.9$ and V_{3max} >=1.1) then $D_1 = V_{2min} - V_{1min}$ $D_2 = V_{3max} - V_{2max}$

Rule 3: if (V_{1min}>0.9 ve V_{1max}<1.1 and $V_{2min} <= 0.9$ and V_{3max} >=1.1) then $D_1 = V_{1min} - V_{2min}$ $D_2 = V_{3max} - V_{1max}$

Rule 4: if (V_{1min}>0.9 and V_{1max}<1.1 and $V_{2max} >= 1.1$ and V_{3min} <=0.9) then $D_1 = V_{1min} - V_{3min}$ $D_2 = V_{2max} - V_{1max}$

Rule 5: if (V_{1max}>=1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ and V_{3max} <1.1) then $D_1 = V_{3min} - V_{2min}$ $D_2 = V_{1max} - V_{3max}$

Rule 6: if (V_{1max}>=1.1 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <0.9) then $D_1 = V_{2min} - V_{3min}$ $D_2 = V_{1max} - V_{2max}$

Rule 7: if (V_{1min}<=0.9 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then $D_1 = V_{3min} - V_{1min}$ $D_2 = V_{2min} - V_{1min}$

Rule 8: if (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ ve V_{3max} <1.1)) then $D_1 = V_{3min} - V_{2min}$ $D_2 = V_{1min} - V_{2min}$

Rule 9: if (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then $D_1 = V_{2min} - V_{3min}$ $D_2 = V_{1min} - V_{3min}$

Rule 10: if (V_{1min} <=0.9 and V_{2max} >=1.1 and V_{3max} >=1.1) then $D_1 = V_{1min} - 0.9$ $D_2 = V_{2max} - 1.1$ $D_3 = V_{3max} - 1.1$

Rule 11: if (V_{1max} >=1.1 and V_{2min} <=0.9 and V_{3max} >=1.1) then $D_1 = V_{1max} - 1.1$ $D_2 = V_{2min} - 0.9$ $D_3 = V_{3max} - 1.1$

Rule 12: if (V_{1max} >=1.1 and V_{2max} >=1.1 and V_{3min} <=0.9) then $D_1 = V_{1max} - 1.1$ $D_2 = V_{2max} - 1.1$ $D_3 = V_{3min} - 0.9$

Rule 13: if (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3max} < 1.1$ and V_{3min} >0.9) then $D_1 = V_{3min} - V_{1min}$ $D_2 = V_{3min} - V_{2min}$

Rule 14: if (V_{1min}<=0.9 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <=0.9) then $D_1 = V_{2min} - V_{1min}$ $D_2 = V_{2min} - V_{3min}$

Rule 15: if (V_{1min}>0.9 and V_{1maz}<1.1 and $V_{2min} <= 0.9$ and V_{3min} <=0.9) then $D_1 = V_{1min} - V_{2min}$ $D_2 = V_{1min} - V_{3min}$

Rule 16: if (V_{1min} <=0.9 and V_{2min} <=0.9 and $V_{3max} >= 1.1$) then $D_1 = V_{1min} - 0.9$ $D_2 = V_{2min} - 0.9$ $D_3 = V_{3max} - 1.1$

Rule 17: if (V_{1min} <=0.9 and $V_{2max} >= 1.1$ and V_{3min} <=0.9) then $D_1 = V_{1min} - 0.9$ $D_2 = V_{2max} - 1.1$ $D_3 = V_{3min} - 0.9$

Rule 18: if (V_{1maz} >=1.1 and $V_{2min} <= 0.9$ and V_{3min} <=0.9)) then $D_1 = V_{1min} - 0.9$ $D_2 = V_{2max} - 1.1$ $D_3 = V_{3min} - 0.9$

Rule 19: if (V_{1min} <=0.9 and V_{2min} <=0.9 and $V_{3min} <= 0.9$)) then $D_1 = V_{1min} - 0.9$ $D_2 = V_{2min} - 0.9$ $D_3 = V_{3min} - 0.9$

Rule 20: if (V_{1max}>=1.1 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then $D_1 = V_{1max} - V_{2max}$ $D_2 = V_{1max} - V_{3max}$

Rule 21: if (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ and V_{3max} <1.1) then $D_1 = V_{2max} - V_{1max}$ $D_2 = V_{2max} - V_{3max}$

Rule 22: if (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ and V_{3max} >=1.1) then $D_1 = V_{3max} - V_{1max}$ $D_2 = V_{3max} - V_{2max}$

Rule 23: if (V_{1max}>=1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ and V_{3max} <1.1) then

$D_1 = V_{1max} - V_{3max}$ $D_2 = V_{2max} - V_{3max}$

Rule 24: if (V_{1max}>=1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ and V_{3max} >=1.1) then $D_1 = V_{1max} - V_{2max}$ $D_2 = V_{3max} - V_{2max}$

Rule 25: if (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 and V_{3max} >=1.1) then $D_1 = V_{2max} - V_{1max}$ $D_2 = V_{3max} - V_{1max}$

Rule 26: if (V_{1max} >=1.1 and V_{2max} >=1.1 and V_{3max} >=1.1) then $D_1 = V_{1max} - 1.1$ $D_2 = V_{2max} - 1.1$ $D_3 = V_{3max} - 1.1$

A score value is calculated by processing the difference values obtained from the above rules according to the scoring algorithm in Figure 6.3. Number of difference values according to event type is 2 (D_1, D_2) or 3 (D_1, D_2, D_3). Firstly, the number of difference values is determined. Scoring is done depending on the difference value.

- if ($D_1 \geq 0.5$ or $D_2 \geq 0.5$) then $S_i = 5$
- if ($0.3 \geq D_1 > 0.2$ or $0.3 \geq D_2 > 0.2$) then $S_i = 3$
- if ($0.2 \geq D_1 > 0.1$ or $0.2 \geq D_2 > 0.1$) then $S_i = 2$
- if ($0.1 \geq D_1 > 0$ or $0.1 \geq D_2 > 0$) then $S_i = 1$
- if ($D_1 \geq 0.5$ or $D_2 \geq 0.5$ or $D_3 \geq 0.5$) then $S_i = 5$
- if ($0.3 \geq D_1 > 0.2$ or $0.3 \geq D_2 > 0.2$ or $0.3 \geq D_3 > 0.2$) then $S_i = 3$
- if ($0.2 \geq D_1 > 0.1$ or $0.2 \geq D_2 > 0.1$ or $0.2 \geq D_3 > 0.1$) then $S_i = 2$
- if ($0.1 \geq D_1 > 0$ or $0.1 \geq D_2 > 0$ or $0.1 \geq D_3 > 0.$) then $S_i = 1$

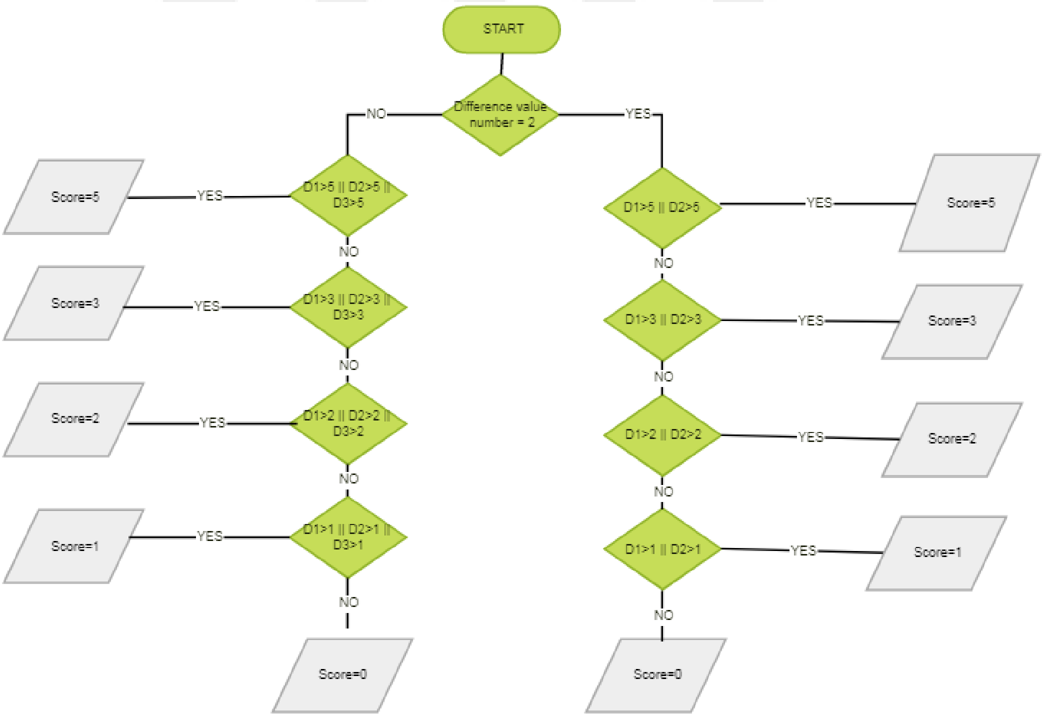


Figure 6.3 Scoring algorithm

6.3.2 Scoring of Max-Min Value of Phase Current

The difference value between the maximum and minimum voltage values of each phase is calculated. If all these difference values are less than 0.02 pu, the algorithm gives a score of minus 5.

- if (($V_{1max} - V_{1min}$ <=0.02) and ($V_{2max} - V_{2min}$ <=0.02) and ($V_{3max} - V_{3min}$<=0.02)) then S_i= -5

6.3.3 Scoring according to the greatest voltage value and the smallest voltage value

The maximum voltage value of V1max, V2max and V3max is found. The minimum voltage value of V1min, V2min and V3min is found. The smallest voltage value is subtracted from the greatest voltage value. then the difference value is scored according to the scoring algorithm in Figure-6.3.

MV_1= max(V_{1max}, V_{2max}, V_{3max})
MV_2= min (V_{1min}, V_{2min}, V_{3min}),
MV= $MV_1 - MV_2$

- İf (MV>0.5) then $S_i = 5$)
- İf(0.5>MV>0.4) then $S_i = 4$)
- İf(0.4>MV>0.3) then $S_i = 3$)
- İf(0.3>MV>0.2) then $S_i = 2$)
- İf(MV<0.2) then $S_i = 0$)

6.4 Scoring by Current Value

6.4.1 Scoring by Max-Min Current Rates

In this scoring block, scoring is done according to whether the conditions of K_{21}, K_{22}, K_{23}, K_{24} , K_{25}, K_{26}, K_{27}, in Table 6.1 are met. If the current condition is satisfied, the algorithm yields 4 score as a result, 0 score if not. If one of these current conditions is met, the other conditions are not absolutely provided. if condition is provided, 4 score are given, if not zero score is given. Therefore, maximum 4 points are given in this scoring block. We will also classify the fault types according to these current conditions. For example, conditions of K_{21}, K_{22}, K_{23}, must be provided. Otherwise, the related event is not classified as two phase faults.

- Then ($C_1 > 1.3$ ve $C_2 > 1.3$ and $C_2 > 1.3$) then $S_i = 4$
- Then ($C_1 < 1.3$ and $C_2 > 1.3$ and $C_2 > 1.3$) then $S_i = 4$
- Then ($C_1 > 1.3$ and $C_2 < 1.3$ and $C_2 > 1.3$) then $S_i = 4$
- Then ($C_1 > 1.3$ and $C_2 > 1.3$ and $C_2 < 1.3$) then $S_i = 4$
- Then ($C_1 < 1.3$ and $C_2 < 1.3$ and $C_2 > 1.3$) then $S_i = 4$
- Then ($C_1 < 1.3$ and $C_2 > 1.3$ and $C_2 < 1.3$) then $S_i = 4$
- Then ($C_1 > 1.3$ and $C_2 < 1.3$ and $C_2 < 1.3$) then $S_i = 4$

6.4.2 Scoring by Max-Max Current Rates

The maximum value of the current for each phase is taken from the database. If the ratio of the maximum current value for one phase to the maximum current value of one of the other two phases is greater than 1.28, then the algorithm yields 4 points as a result. It is not possible to provide two conditions at the same time. Therefore, maximum 4 points are taken from this scoring block.

- İf ($\mathrm{MC}_1 > 1.28$ then $S_i = 4$)
- İf ($\mathrm{MC}_2 > 1.28$ then $S_i = 4$)
- İf ($\mathrm{MC}_3 > 1.28$ then $S_i = 4$)
- İf ($\mathrm{MC}_4 > 1.28$ then $S_i = 4$)
- İf ($\mathrm{MC}_5 > 1.28$ then $S_i = 4$)
- İf ($\mathrm{MC}_6 > 1.28$ then $S_i = 4$)

6.5 Conditions of Fault Type

After direction of event is determined by scoring we will define fault type. If the direction of the event is downstream, then determine the type of fault that caused the fault to be downstream of the event. In this case the conditions specified for the fault types are given below.

LG: Condition of single phase ground fault

LLG: Condition of two phase ground fault

LLLG: Condition of three phase ground fault

CLLLG: Current conditions of three phase fault

LL: Condition of two phase fault

UD 3: Undefined Data 3

- İf (V_{1min}<=0.9 and V_{2max}>=1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then LG
- İf (V_{1min}<=0.9 and V_{2max}<1.1 and $V_{2min} > 0.9$ and V_{3max} >=1.1) then LG
- İf (V_{1min}>0.9 and V_{1max}<1.1 and $V_{2min} <= 0.9$ and V_{3max} >=1.1) then LG
- İf (V_{1min}>0.9 and V_{1max}<1.1 and $V_{2max} >= 1.1$ and V_{3min} <=0.9) then LG
- İf (V_{1max}>=1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ and V_{3max} <1.1) then LG
- İf (V_{1max}>=1.1 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <0.9) then LG
- İf (V_{1min}<=0.9 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then LG
- İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}<=0.9 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then LG
- İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2min}>0.9 and $V_{2max} < 1.1$ ve V_{3min} <=0.9) then LG
- İf (V_{1min}<=0.9 and V_{2max}>=1.1 and V_{3max} >=1.1) then LG
- İf (V_{1max}>=1.1 and V_{2min}<=0.9 and V_{3max} >=1.1) then LG
- İf (V_{1max}>=1.1 and V_{2max}>=1.1 and V_{3min} <=0.9) then LG
- İf (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3max} < 1.1$ and V_{3min} >0.9) then LL
- İf (V_{1min}<=0.9 and V_{2min}>0.9 and $V_{2max} < 1.1$ and V_{3min} <=0.9) then LL
- İf (V_{1min}>0.9 and V_{1maz}<1.1 and $V_{2min} <= 0.9$ and V_{3min} <=0.9) then LL
- İf (V_{1min}<=0.9 and V_{2min}<=0.9 and $V_{3max} >= 1.1$) then LLG
- İf (V_{1min}<=0.9 and $V_{2max} >= 1.1$ and V_{3min} <=0.9) then LLG

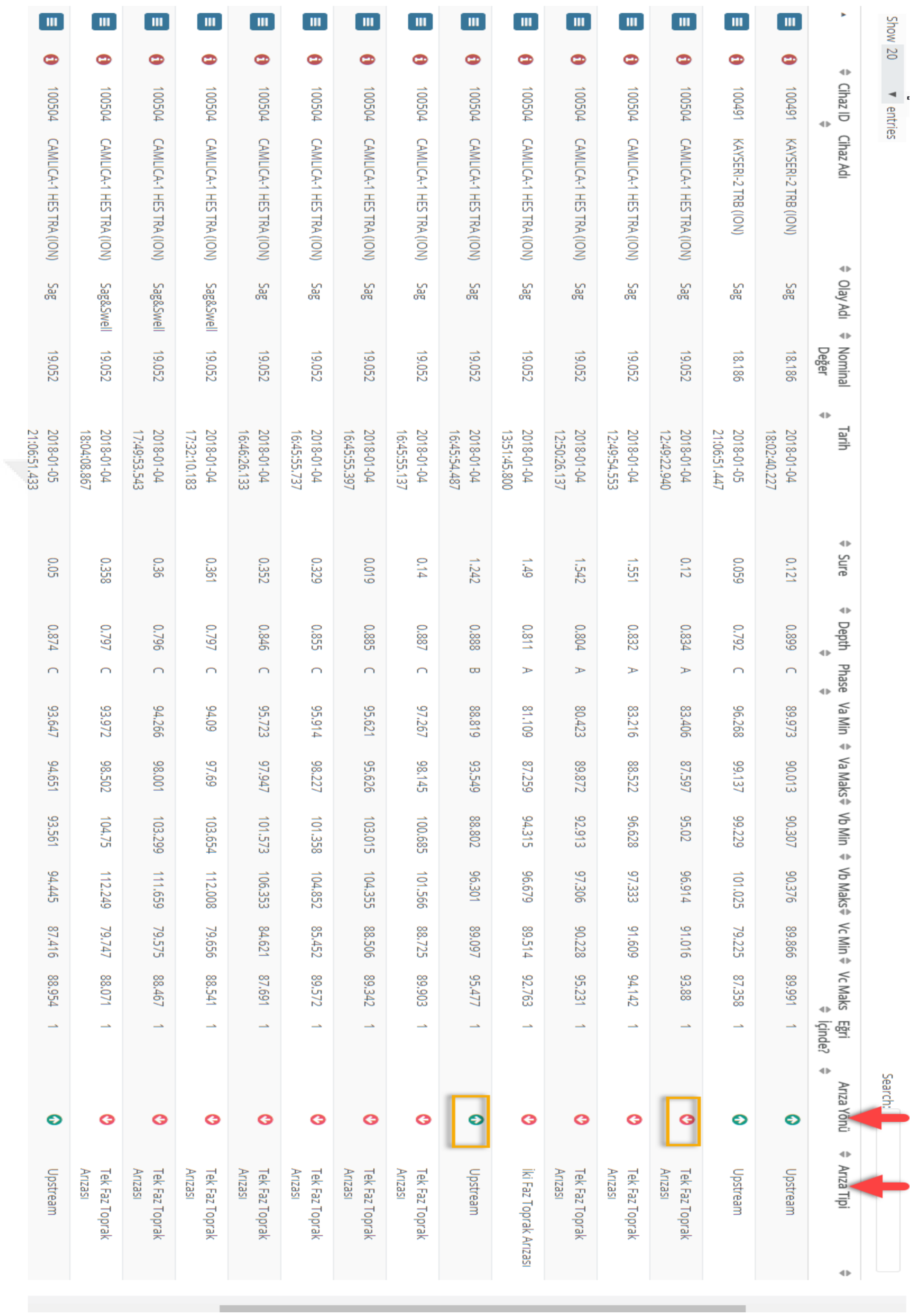
- İf (V_{1maz}>=1.1 and V_{2min} <= 0.9 and V_{3min} <=0.9) then LLG
- İf (V_{1min}<=0.9 and V_{2min}<=0.9 and V_{3min} <= 0.9) then LLLG
- İf ($C_1 > 5$ and $C_2 > 5$ ve $C_3 > 5$) then CLLLG
- İf (V_{1max}>=1.1 and V_{2min}>0.9 and V_{2max}<1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then UD 3
- İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then UD 3
- İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ ve V_{3max} >=1.1) then UD 3
- İf (V_{1max}>=1.1 and V_{2max}>=1.1 and $V_{3min} > 0.9$ ve V_{3max} <1.1) then UD 3
- İf (V_{1max}>=1.1 and V_{2max}<1.1 and $V_{2min} > 0.9$ ve V_{3max} >=1.1) then UD 3
- İf (V_{1min}>0.9 and V_{1max}<1.1 and V_{2max}>=1.1 ve V_{3max} >=1.1) then UD3

If any of the above conditions are met for an event and the total score is greater than or equal to 6, the type of fault is determined according to the condition provided. For example, if the voltage values provide a single phase ground fault condition and at the same time the total result is greater than or equal to 6, the fault type is determined as single phase ground fault (LG) according to the event data.

6.6 Implementatıon of Proposed Algorithm

The designed algorithm has been tested in Excel and Matlab programs. After the test stage, the software has been implemented in Inavitas software. On the event page of the Inavitas, two columns indicating the type and direction of the fault were added to the TKI (TQM) event examination screen. In Figure 6.4, TQM event examination screen is shown. The downward white arrow on the red floor in the fault direction column indicates that the direction of fault is DOWNSTREAM. Upward white arrow on the green floor in the fault type column indicates that the type of fault is UPSTREAM. For each event, the fault direction and type of fault are determined. Comtrade files are also recorded about these events during the event. Correctness of direction and type of event is controlled with comtrade file.

KCETAS has been established to provide electrical energy production, transmission, distribution and trading services for Kayseri and surrounding settlements. The energy consumed in this region are provided from ownership and operation of TEIAS (Turkey Electricity Transmission Co.) and connected to the national electricity system which is 154 / 31.5 kV Kayseri 1 substation, Kayseri 2 substation, Kayseri 3 substation, Cinkur substation, Taksan substation, Sendiremeke substation, Kalaba substation, Pınarbaşı substation, Kapasitör substation, Yeşilhisar substation, Sızır 2 substation, Bünyan and Sızır Hydroelectric Power Plants, which are owned by TEIAS. The average annual energy production of the Sızır Hydroelectric Power Plant, is 28.197.664 kWh and the average annual energy production of Bünyan Hydroelectric Power Plant is 2.910.678 kWh, which is owned by TEAŞ. These two Hydroelectric Power Plant is operated by KCETAS. Kayseri Electricity Generation Industry and Trade Co. Inc., in which KCETAS has a share of 3.75%. approximately 422 GWh of electricity is produced annually at the Yamula dam on the 2 × 50 MW installed power plant with a capacity of 450 million kWh annually.



Show 20 entries

Search:

		Cihaz ID	Cihaz Adı	Olay Adı	Nominal Değer	Tarih	Sure	Depth	Phase	Va Min	Va Maks	Vb Min	Vb Maks	Vc Min	Vc Maks	Eğri İçinde?	Arıza Yönü	Arıza Tipi
		100491	KAYSERI-2 TRB (ION)	Sag	18.186	2018-01-04 18:02:40.227	0.121	0.899	C	89.973	90.013	90.307	90.376	89.866	89.991	1		Upstream
		100491	KAYSERI-2 TRB (ION)	Sag	18.186	2018-01-05 21:06:51.447	0.059	0.792	C	96.268	99.137	99.229	101.025	79.225	87.358	1		Upstream
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 12:49:22.940	0.12	0.834	A	83.406	87.597	95.02	96.914	91.016	93.88	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 12:49:54.553	1.551	0.832	A	83.216	88.522	96.628	97.333	91.609	94.142	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 12:50:26.137	1.542	0.804	A	80.423	89.872	92.913	97.306	90.228	95.231	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 13:51:45.800	1.49	0.811	A	81.109	87.259	94.315	96.679	89.514	92.763	1		İki Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 16:45:54.487	1.242	0.888	B	88.819	93.549	88.802	96.301	89.097	95.477	1		Upstream
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 16:45:55.137	0.14	0.887	C	97.267	98.145	100.685	101.566	88.725	89.903	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 16:45:55.397	0.019	0.885	C	95.621	95.626	103.015	104.355	88.506	89.342	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 16:45:55.737	0.329	0.855	C	95.914	98.227	101.358	104.852	85.452	89.572	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-04 16:46:26.133	0.352	0.846	C	95.723	97.947	101.573	106.353	84.621	87.691	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag&Swell	19.052	2018-01-04 17:32:10.183	0.361	0.797	C	94.09	97.69	103.654	112.008	79.656	88.541	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag&Swell	19.052	2018-01-04 17:49:53.543	0.36	0.796	C	94.266	98.001	103.299	111.659	79.575	88.467	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag&Swell	19.052	2018-01-04 18:04:08.867	0.358	0.797	C	93.972	98.502	104.75	112.249	79.747	88.071	1		Tek Faz Toprak Arızası
		100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2018-01-05 21:06:51.433	0.05	0.874	C	93.647	94.651	93.561	94.445	87.416	88.954	1		Upstream

Figure 6.4 TKI event examination screen

6.6.1 Examples of Single Phase Ground Fault in Inavitas

Single phase ground fault is most common fault in distribution systems. Because 7 single phase ground fault events are considered for the confirmation of proposed algorithm.

- **Event 1:** Sag- Swell event is recorded at Pınarbaşı TRA substation on 2017-10-12 at 02.15. In Figure 6.5, event data is given. Proposed algorithm determined that direction of event is downstream and type of event is single phase ground fault according to Figure 6.5. Voltage waveform during the event is given in Figure 6.6. In Figure 6.7, current waveform during the event is demonstrated. When the voltage and current waveform is examined, the current value of C phase increases about 5 times while there is a voltage sag in C phase. There is a voltage swell in A and B phases. The characteristics of the waveforms obtained in simulation for the single phase ground fault are similar to those of the current and voltage waveforms during the event for all example.

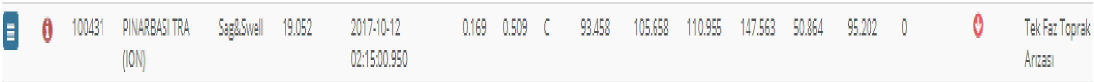


Figure 6.5 Event data in Inavitas

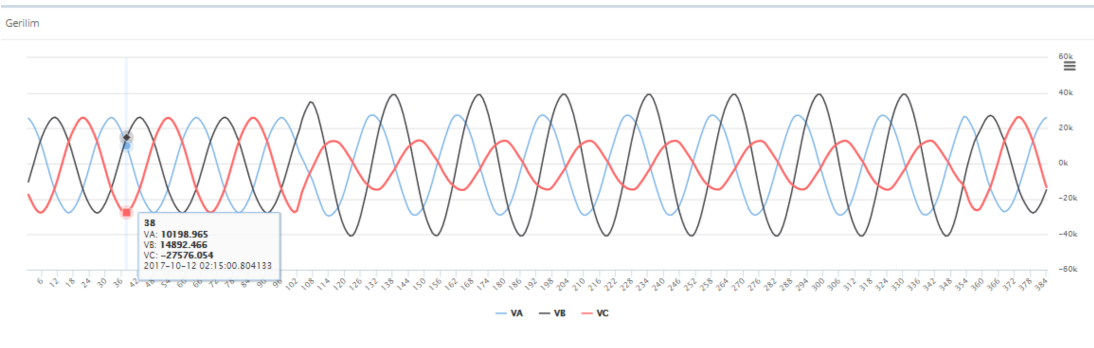


Figure 6.6 Voltage waveform during the events

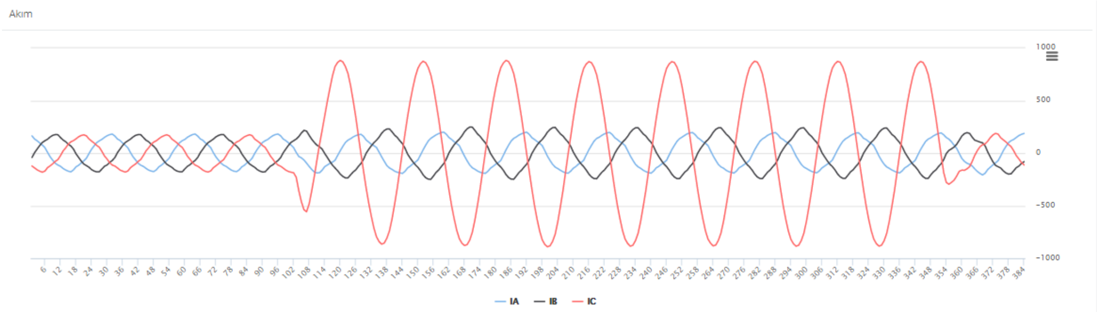


Figure 6.7 Current waveform during the event

- **Event 2:** Sag- Swell event is recorded at Pınarbaşı TRA substation on 2017-10-14 at 06.29. Event data is shown in Figure 6.8. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of A phase increases about 1.9 times while there is a voltage sag in A phase. There is a voltage swell in C phases. Voltage waveform during the event is given in Figure 6.9 In Figure 6.10, current waveform during the event is demonstrated.

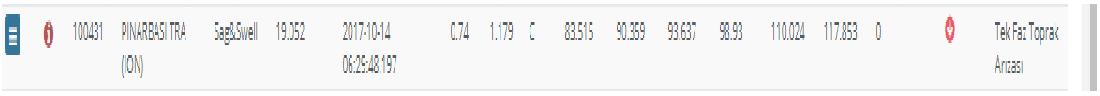


Figure 6.8 Event data in Inavitas

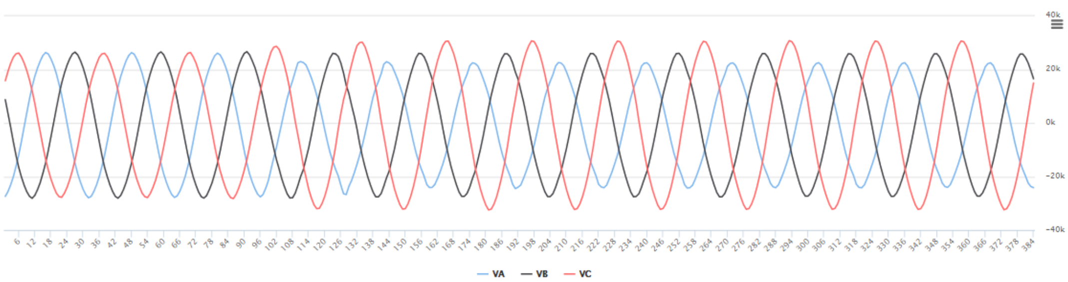


Figure 6.9 Voltage waveform during the event

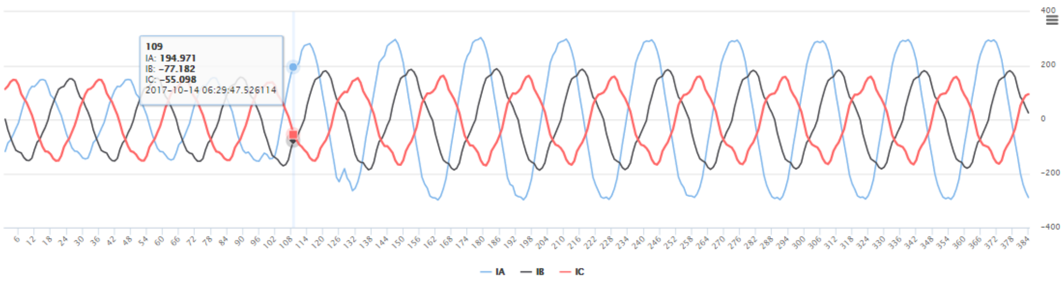


Figure 6.10 Current waveform during the event

- **Event 3:** Sag- Swell event is recorded at Talas TRB substation on 2017-10-24 at 08.53. Event data is shown in Figure 6.11. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of this phase increases about 4 times while there is a voltage sag in A phase. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.12 In Figure 6.13, current waveform during the event is demonstrated.

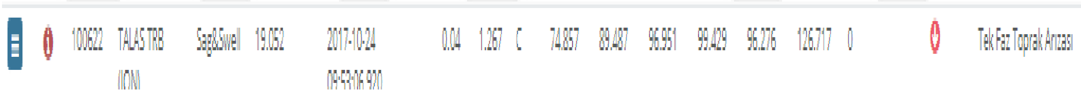


Figure 6.11 Event data in Inavitas

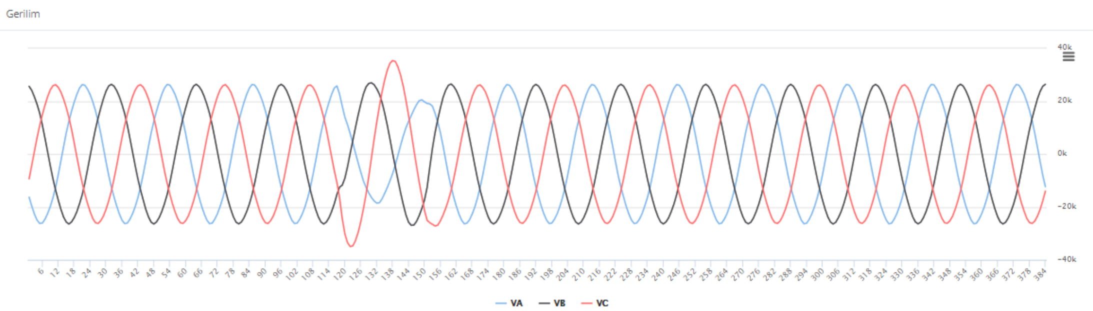


Figure 6.12 Voltage waveform during event

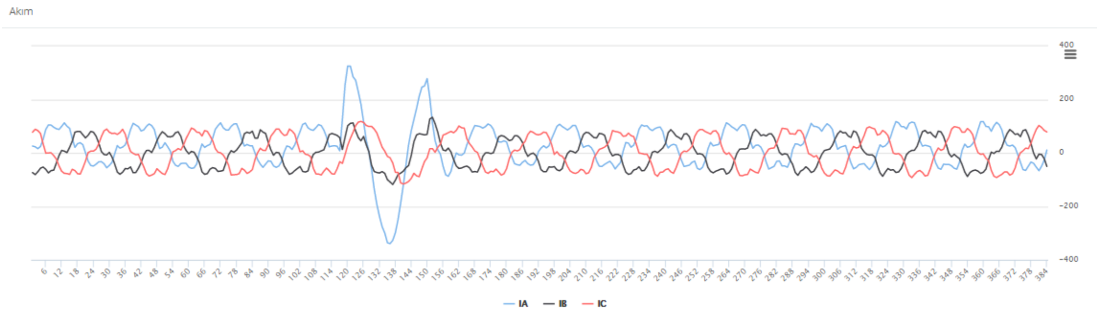


Figure 6.13 Current waveform during event

Event 4: Sag- Swell event is recorded at Talas TRA substation on 2017-10-23 at 10.38. Event data is shown in Figure 6.14. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of this phase increases about 1.9 times while there is a voltage sag in A phase. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.15 In Figure 6.16, current waveform during the event is demonstrated.

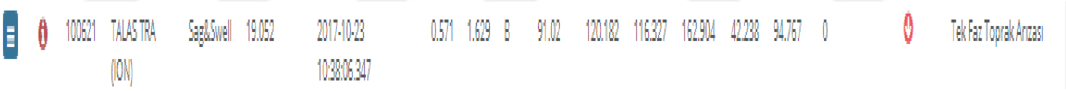


Figure 6.14 Event data in Inavitas

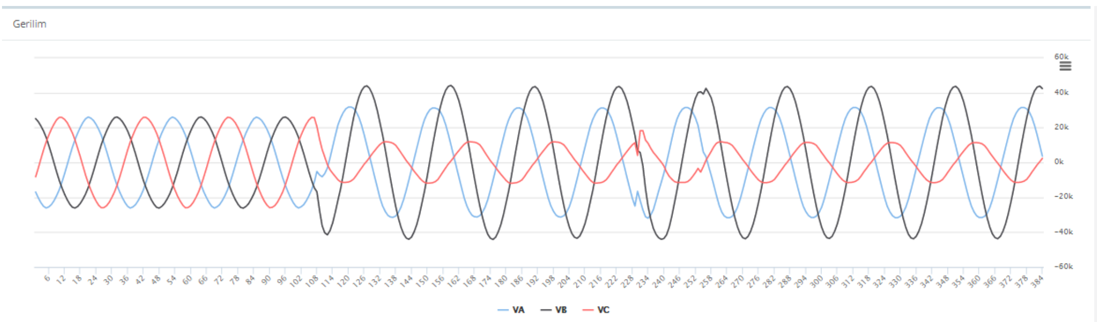


Figure 6.15 Voltage waveform during the event

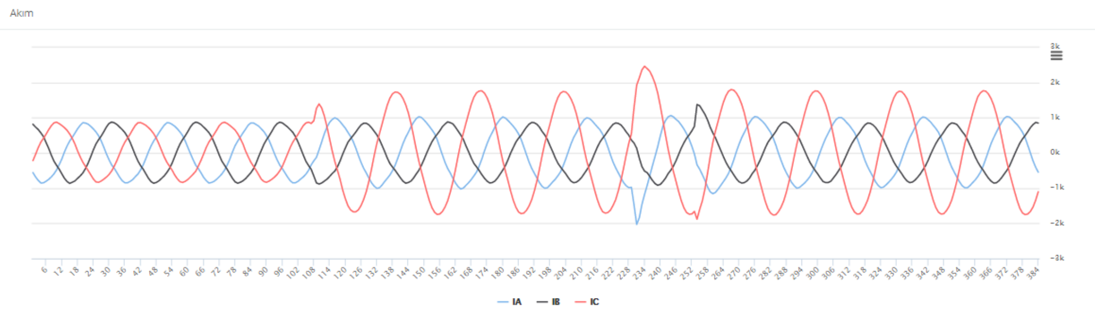


Figure 6.16 Current waveform during the event

Event 5: Sag- Swell event is recorded at Pınarbaşı TRA substation on 2017-10-15 at 08.11. Event data is shown in Figure 6.17. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of this phase increases about 2 times while there is a voltage sag in A phase. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.18. In Figure 6.19, current waveform during the event is demonstrated.

100431	PINARBASI TRA (ION)	Sag&Swell	19.052	2017-10-15 08:11:25.403	0.088	0.611	A	61.065	80.219	100.495	105.831	116.707	130.491	0	Tek Faz Toprak Arızası

Figure 6.17 Event data in Inavitas

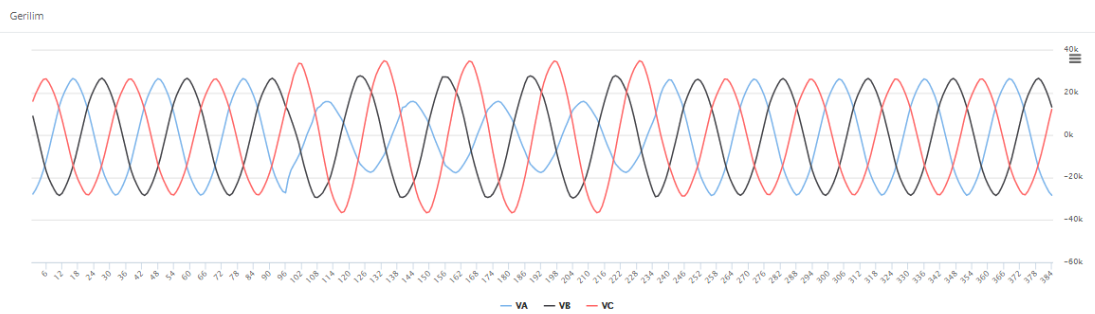


Figure 6.18 Voltage waveform during the event

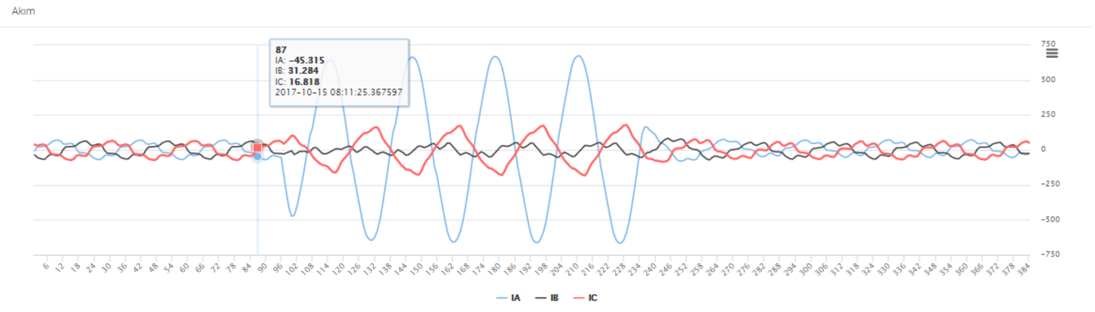
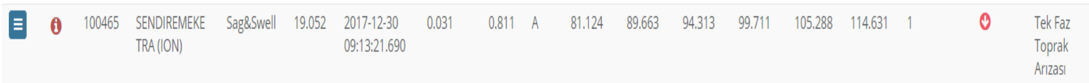


Figure 6.19 Current waveform during the event

Event 6: Sag- Swell event is recorded at Sendiremeke TRA substation on 2017-12-30 at 09.13. Event data is shown in Figure 6.20. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of this phase increases about 2.1 times while there is a voltage sag in A phase. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.21 In Figure 6.22, current waveform during the event is demonstrated.



100465	SENDIREMEKE TRA (ION)	Sag&Swell	19.052	2017-12-30 09:13:21.690	0.031	0.811	A	81.124	89.663	94.313	99.711	105.288	114.631	1	Tek Faz Toprak Arızası

Figure 6.20 Event data in Inavitas

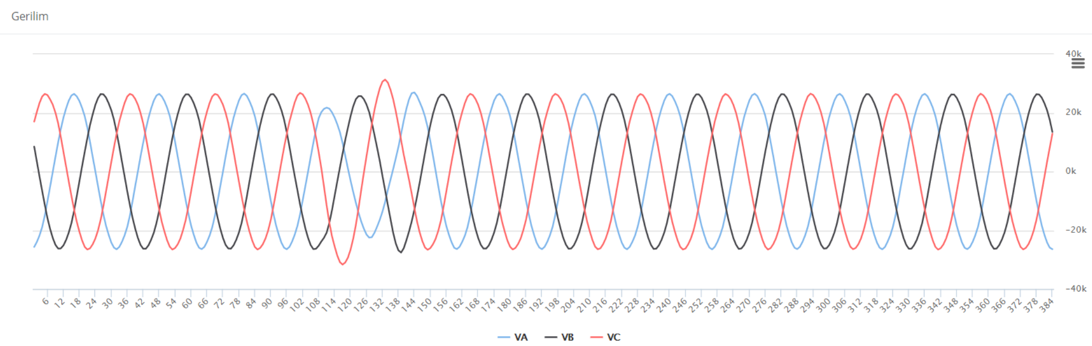


Figure 6.21 Voltage waveform during the event

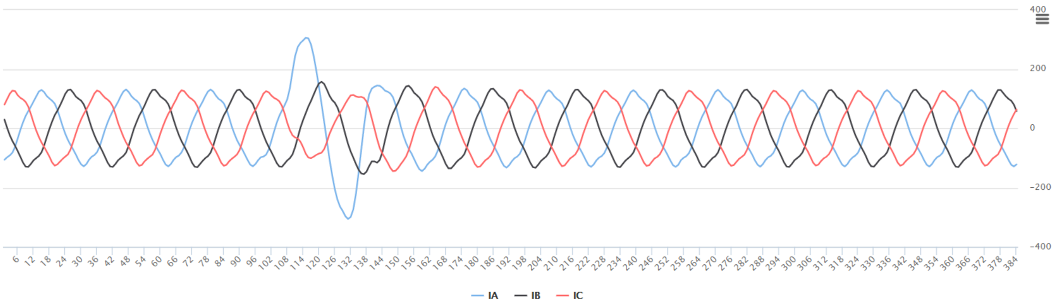


Figure 6.22 Current waveform during the event

Event 7: Sag- Swell event is recorded at Sendiremeke TRB substation on 2017-12-30 at 09.13. Event data is shown in Figure 6.23. In this example, the direction of the fault is DOWNSTREAM, the type of fault is single phase ground fault. When the voltage and current waveform is examined, the current value of this phase increases about 2 times while there is a voltage sag in A phase. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.24. In Figure 6.25, current waveform during the event is demonstrated.

100466	SENDIREMEKE TRB (ION)	Sag&Swell	18.186	2017-12-30 09:13:21.690	0.03	1.203	C	85.597	94.603	99.58	105.202	110.421	120.265	0	Tek Faz Toprak Arızası

Figure 6.23 Event data in Inavitas

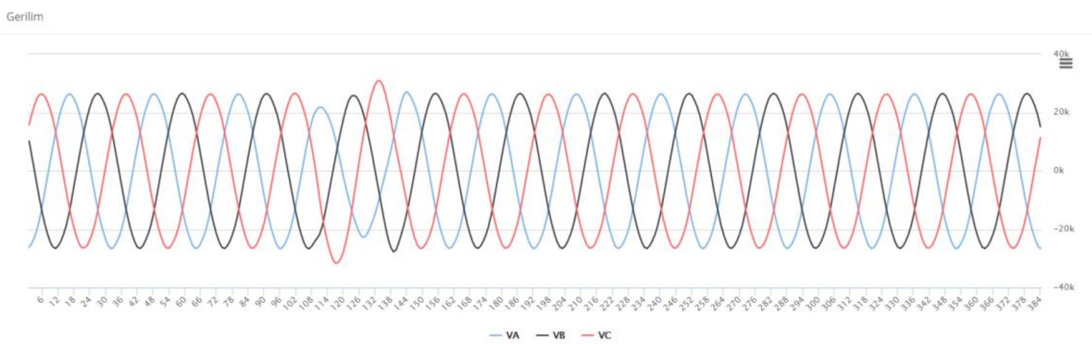


Figure 6.24 Voltage waveform during the event

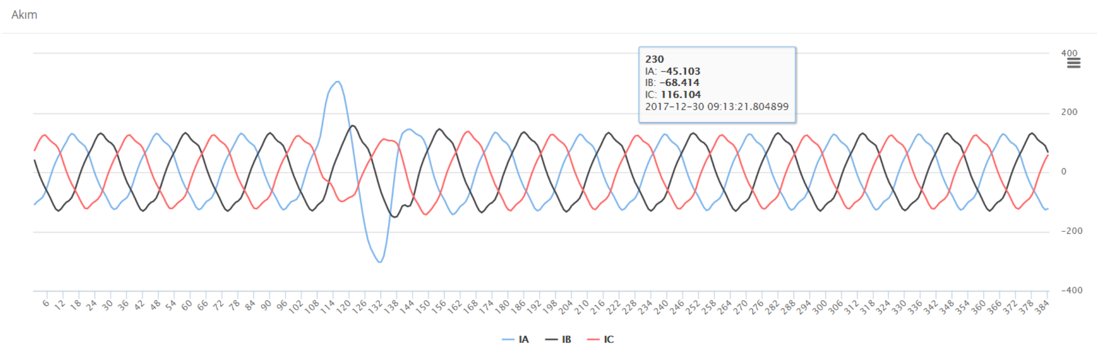
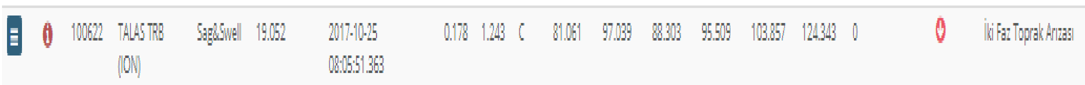


Figure 6.25 Current waveform during the event

6.6.2 Examples of Two Phase Ground Fault in Inavitas

Two phase ground fault is at least common fault in distribution systems. About 50 events are examined related two phase ground fault. But Comtrade file for all events is not available in PQ analyzer. So One two phase ground fault event which has comtrade file are considered for the confirmation of proposed algorithm.

- **Event 1:** Sag- Swell event is recorded at Talas TRB substation on 2017-10-25 at 08.05. Event data is shown in Figure 6.26. In this example, the direction of the fault is DOWNSTREAM, the type of fault is two phase ground fault. When the voltage and current waveform is examined, there is a voltage sag in A and B phases. There is a voltage swell in C phase. Voltage waveform during the event is given in Figure 6.27 In Figure 6.28, current waveform during the event is demonstrated. The characteristics of the waveforms obtained in simulation for the two phase ground fault are similar to those of the current and voltage waveforms during the event for all example.



100622	TALAS TRB (ION)	Sag&Swell	19.052	2017-10-25 08:05:51.363	0.178	1.243	C	81.061	97.039	88.303	95.509	103.857	124.343	0	İki Faz Toprak Arızası

Figure 6.26 Event data in Inavitas

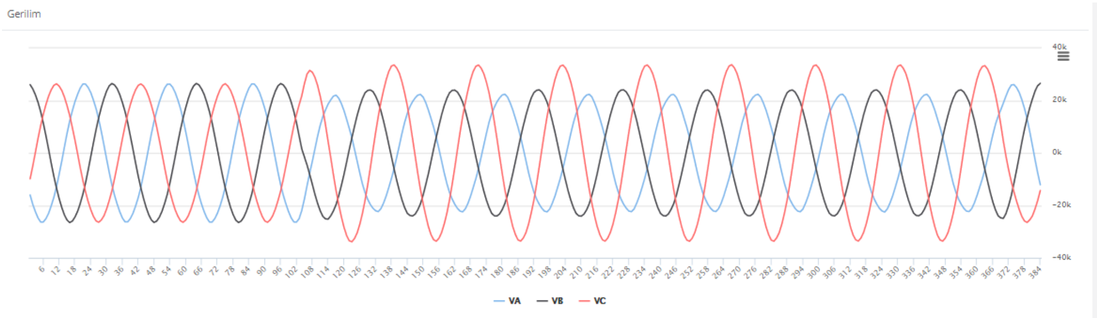


Figure 6.27 Voltage waveform during the event

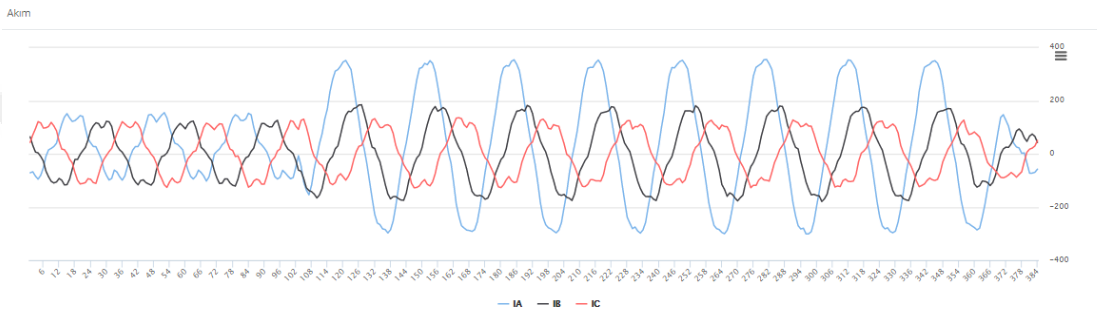


Figure 6.28 Current waveform during the event

6.6.3 Examples of Three Phase Ground Fault in Inavitas

Three phase ground faults are rare fault in distribution systems. About 60 events are examined related two phase ground fault. But Comtrade file for all events is not available in PQ analyzer. So 2 three phase ground fault event which has comtrade file are considered for the confirmation of proposed algorithm.

- **Event 1:** Sag event is recorded at Çamlıca-1 Hes TRA substation on 2017-12-24 at 13.45. Another case study is shown in Figure 6.29. In this example, the direction of the fault is DOWNSTREAM, the type of fault is Three phase ground fault. When the voltage and current waveform is examined, while there is a voltage sag in all phase the current value of this all phase increases about 47 times. Voltage waveform during the event is given in Figure 6.30. In Figure 6.31, current waveform during the event is demonstrated.

100504	CAMLICA-1 HES TRA (ION)	Sag	19.052	2017-12-24 13:45:11.277	0.77	0.673	B	76.44	99.347	67.327	87.351	81.394	107.095	0	Üç Faz Toprak Arızası

Figure 6.29 Event data in Inavitas

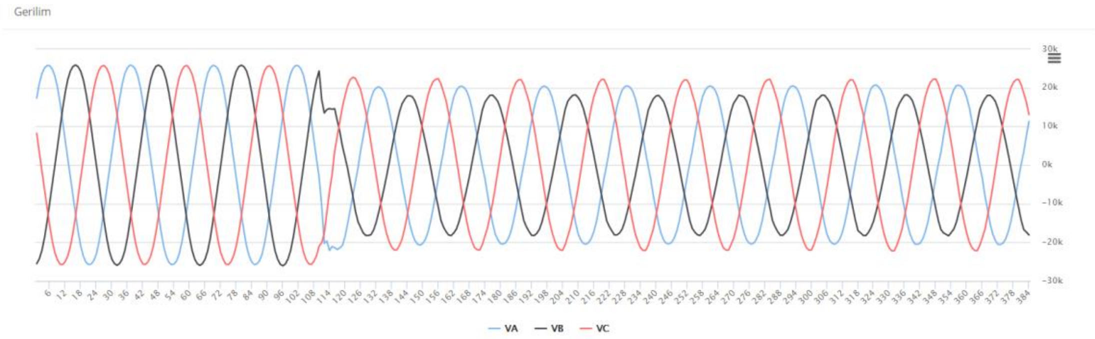


Figure 6.30 Voltage waveform during the event

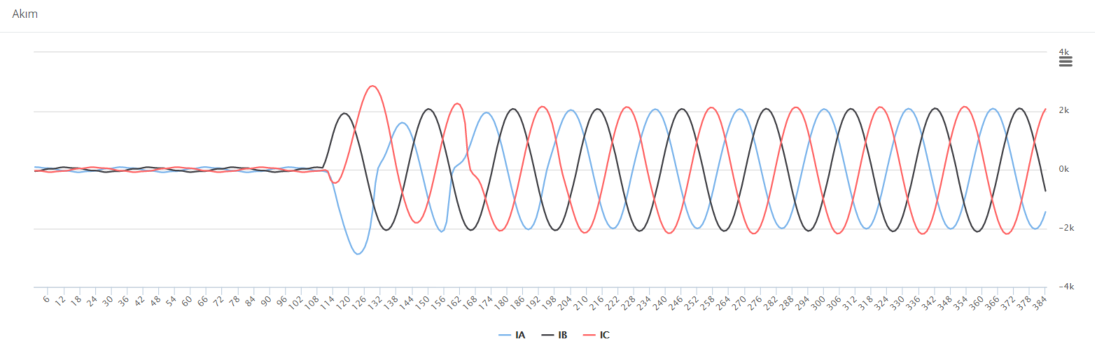


Figure 6.31 Current waveform during the event

- **Event 2:** Sag event is recorded at Çamlıca-1 Hes TRA substation on 2017-12-24 at 13.48. Event data is shown in Figure 6.32. In this example, the direction of the fault is DOWNSTREAM, the type of fault is three phase ground fault. When the voltage and current waveform is examined, while there is a voltage sag in all phase the current value of this all phase increases about 47 times. Voltage waveform during the event is given in Figure 6.33 In Figure 6.34, current waveform during the event is demonstrated.

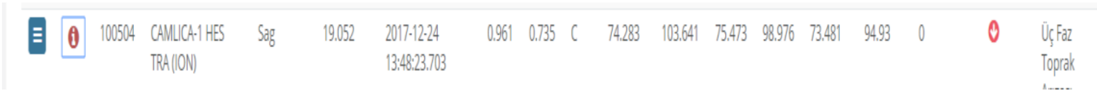


Figure 6.32 Event data in Inavitas

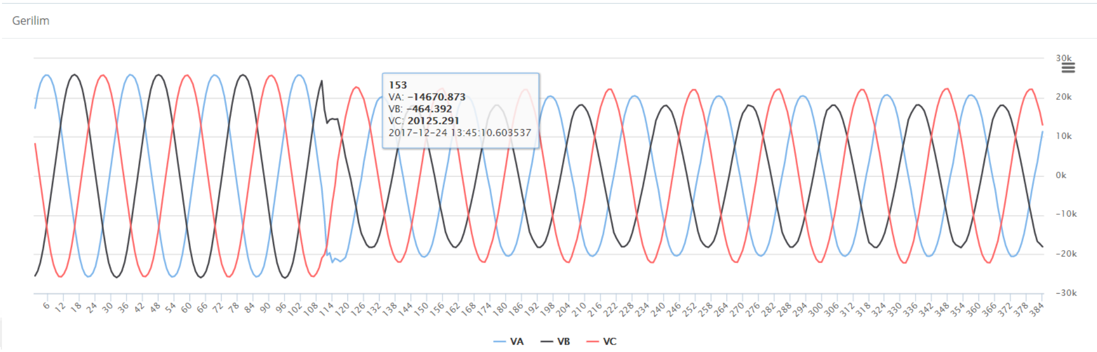


Figure 6.33 Voltage waveform during the event

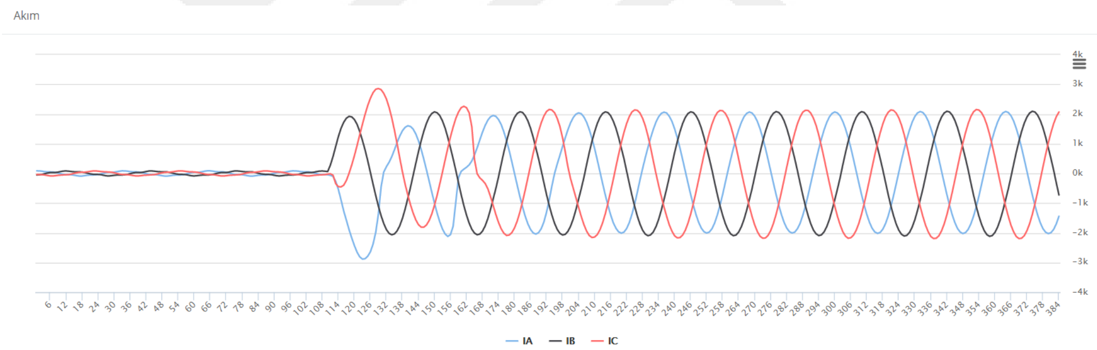
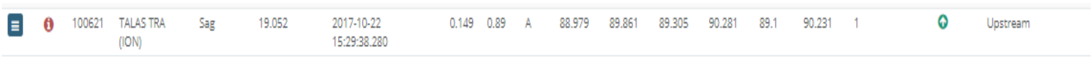


Figure 6.34 Current waveform during the event

6.6.4 Examples of Inavitas Application for UPSTREAM Events

UPSTREAM events are common in distribution systems. About 100 events are examined related two phase ground fault. So 4 three phase ground fault events which have comtrade file are considered for the confirmation of proposed algorithm.

- **Event 1**: Sag event is recorded at Talas TRA substation on 2017-10-22 at 15.29. Event data is shown in Figure 6.35. In this example, the direction of the fault is UPSTREAM. Voltage waveform during the event is given in Figure 6.36. In Figure 6.37, current waveform during the event is demonstrated. When the voltage and current waveform is analyzed, a decrease in voltage is observed in three phases while a decrease is observed in three phase currents. That feature show that direction of event is UPSTREAM.



100621	TALAS TRA (ION)	Sag	19.052	2017-10-22 15:29:38.280	0.149	0.89	A	88.979	89.861	89.305	90.281	89.1	90.231	1	Upstream

Figure 6.35 Event data in Inavitas

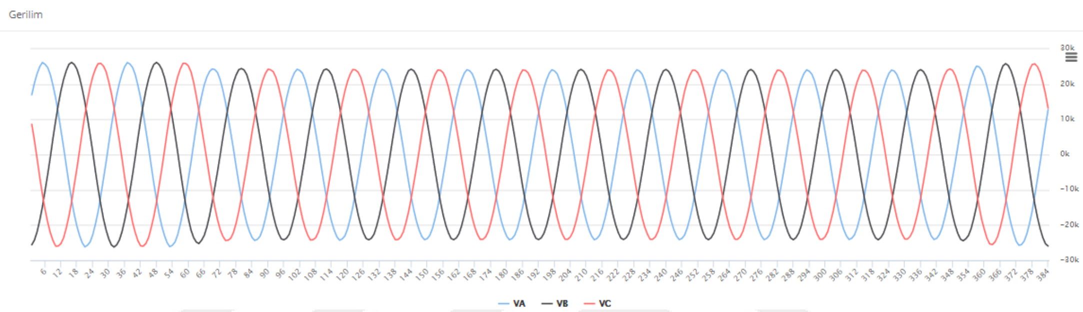


Figure 6.36 Voltage waveform during the event

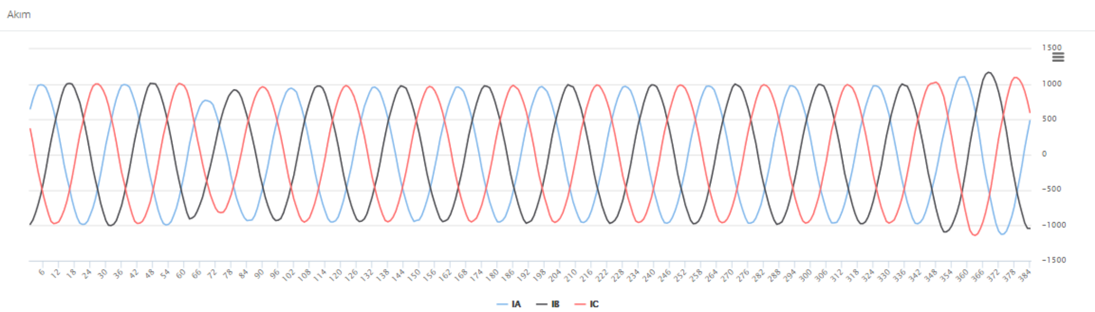


Figure 6.37 Current waveform during the event

Event 2: Sag event is recorded at Talas TRA substation on 2017-10-29 at 02.38. Event data is shown in Figure 6.38. In this example, the direction of the fault is UPSTREAM. Voltage waveform during the event is given in Figure 6.39. In Figure 6.40, current waveform during the event is demonstrated. When the voltage and current waveform is analyzed, a decrease in voltage is observed in single phase while a decrease is observed in that phase currents. That feature show that direction of event is UPSTREAM.

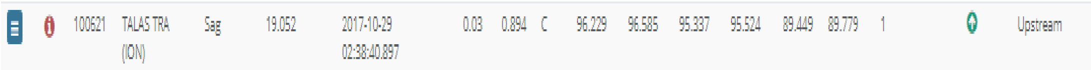


Figure 6.38 Event data in Inavitas

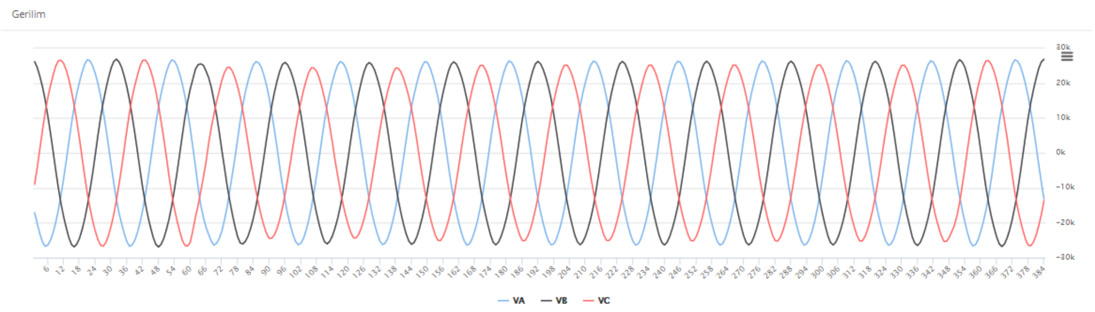


Figure 6.39 Voltage waveform during the event

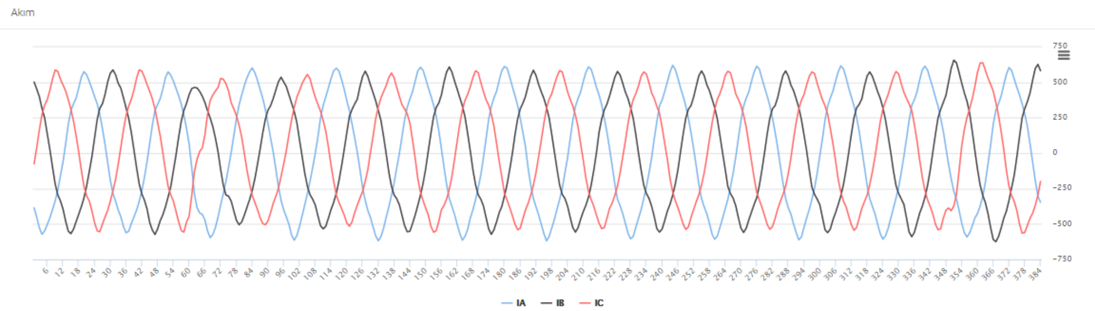


Figure 6.40 Current waveform during the event

Event 3: Sag event is recorded at Talas TRA substation on 2017-10-31 at 06.42. Event data is shown in Figure 6.41. In this example, the direction of the fault is UPSTREAM. Voltage waveform during the event is given in Figure 6.42. In Figure 6.43, current waveform during the event is demonstrated. When the voltage and current waveform is analyzed, a decrease in voltage is observed in single phase while a decrease is observed in that phase currents. That feature show that direction of event is UPSTREAM

100621	TALAS TRA (ION)	Sag	19.052	2017-10-31 06:42:14.400	0.05	0.872	A	87.151	88.513	95.539	96.485	94.813	95.701	1		Upstream

Figure 6.41 Event data in Inavitas

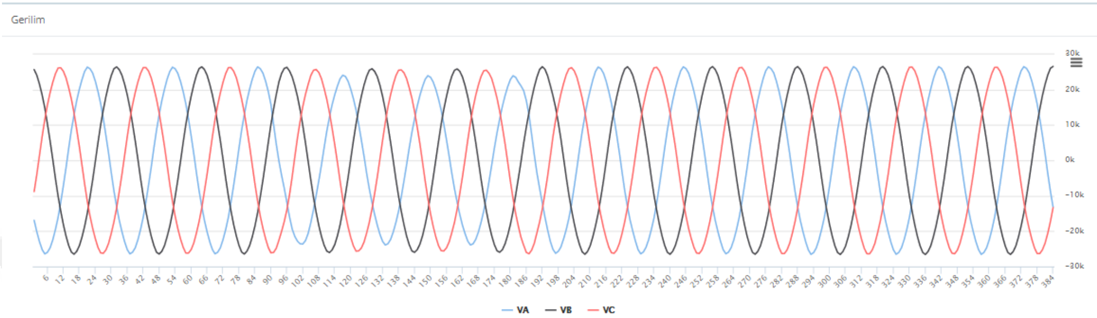


Figure 6.42 Voltage waveform during the event

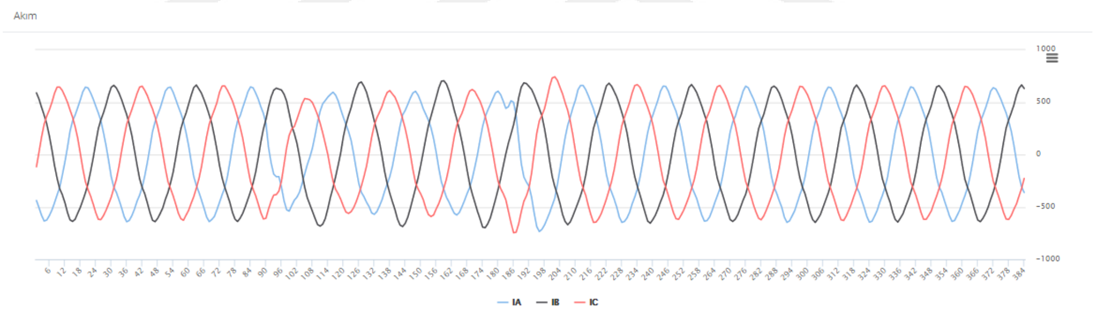


Figure 6.43 Current waveform during the event

Event 4: Sag event is recorded at Taksan TRA substation on 2018-02-09 at 04.21. Event data is shown in Figure 6.44. In this example, the direction of the fault is UPSTREAM. Voltage waveform during the event is given in Figure 6.45. In Figure 6.46, current waveform during the event is demonstrated.

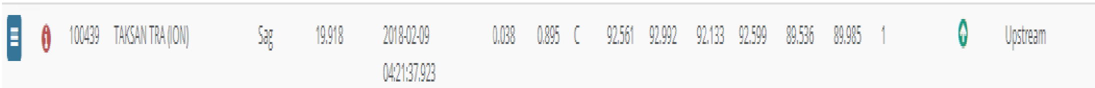


Figure 6.44 Event data in Inavitas

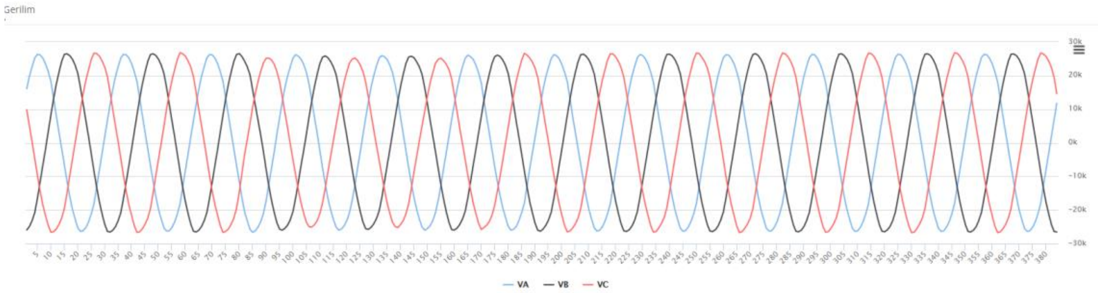


Figure 6.45 Voltage waveform during the event

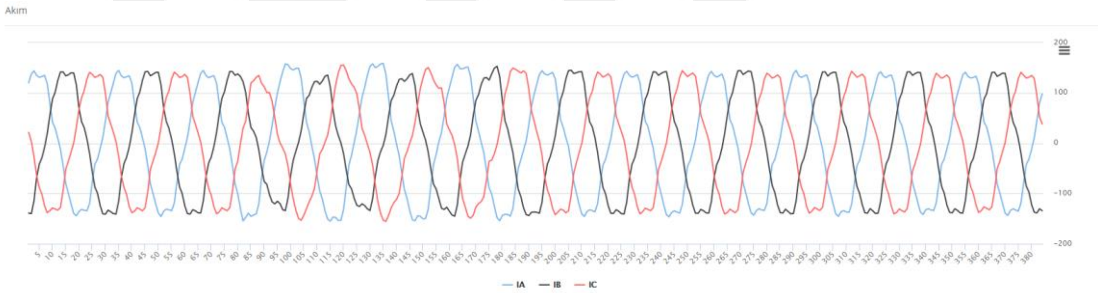


Figure 6.46 Voltage waveform during the event

Table 6.2 Discussion on the case studies

Event Type	Substation	Time	Event Direction	Fault Type	Waveform Check
Sag&Swell	Pınarbaşı TRA	2017-10-12 02:15	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Pınarbaşı TRA	2017-10-14 06:29	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Talas TRB	2017-10-24 08:53	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Talas TRA	2017-10-23 10:38	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Pınarbaşı TRA	2017-10-15 08:11	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Sendıremeke TRA	2017-12-30 09:13	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Sendıremeke TRB	2017-12-30 09:13	Downstream	Single Phase Ground Fault	✓
Sag&Swell	Talas TRB	2017-10-25 08:05	Downstream	Two Phase Ground Fault	✓
Sag	Çamlıca -1 HES TRA	2017-12-24 13:45	Downstream	Three Phase Ground Fault	✓
Sag	Çamlıca -1 HES TRA	2017-12-24 13:48	Downstream	Three Phase Ground Fault	✓
Sag	Taksan TRA	2018-02-09 04:21	Upstream	-------------	✓
Sag	TALAS TRA	2017-10-22 15:29	Upstream	--------------	✓
Sag	TALAS TRA	2017-10-29 02:38	Upstream	--------------	✓
Sag	TALAS TRA	2017-10-31 06:42	Upstream	--------------	✓

In Table 6.2, discussion on the case studies is given. Because single phase ground fault is moss common in distribution systems, it was given many examples related to single phase ground fault. Two phase ground fault is rare event in distribution systems. So it was given less examples about this fault.

CHAPTER 7

CONCLUSION

Power quality is a popular issue nowadays due to increasing sensitive load in modern industry. Voltage sags/swells caused by fault, sudden changes of load, capacitor energizing is the most encountered in electrical distribution system. It may cause mal operation of equipment, tripping of sensitive load and increase in losses. DVR, STATCOM and UPQC is preferred to mitigate power quality problems such as voltage sag and voltage swell. Distribution companies want to provide higher power quality in electric service due to the increasing competition in the electricity market. With this purpose, they improve overall efficiency and provide high reliability in power systems.

Another popular issue is the identification of fault direction occurred in distribution network. In literature a lot of method such as SVM, WT, FL is proposed. These methods use simulation data. Data taken by PQ analyzer is shown by Inavitas that is basically a central monitoring, analysis and management system software for smart grid, smart buildings and renewable energy sources. Distribution network operators (DNO) examine this data for each event recorded by PQ analyzer. So DNO should have sufficient experience, technical knowledge. This also requires long time.

In this thesis, about 10000 event data are examined during the design of algorithm. A novel algorithm that automatically identifying fault type and fault direction is proposed. This algorithm is tested MATLAB and Excel program. It is implemented Inavitas software used by 21 distribution company. A comprehensive literature survey on power quality problems, solution and fault type and event direction is conducted. Power quality regulation in different countries is given in terms of similarity to EN50160 The lacks of existing literature are determined. There is not a method that uses data recorded by PQ analyzer. PQ analyzers named ION 7650 record maximum voltage and current, minimum voltage and current and event duration during voltage sags/swells. Proposed novel algorithm determines event direction and fault type using these data. It also helps network operator to be more understandable of big data. Event direction is either UPSTREAM or DOWNSTREAM. If event direction is DOWNSTREAM, fault current passes over power quality analyzer that records this event. If event direction is UPSTREAM, fault current does not pass over power quality analyzer that records this event. The design procedure of novel algorithm determined event direction and fault type is presented in detail.

Single phase ground fault, two phase ground fault, three phase ground fault and two phase fault are simulated in MATLAB/SIMULINK program to extract feature of voltage and current waveform that occur during fault.

- Feature of single phase ground fault: There is voltage sag in faulty phase and current of this phase increases. There is voltage swell in one or two phase that are not faulty phases.
- Feature of two phase ground fault: There is voltage sag in faulty phases and current of this phases increases. There is voltage swell in other phase that is not faulty
- Feature of two phase ground fault: There is voltage sag in all phases and current of these phases increase.
- Feature of two phase fault. There is voltage sag in faulty phases and current of these phases increase. There is not any event in other phase that is not fault.

Result of algorithm is evaluated with voltage and current waveform in comtrade file recorded by PQ analyzer and shown by Inavitas. When voltage sags/swells occur in distribution system short term flicker value is increasing. Consequently, long term flicker value is increasing. Although there is not a flicker in power systems, due to voltage sags/swells short term flicker value is greater than 1 in weekly report prepared by Inavitas software. Therefore, while the short time flicker is calculated, the data recorded during the fault must be deemed invalid.

As a future work, a data set can be prepared using the results of the algorithm. This data set can be trained with artificial neural networks or support vector machine to detect the event direction and type of fault. Fuzzy logic method can be applied to determine event direction. This algorithm can be applied to transmission systems Results of algorithm can be compared to in transmission and distribution systems. Voltage and current waveform recorded by PQ analyzer during event can be detected by signal processing methods to determine the type and direction of the fault. Event direction and fault type is determined by using signal processing method and machine learning of the Voltage and current waveform recorded by PQ analyzer during event.

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