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A RESEARCH AND SOLUTION PROPOSAL FOR REACTIVE POWER PROBLEMS IN NORTH CYPRUS INDUSTRIES

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To my dear wife

ABSTRACT

This thesis is about the study of compensation techniques application in North Cyprus industries. A compensation system was built for an industrial mine and mill company. The power ratings were recorded before and after the compensation. The data were discussed with modern compensation systems. FACTs technology was simulated for a similar system and results were examined and compared with the practical system.

Keywords: Reactive Power Compensation, Power Factor, Sag, StatCom, Power Quality, Harmonics.

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Introduction

1.1 Overview

Identifying problems in an electrical network before any extensive damage accurse is advisable for any power system. Not only does monitoring of power quality necessary for the accurate operation of sensitive equipment, it also serves to identify unnecessary energy losses in a power system which could earn more profits, especially for mines.

AC electrical machines and other inductive loads used in industry draw reactive power from the line. The reactive power causes overloading effects on the line, circuit breakers, transformers, relays and insulations. Reactive power cannot be transformed into mechanical power. In addition, the reactive power also increases the dimension of cables used in the transmission line. Therefore, the structure of all equipments used in the line has to be strong enough to carry the huge weight of the cables. Therefore, the cost of the system is increased, and the efficiency of the system is reduced. To reduce the cost and to improve the efficiency, the reactive power drawn from the line has to be decreased by supplying it from some other source.

The common power quality problems prevalent in Northern Cyprus are Reactive Power and Harmonics. Reactive Power Compensation is analyzed in this thesis.

1.2 Scope of Thesis

This thesis seeks to investigate reactive power problems in the Bozkaya power system located in the Güngörköy of North Cyprus. For the problems identified, standards are applied to see their compatibility and recommendations are suggested and compensation system is built to improve the power quality. Experimentally measured data collected from the mine will be analyzed and a simulation with FACTs devices will be introduced.

Measured and simulated results will be discussed and correct mitigation techniques will be recommended to increase the power quality of the system.

1.3 Overview of The Thesis

Chapter 2 gives a summary of "*Power Quality*". It examines the use of the term and what voltage phenomena are categorized under it. The two main problems, Reactive Power and Harmonics, are presented here with their definition, causes, effects and common mitigation techniques for each one respectively.

Chapter 3 covers the power quality problem of Bozkaya industrial mine are and describes the methods used to overcome those problems in this chapter, measured data before and after compensation is presented and discussed

Chapter 4 presents the modern power quality improvement using FACTs techniques (StatCom). Simulation of this technique on a power system is done to insure the similarities and differences between the classical system FACTs.

Chapter 5 discusses and gives conclusion for the complete thesis. The results for the work done are discussed and the recommendations are done for the future power system management policies. Some suggestions are also done for the future work.

CHAPTER TWO

Power Quality

2.1 Overview

The concern for the quality of electric power is increasing very rapidly due to advances in power system components. The last decade has seen a significant change in components of power system from being largely linear to partially nonlinear. This change has meant that sensitivity of equipment to disturbances has increased and the reliability power is much concern. Therefore to increase or maintain the reliability of a system constant monitoring of the power quality is required. An enormous amount of research papers are written concerning the monitoring and analysis of power quality in power systems.

Any power problem manifested in voltage, current or frequency deviation that results in failure or disoperation of customer can be defined as a power quality problem [1]. The term power quality is a more distinguished name for the concept of having high performance from a power system. It is an umbrella concept for a multitude of individual types of power system disturbances. Although the issues of disturbance are not necessarily new, the recent change has been that engineers are now attempting to solve these problems to increase efficiency or using the definition itself to increase the power quality of electric systems.

The interest in power quality has come about due to several reasons [1]:

1. There is a growing need for standardization and performance criteria.
2. Equipment has become more sensitive to disturbances.
3. New technological equipment such as Variable Speed Drives (VSD) causing the disturbances.
4. Power Quality monitoring equipments have advanced.
5. Increased competition and the fact that customers nowadays expect good quality power.

In most cases the quality of power refers to the quality of the voltage. Any significant deviation in the waveform magnitude, frequency or purity of a sinusoidal voltage is a potential power quality problem. Power quality problems can be caused by Electrical system design and construction errors, improves grounding techniques, harmonies or simply just load interactions. Some symptoms caused by power quality problems include:

1. Function of equipment.
2. Frequent System reboots becoming necessary.
3. High failure rate of electric system.
4. Over heading of transformers.
5. Motors and capacitor bank failures.
6. Inaccuracy of testing and measuring equipment.
7. Lights dimming or blinking.

The following tables give a good summary of power quality problems. The IEC classifies electromagnetic phenomena in to the groups depending on if they are conducted or reseated being of either low or high frequency. Table 2.1 provides information regarding a typical spectral content, duration, and magnitude where appropriate for each category of electromagnetic phenomena [1].

Table 2.1 Categories and Characteristics of Power System Electromagnetic Phenomena

Categories	Typical spectral content	Typical duration	Typical Voltage magnitude
1.0 Transient			
1.1 Impulsive			
1.1.1 Nanosecond	5 nsec rise	< 50 ns	
1.1.2 Microsecond	1 µsec rise	50 nsec – 1 ms	
1.1.3 Millisecond	0.1 msec rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3 – 50 msec	0 – 4 pu
1.2.2 Medium frequency	5 – 500 kHz	20 µsec	0 – 8 pu
1.2.3 High frequency	0.5 – 5 MHz	5 µsec	0 – 4 pu
2.0 Short-duration variation			
2.1 Instantaneous			
2.1.1 Interruption		0.5 – 30 cycles	< 0.1 pu
2.1.2 Sag (dip)		0.5 – 30 cycles	0.1– 0.9 pu
2.1.3 Swell		0.5 – 30 cycles	1.1– 1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles – 3 s	< 0.1 pu
2.2.2 Sag (dip)		30 cycles – 3 s	0.1– 0.9 pu
2.2.3 Swell		30 cycles – 3 s	1.1– 1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s - 1 min	< 0.1 pu
2.3.2 Sag (dip)		3 s – 1 min	0.1– 0.9 pu
2.3.3 Swell		3 s – 1 min	1.1 – 1.2 pu
3.0 Long -duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Under voltages		> 1 min	0.8 – 0.9 pu
3.3 Over voltage		> 1 min	1.1 – 1.2 pu
4.0 Voltage unbalance		Steady state	0.5 – 2 %
5.0 Wave distortion			
5.1 Dc offset		Steady state	0 – 0.1 %
5.2 Harmonics	0 – 100th harmonic	Steady state	0 – 20 %
5.3 Inter-harmonic	0 – 6 kHz	Steady state	0 – 2 %
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0-1 %
6.0 Voltage fluctuations	< 25 Hz	Intermittent	0.1 – 7 % 0.2-2Pst
7.0 Power frequency variation		< 10 sec	

2.2 Active, Reactive and Apparent Power

Reactive loads such as inductors and capacitors dissipate zero power, that they drop voltage and draw current gives the deceptive impression that they actually to dissipate power. This ‘’ phantom power’’ is called reactive power, and it is measured is a unit called Volt Amps Reactive (VAr), rather than watts. The mathematical symbol for reactive power is the capital letter Q. The actual amount of power being used or dissipated in a circuit is called true power and it is measured in watts and symbolized by the capital letter P. The combination of reactive power and true power is called apparent power and it is the product of a circuit’s voltage and currents, without reference to phase angle. Apparent power is measured in the unit of Volt-Amp (VA) and is symbolized by the capital letter S.

As a rule true power is a function of circuit’s dissipative elements, usually resistance (R). Reactive power is a function of a circuit’s reactance (X). Apparent power is a function of a circuit’s total impedance (Z).

These tree types of power Active, Reactive and Apparent power relate to one another in trigonometric form.

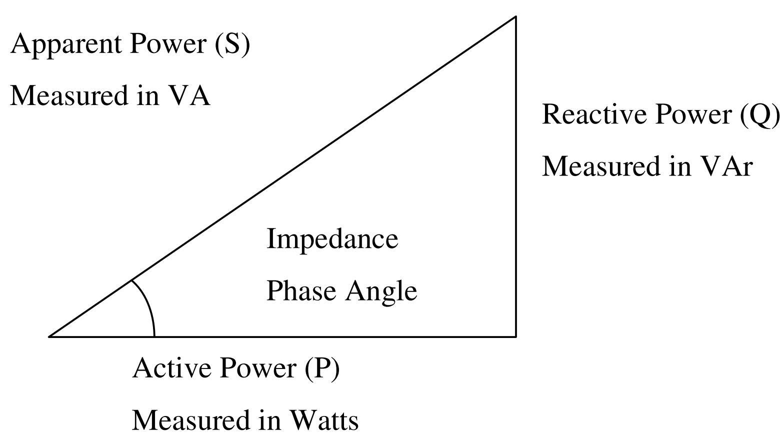

Figure 2.1 The Power Triangle

2.3 Power Factor

The angle of power triangle graphically indicates the ratio between the amount of dissipated or consumed power and the amount of absorbed / returned power. It also happens to be the same angle as that of the network impendence in polar form. When expressed as a fraction, this ratio between true power and apparent power is called the power factor for that network. Because true power and apparent power form the adjacent and hypotenuse sides of right triangle, respectively, the power factor ratio is also equal to the cosine of that phase angle.

For the purely resistive circuits, the power factor is zero, because reactive power equals zero. In this case the power triangle would look like a horizontal line, because the opposite (Reactive Power) side would have zero length.

For the purely inductive circuit the power factor is zero because true power equals zero. In this case the power triangle would look like a vertical line, because the adjacent (Active Power) side would have zero length.

The same could be said for a purely capacitive circuit if there are no dissipative (resistive) components in this circuit, then the true power must be equal to zero, making any power in the circuit purely reactive. The power triangle for a purely capacitive circuit would again be a vertical line.

Power factor can be an important aspect to consider in an AC network, because any power factor less than 1 means that the circuit's wiring has to carry more current than what would be necessary with zero reactance in the circuit to deliver the same amount of Active power to deliver a full power to the load with the same current. The poor power factor makes for an inefficient power delivery system.

2.4 Solution

If a capacitor and an inductor are placed in parallel, then the currents flowing through the inductor and the capacitor tend to cancel out rather than adding. Conventionally, capacitors are considered to generate reactive power and inductors to consume it. This is the fundamental mechanism for controlling the power factor in electric power transmission, capacitors or inductors are inserted in a circuit to partially cancel reactive power of the load.

2.5 Voltage Sag

2.5.1 Definition and Characterization

It is important to understand the expected voltage sag performance of the supply system so that facilities can be designed and equipment specifications develop to assure the optimum operation of production facilities. The IEEE Standard 1159-1995 gives an excellent graphical demarcation for the various power problems [1].

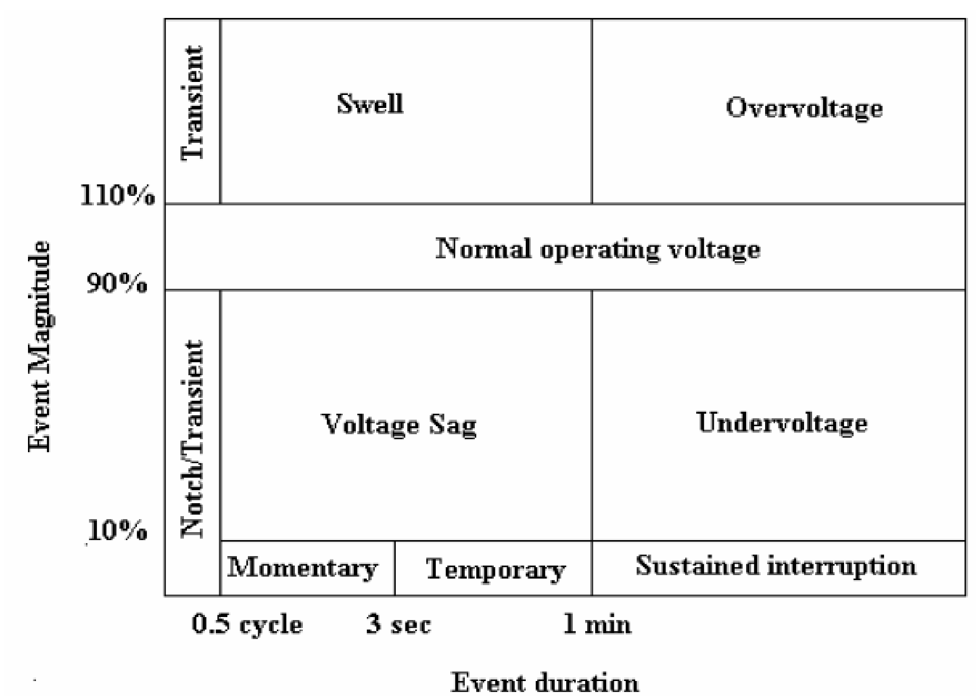

Figure 2.1 IEEE std.1159-1995

Voltage sag (dip) is a power quality problem that is prevalent in any power system. It is said to be one of the main problems of power quality. It is a decrease of the RMS voltage or current to between 0.9 and 0.1 per unit (pu) at the power frequency for a duration of ½ a cycle to 1 minute [2]. An example of the voltage sag Phenomena on a single phase is shown in figure 2.2.

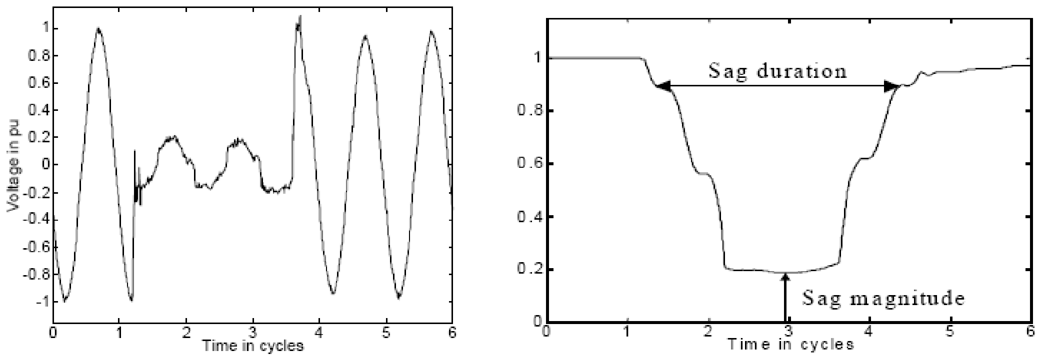

Figure 2.2 The voltage sag phenomena in one phase

The fundamental components which characterize sag are magnitude duration and phase jumps. Power quality measuring instruments use sampling techniques to capture disturbance events. Typical resolutions when sampling are 128 and 256 samples per cycle. When the sags events are sampled, the RMS voltage is given by [3]:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} Vi^2} \qquad (2.1)$$

Where N: the number of samples per cycle and,

Vi: is the i^{th} sampled voltage in the time domain.

Although there is no definite algorithm governing the duration of voltage sag the duration of the voltage sag is predominant determined by the fault clearing time. Hence the circuit breakers, relays and other over-current protection devices are essential in any power system.

Phase jumps occur due to the difference of X/R ratio the source and that of the faulted feeder [4]. This characteristic of voltage sag with phase jumps is shown in the figure 2.3 [5].

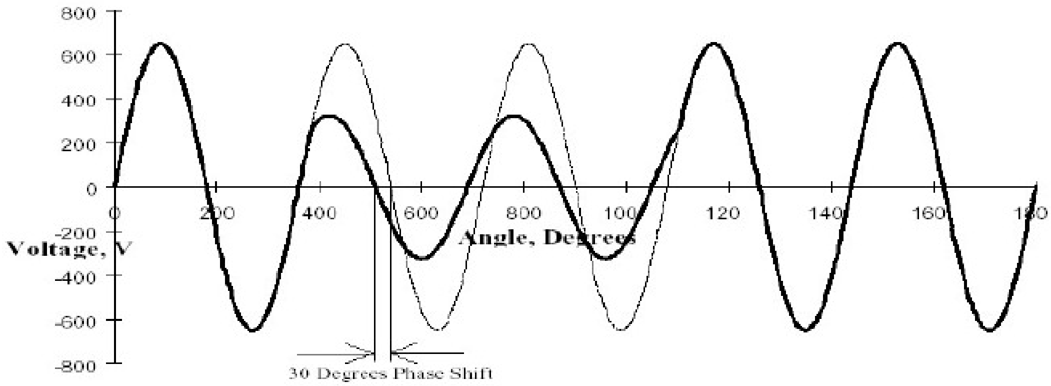

Figure 2.3 Phase shifts or jumps

2.5.2 Causes of Voltage Sags

Voltage sags are generally caused by faults (short circuit) on the system [1]. Overloads can be another cause although it can be termed as being an under voltage phenomenon or a voltage step the other causes of sags of sags is that caused when large motors start [6]. Motors have the undesirable effect of drawing several times their full load current while starting. This high reactive current (5-7 times of rated current) from the supply during the starting process lost for about 30 cycles. This sudden rise of current flow through the network impedance results in the voltage sag at the terminal bus. The sag magnitude mainly depends on the starting motors power rating the network impedance and the system source strength [7].

Figure 2.4 shows voltage sags and interruptions originating from various system events and characterized with their sag depth and duration.

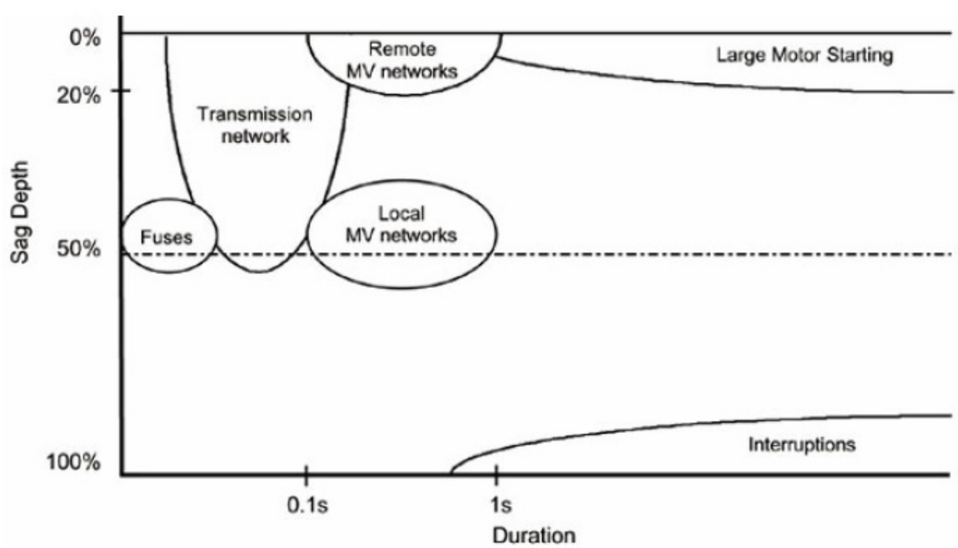

Figure 2.4 Sag depth Vs duration plot

2.5.2.1 System Faults

For theoretical calculations the magnitude of the voltage say for a radial system is given by [6]:

$$V_{sag} = \frac{Zf}{Zs + Zf} E \tag{2.2}$$

$$V_{sag} = \frac{ZL}{Zs + ZL} E \tag{2.3}$$

Where L is the distance of the fault form the point of common coupling (PCC). It is concluded that voltage going magnitude is a function of the distance L.

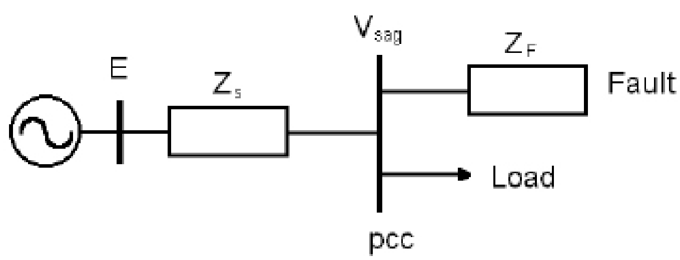

Figure 2.5 Voltage divider model for voltage sag caused by a system fault

Studies have shown that the most common type of system faults is the single-line-to-ground faults(SLGF)/ The probability of each of fault resulting from the study is shown in figure 2.6 [8].

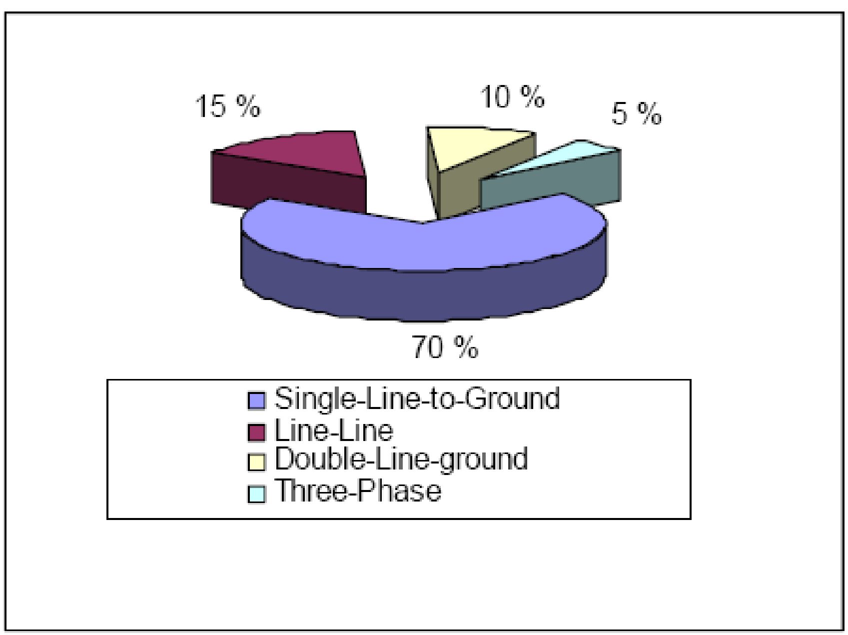

Figure 2.6 Probabilities of voltage sag due to system faults

2.5.2.2 Starting A Large Motors

Voltage sags due to the starting of large motors can again be theoretically calculated similar to the one caused by system faults [6].

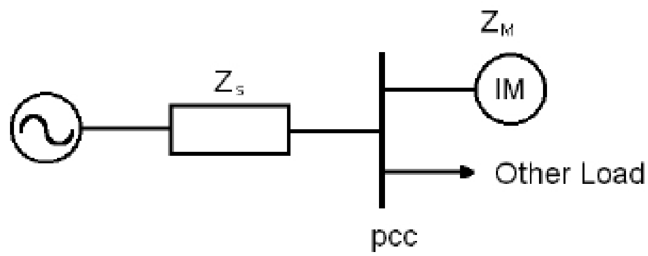

Figure 2.7 Equivalent circuit for induction motor starting

The voltage at the PCC is given by

$$V_{sag} = \frac{ZM}{Zs + ZM} E \qquad (2.4)$$

Where ZM is the impedance of the motor under study and Zs is the source impedance. It is realized that these calculations are only for approximations. However to have an accurate result of voltage sag phenomena, a power system analysis package should be used [1].

2.5.3 Effects

The sag magnitude simply indicates the severity of the sag and duration is the time. The sag is maintained for sensitive equipment such as Adjustable Speed Drives (ASDs). Control equipment, and computer are very sensitive to sags. Sags caused by faults are ones that cause the majority of equipment trips [6].

The effect of phase jumps in a voltage sag phenomenon is the most recent characteristic of it to be a problem, especially for ASDs. Failures of the adjustable speed drivers were found to be caused, not due magnitude level of the supply, but rather the waveform anomalies phase shifts or jumps [5].

2.5.4 Solutions

Voltage sag problems are solved at different levels. These levels are utility level, the customer level and the level of equipment manufactures.

Fast clearing times are designed by utilities design systems to reduce the effects of voltage sags [9]. Although voltage sags due to faults can never be eliminated, mitigating techniques are available and should be considered. The use of parallel feeders and re-closer technique do ensure the reliability of a system.

Equipment immunity to voltage sag can be a big bonus, a goal and a good selling point if manufactures can improve equipment voltage tolerance thresholds. The CBEMA (now ITI) cure is a frequency used to tolerance curve for sensitive equipment. It was developed to describe the tolerance of mainframe computer equipment to the magnet and duration of voltage variations in a power system [1]. It gives tolerance regions which are very useful when analyzing the characteristics of voltage sags.

Available mitigation at the user level are the use of Ferro resonant transformers, Magnetic Synthesizers, Active Series Compensators, Standby and Hybrid Uninterruptible Power supplies (UPS), Superconducting Magnetic Energy Storage (SMES) devices, Motor generator sets, Flywheel energy storage systems are finally static transfer and Fast Transfer Switches such as STATCOM [1].

STATCOM is one of the recommended solutions for the problems identified at Bozkaya mine and will be discussed when results are presented.

2.6 Harmonics

2.6.1 Definition

Harmonics are a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency [1]. These harmonics interact with the fundamental frequency waveform and each other to produce a distorted waveform which can cause significant damage to power system. The magnitude of the harmonics and their phase shifts determine the shape of the resulting waveform.

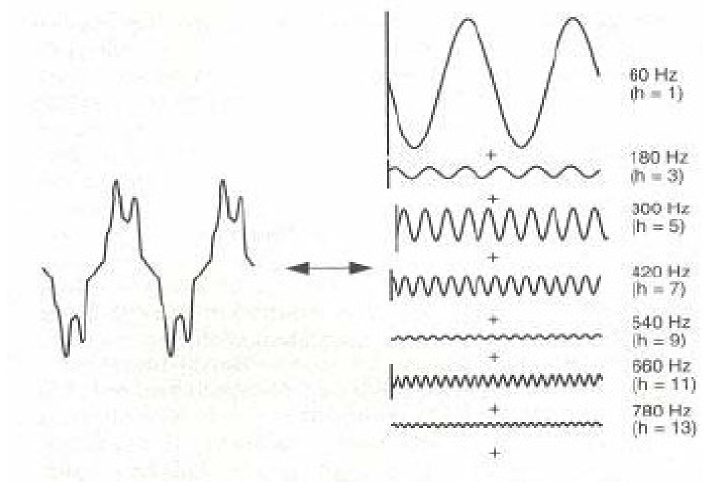

Figure 2.8 Fourier series representation of a distorted waveform

Any voltage and current waveform may be reproduced from the fundamental frequency component and the sum of harmonic components using the Fourier series representation as shown in figure 2.10. The equation as follows:

$$V(t) = a_0 + \sum_{h=1}^{\infty} V_h Sin(h2\pi \mathrm{ft} + \theta_\mathrm{h}) \qquad (2.5)$$

Where

a_0 is the DC component V_h is the peak voltage

f is the fundamental frequency

θ_h is the Phase angle

The Fourier series is also used to deconstruct a waveform into the fundamental and harmonic components. This is the principle behind performing a harmonic analysis on a power system.

In order to determine the related distortion due to harmonics on a power system, the term Total Harmonic Distortion (THD) is used. It also measures the amount of distortion harmonics cause on the system voltage. Expressed as a percentage of the fundamental, both voltage and current waveform distortion may be represented by (THVD). Total Harmonic Current Distribution (THCD) used at times to distinguish between voltage and current waveform.

$$THVD = \frac{\sqrt{\sum_{h=2}^{\infty} Vh^2}}{V_1} x100\% \qquad (2.6)$$

Where

Vh is the RMS value of the harmonic component

V_1 is the RMS value of the fundamental component

2.6.2 Causes

Non ideal sinusoidal waveforms were produced by synchronous generators in the past. However, modern generators are far more advanced. Generators nowadays have excellent control systems which allow them to produce almost perfect sinusoidal waveforms. Nevertheless, transformer saturation is still a cause of harmonics in non-linear loads. This is due their tendency to draw a current that is far from being sinusoidal.

Common causes of harmonics are:

- Fluorescent Lighting.
- Arc furnace.
- Power Supplies and Converter.
- Adjustable Speed Drives.
- Cycle converters.

2.6.3 Effects

Capacitor failure computer function, conductor failure, flickering fluoresce lightning, overheating equipment, elating of transformer wire and power interference in communications are only some of the undesirable effects harmonics may in an electricity network.

Harmonics also increase the possibility of introducing resonance into the system. Resonances occur when the capacitance and inductance of a system are equal of a certain frequency. Inductance and capacitance associated to power cables of a system are equal at a certain frequency. Many systems also have power factor correction capacitors which can fail due to the result harmonic through them.

Another effect of harmonics in power system is overheated neutral cables of transformers. This is generally caused by high third harmonic currents. Equipment function and computer system reset may also result from increased harmonic voltages.

2.6.4 Solutions

The simplest method to reduce the effect of harmonics in a system is in the physical configuration of an electrical system. Placing capacitors and chosen impedance configurations strategically to avoid resonance and the flow of third harmonics are also common practices. For example: a delta connection of a transformer having no neutral or ground wire does not allow the flow of third harmonics.

Harmonic filters both active and passives also prevent harmonic current to flow in a network. Another technique to cope with harmonic is to de-rate equipment especially transformers making sure that it does not operate at 100% load.

2.7 Summary

Power quality investigations especially voltage studies are carried out on power system often. There were many relevant papers written relating to the scope of this project. Although there are specks of the studies or research that will overlap, almost invariably each system has to be studied independently to measure and monitor the extend of their problems. The problems analyzed in this chapter are a literature review of the power system quality problems. These problems and the proposed solutions were considered while analyzing the Bozkaya power system problems discussed in next chapter and developing the solutions of these problems.

CHAPTER THREE

The Bozkaya Mine Power System

3.1 Overview

In this chapter, reactive power problems in the Bozkaya power system located in the Güngörköy are investigated as a pilot case of reactive power problems in North Cyprus. Also proposed solutions, methodology and power quality calculations are discussed.

3.2 Bozkaya Mine Single Line Diagram

The Sag mill of the Bozakaya Ltd. is a huge interconnected network of conveyor belts, pumps and other machines that follow a starting sequence as seen figure 3.4 and figure 3.5. It is just sensible that the mill starts before the conveyor belt starts loading the mill. Therefore there is loading of the system before the motors start which have a big effect on the sag.

Figure 3.1 Bozkaya single line diagram

Figure 3.2 Pumps motor in Bozkaya Ltd

As mentioned previously in The Bozkaya Ltd two Sag Mills systems energized by Soft Starters. Both motors are fixed speed motors as seen in figure 3.2 and 3.3 that need to be jogged before starting to position the motors. Therefore starting the sag mills will cause only one voltage sag event while starting the ball mills can cause several voltage sag events due to jogging.

Figure 3.3 Belts motor in Bozkaya Ltd

3.3 Power Factor Correction with Mechanical Switches Capacitors

Capacitor is a practical and economical power factor improvement device. As stated previously, all inductive loads produce inductive reactive power. Capacitors on the other hand produce capacitive reactive power, which is the exact complement of inductive reactive power. In this instance, the current peak occurs before the voltage peak, leading by a phase angle of 90 degrees. Careful selection of capacitance is required; it is possible to cancel out totally the inductive reactive power when required capacitance is placed in the circuit.

3.3.1 Power Factor Component System

3.3.1.1 Capacitor

Traditionally power factor capacitors are made up of single phase metalized polypropylene windings, placed into a plastic cylinder impregnated with epoxy resin. These cylinders (windings) are coupled in a delta configuration and placed into an enclosed sheet metal box which offers desired protection in the event of explosion due to undue stresses placed on the capacitor through potential exposure to over voltage, increased frequency, harmonic effects and over temperature.

Capacitor manufacture in no way takes heating into consideration. Capacitors have power losses of ±0.05% which stands to reason that a 60 kVAr capacitor for instance, would have to dissipate ±30 watts of generated heat inside a enclosed sheet metal enclosure. Temperatures measured inside these enclosures could reach 15- 20°C higher than the ambient temperature that they are exposed to, drastically effecting the overall life of the capacitor.

The use of 440V capacitors is highly recommended, which generally accommodate over voltages in systems due to the presence of harmonics a permanent 20% over voltage factor without any negative effects on the capacitor itself.

In order to increase power factor of Bozkaya mine power system, Totally 320 KVAR sixteen different traditional capacitors are parallel connected in parallel to the system as shown in figure 3.4.

Figure 3.4 Traditionally power factor capacitors in Bozkaya mine system

3.3.1.2 Contactors

The contactor during the closing transition is influenced by electrical currents having high frequencies and high amplitudes. The frequencies of these currents range between 1 and 10 kHz; the amplitudes must have values lower than the maximum permissible current peak of the contactor to be used. If this condition cannot be verified, it is necessary to use limiting inductances or special capacitor switching contactors. AEG contactors utilized in our systems are specially designed for capacitor switching as seen in figure 3.5 and are equipped with quick contacts which introduce resistors to limit the connecting current of capacitors for a very brief interval, (2-3 ms) during the contactor closing. These resistors are then disconnected from the circuit once the contactor closing operation is completed and the current capacity is then conveyed through the main contacts of the contactor, dramatically reducing wear of contactors, capacitors and fuses, ensuring longer life and reliability of the system.

Figure 3.5 Contactors and fuses

3.3.1.3 Fuse Protection

Specific fuse protection is essential for each capacitor bank of a system. Exposure to over voltage, increased frequency and the effects of harmonics, permit capacitors to be continuously overloaded at up to 1.35 times their nominal rating. This overload as well as high initial switching currents of the capacitors must be considered when calculating fuse requirements for capacitor bank protection. Which can be seen in figure 3.5 and the complete wiring diagram of the system is given in figure 3.6.

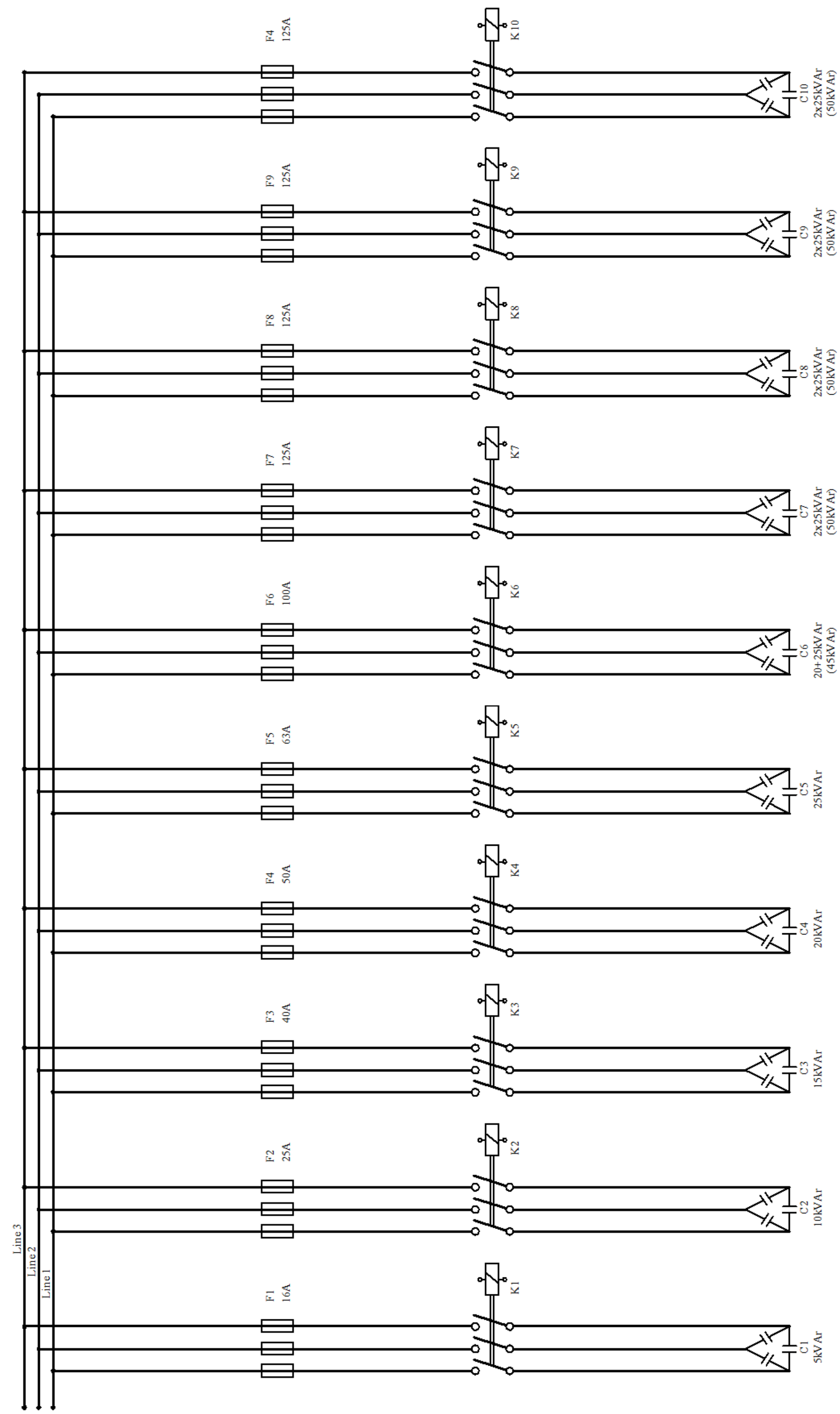

Figure 3.6 Compensation diagram

3.3.1.4 Reactive Control Relay

Reactive power control relays more than meet the above requirements. They perform the control and adjustment functions in a totally digital manner and incorporating latest microprocessor technology, facilitating accurate, reliable power factor control. An appropriate algorithm ensures accurate operation even in systems characterized by high harmonic content.

The capability of performing complex calculations regarding reactive power, permits the rapid switching of capacitor banks in a timeouts, explicit manner, resulting in a drastic reduction in the number of operations and their homogeneous use. In our practical application the reactive power control relay seen in figure 3.7 is used.

Figure 3.7 Reactive power control relay

3.4 Measurement of Power Quality

The Data given in this thesis was measured with “C.A. 8335 Qualistar Plus”, three phase electrical network analyzer using the *DataWiever®* Software given in figure 3.8. They were measured from 05th of December 2008. Although all waveforms were recorded, there were complications with current waveforms.

The C.A.8335 Qualistar Plus measures current waveforms by sampling voltage induced by current transformers (CTs) that have a ratio of 6500/5. the big drives for the motor have circuit breaker (CB) panels from which drive protection is implemented each panel has two CTs of its own; one for the drive over current protection and the other for the display for panel monitoring facilities. These CTs themselves have ratio of 200/5 each. The C.A. 8335 was connected after one of these CTs. Again in terms of monitoring purposes on the CB panels, Voltage Transformers (VTs) use the C.A. 8335.

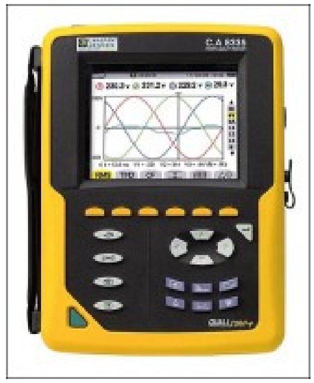

Figure 3.8 The C.A.8335 Qualistar

3.5 Collected Data before Compensation

The following severe Voltage sags were recorded due to motors starting. Figure 3.9, Figure 3.10 and Figure 3.11 show the results in voltage magnitude, during induction motor starting before compensation. The voltage change can be +/- 9 Volt.

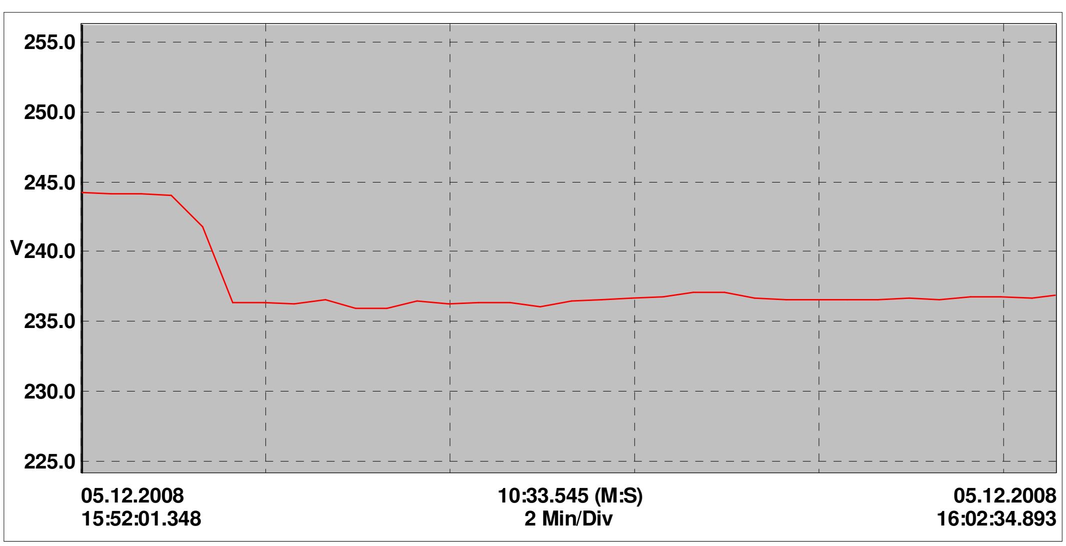

Figure 3.9 V_{rms} of line 1 before compensation

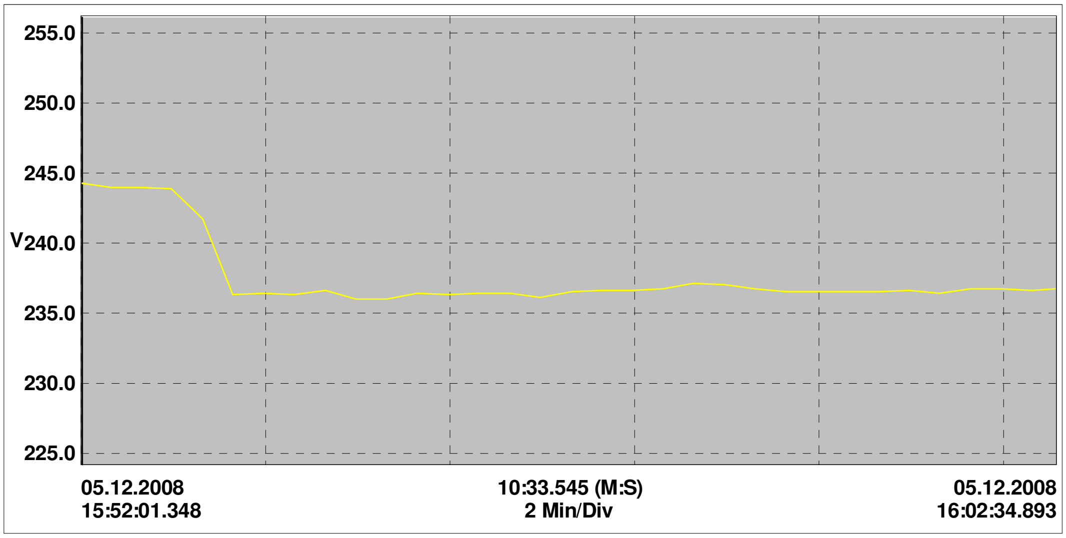

Figure 3.10 V_{rms} of line 2 before compensation

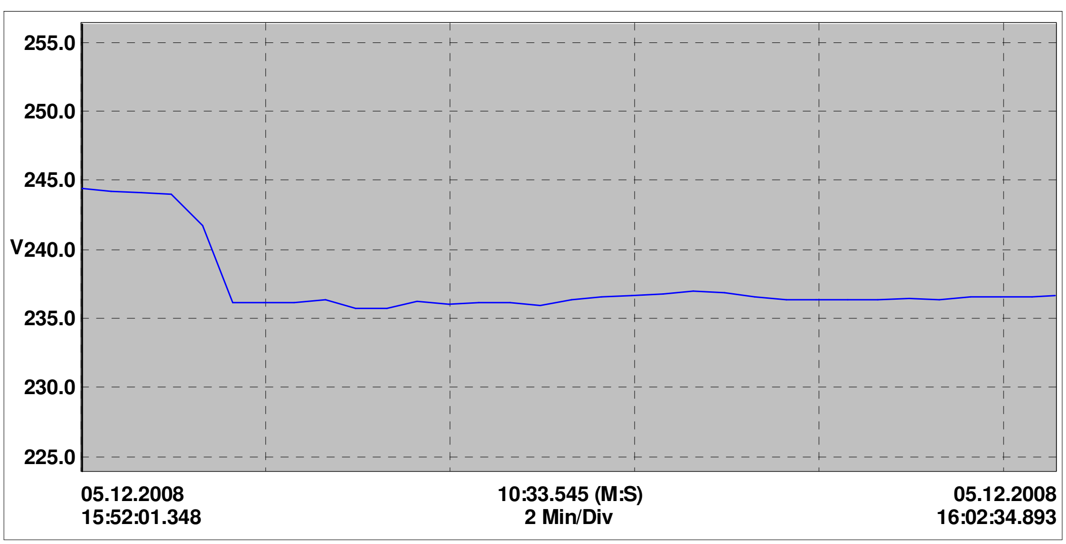

Figure 3.11 V_{rms} of line3 before compensation

The following Current wave forms were recorded due to motors starting. Figure 3.12, Figure 3.13 and Figure 3.14 show the results in current magnitude, during induction motor starting before compensation.

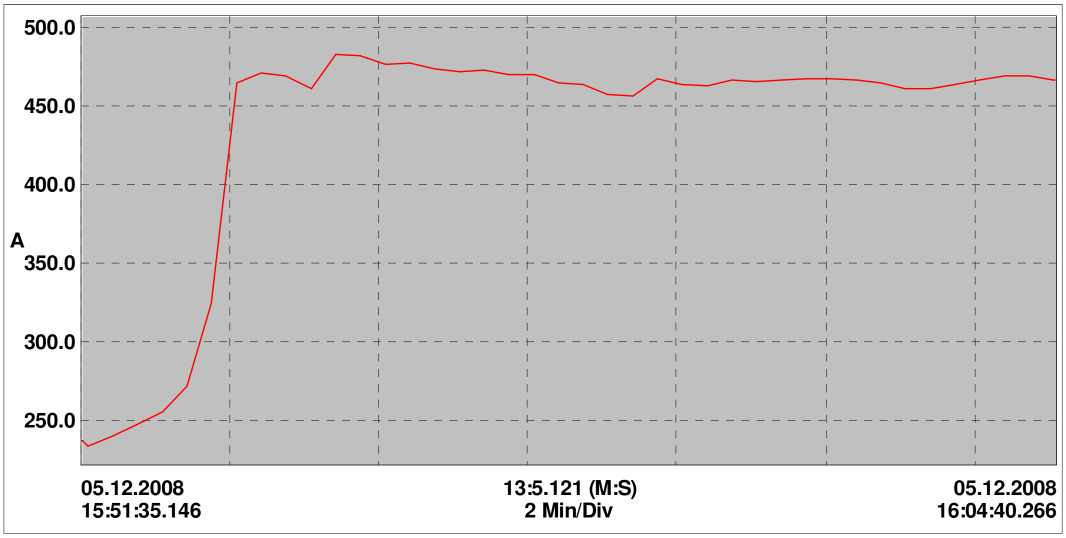

Figure 3.12 Motor starting before compensation and results current in line 1

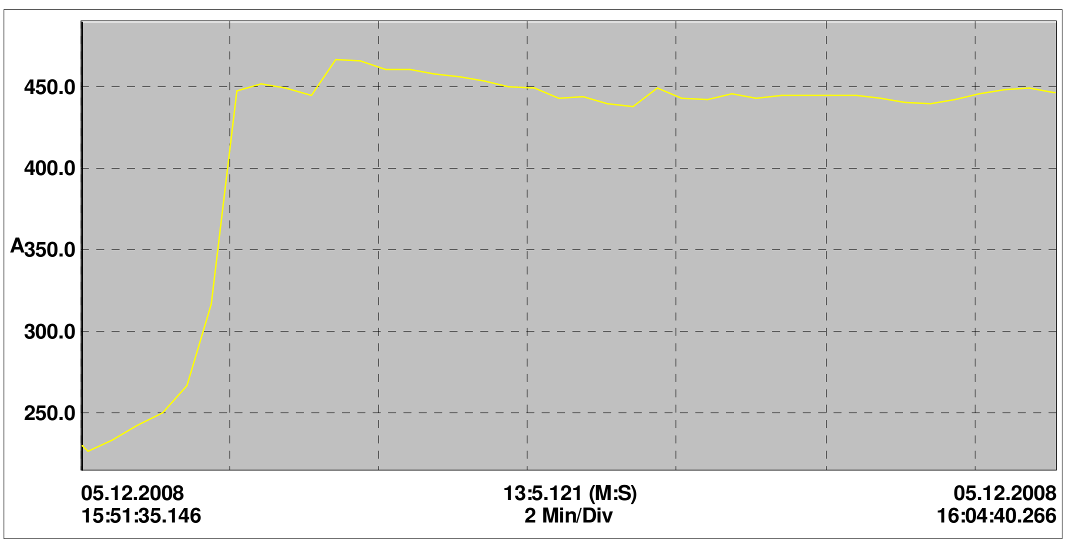

Figure 3.13 Motor starting before compensation and results current in line 2

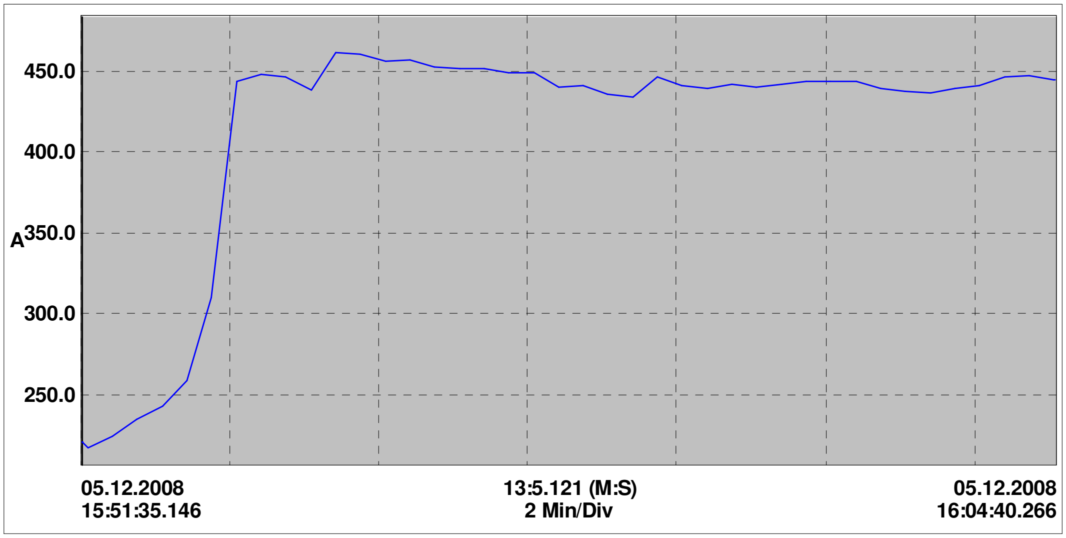

Figure 3.14 Motor starting before compensation and results current in line 2

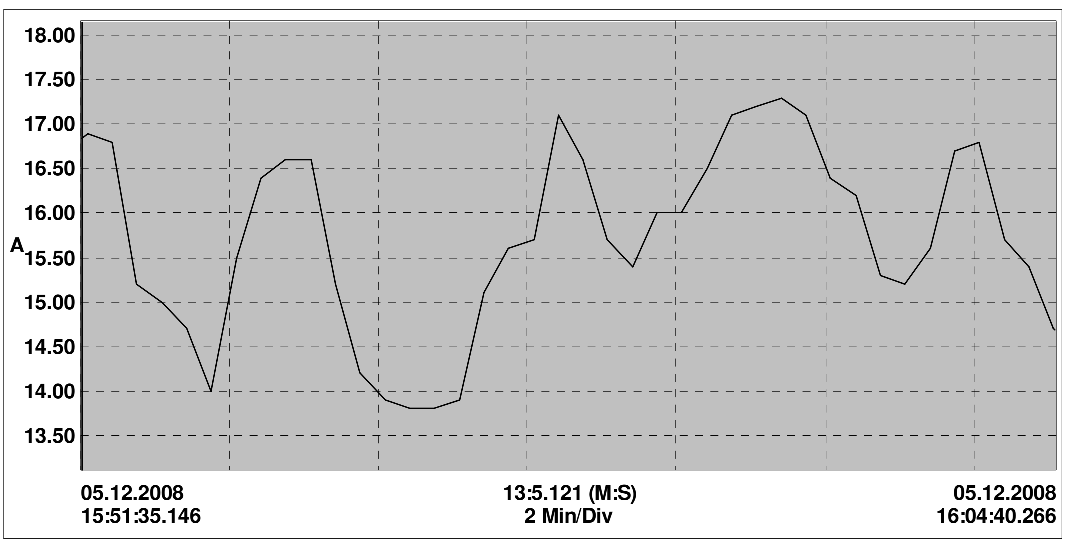

Figure 3.15 Motor starting before compensation and results current in natural

.

As mentioned earlier, further research should be carried out to complete the power quality analysis in terms of a harmonic study of the system. With the complication of measuring the current waveforms, the following are some waveforms showing that the current is seen to be completely void of any kind of waveform.

The Voltage and Current Total Harmonic Distortion trends were recorded and sample trends are given in figure 3.16, figure 3.17, figure 3.18, figure 3.19, figure 3.20 analyzed and the bus frequency before compensation is given in figure 3.22. They are shown below as displayed by Data Viewer.

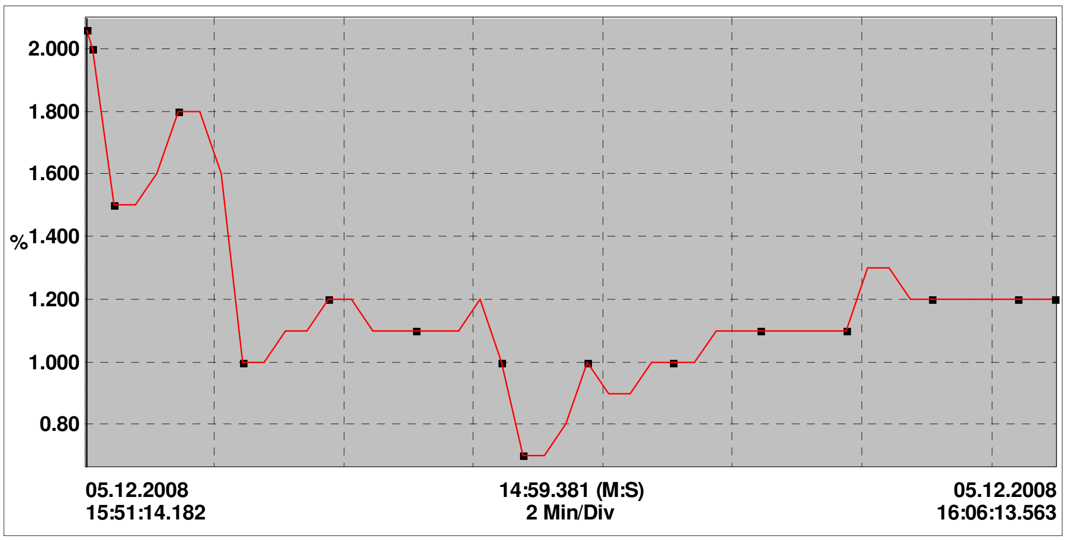

Figure 3.16 Voltage THD of line1 before compensation

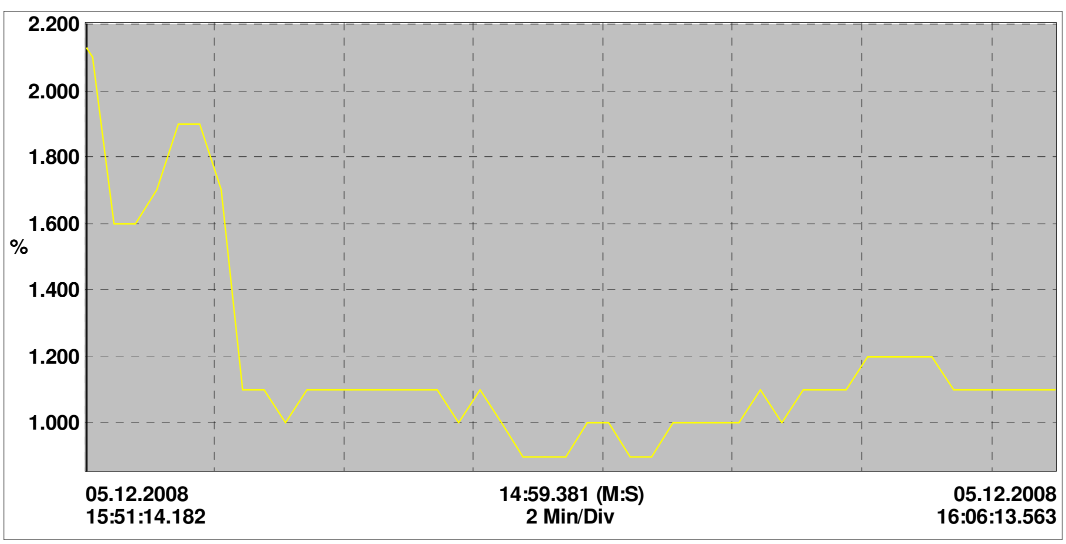

Figure 3.17 Voltage THD of line2 before compensation

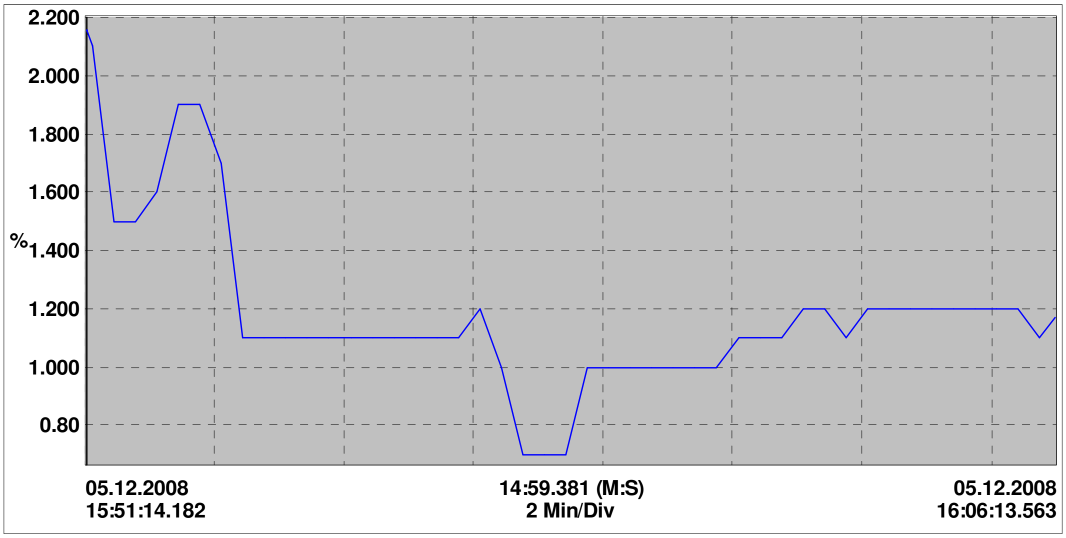

Figure 3.18 Voltage THD of line3 before compensation

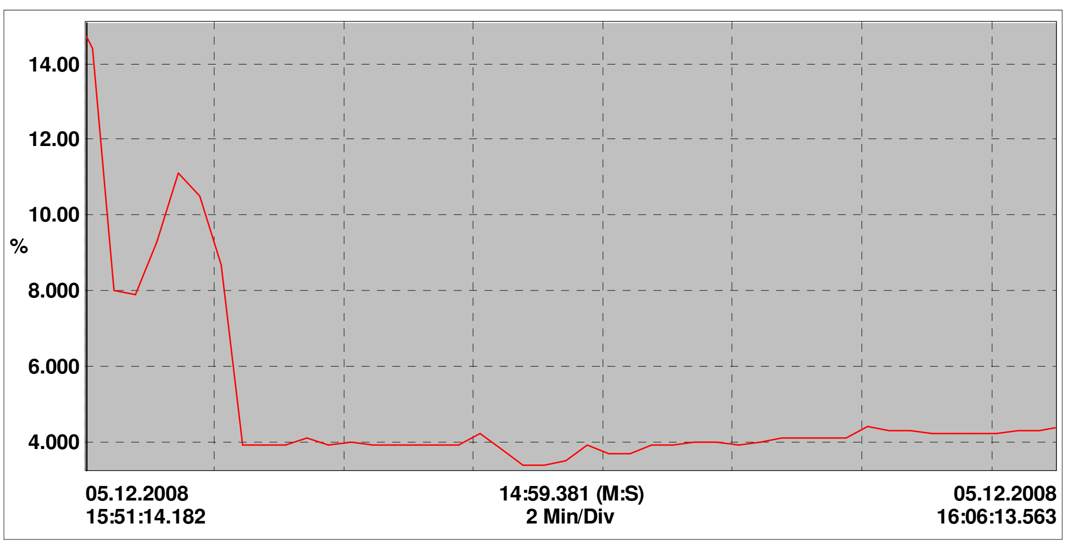

Figure 3.19 Current THD of line1 before compensation

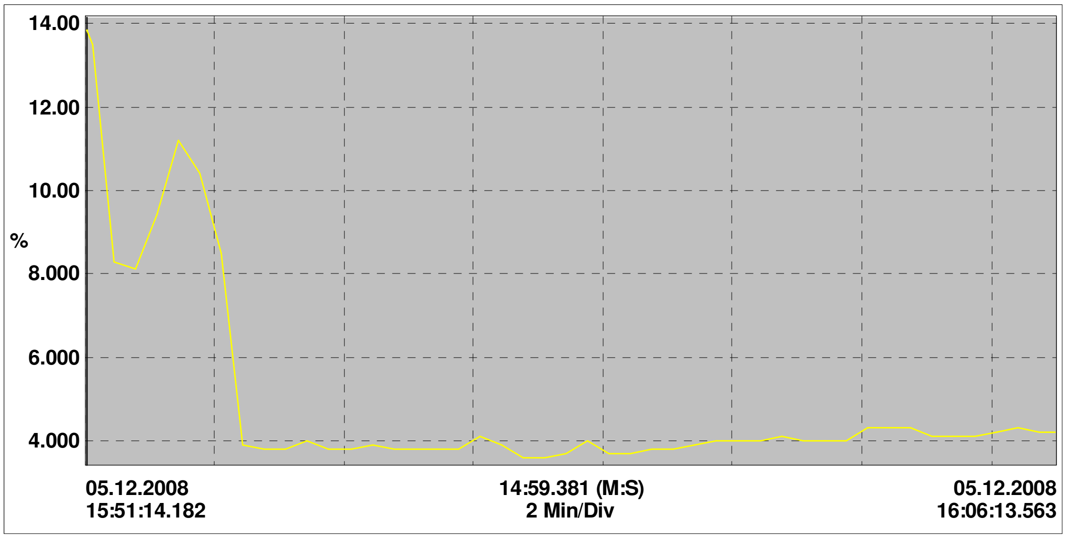

Figure 3.20 Current THD of line2 before compensation

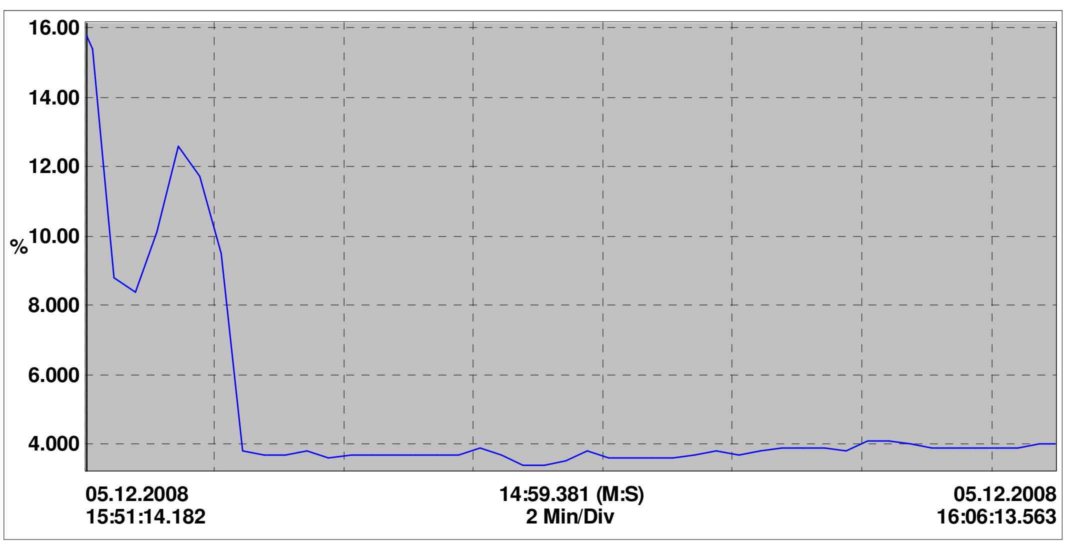

Figure 3.21 Current THD of line3 before compensation

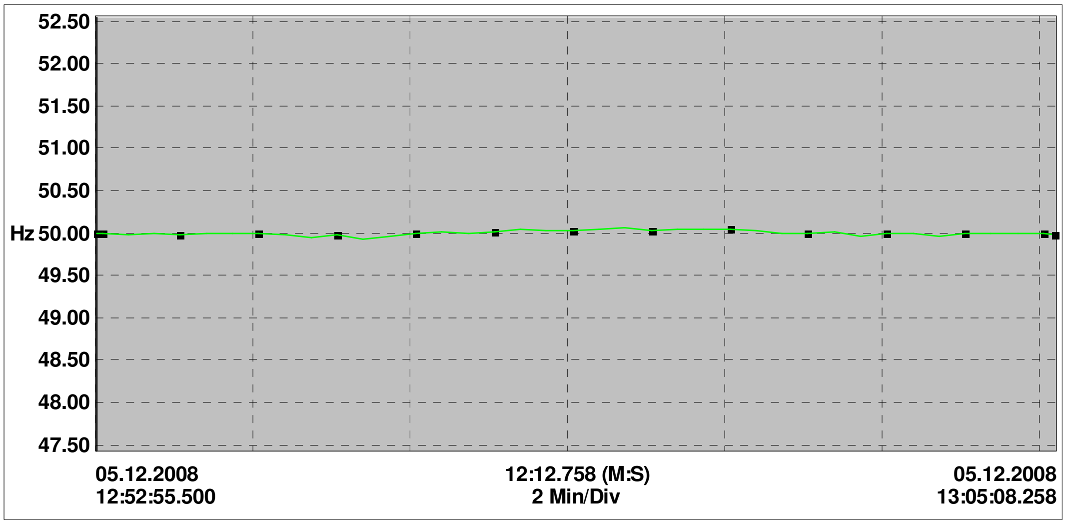

Figure 3.22 Bus frequency before compensation

Active power analysis shows that the average active power is 65 kW for each line. This is shown in figure 3.23, figure3.24 and figure 3.25. Total active power is shown on figure 3.26.

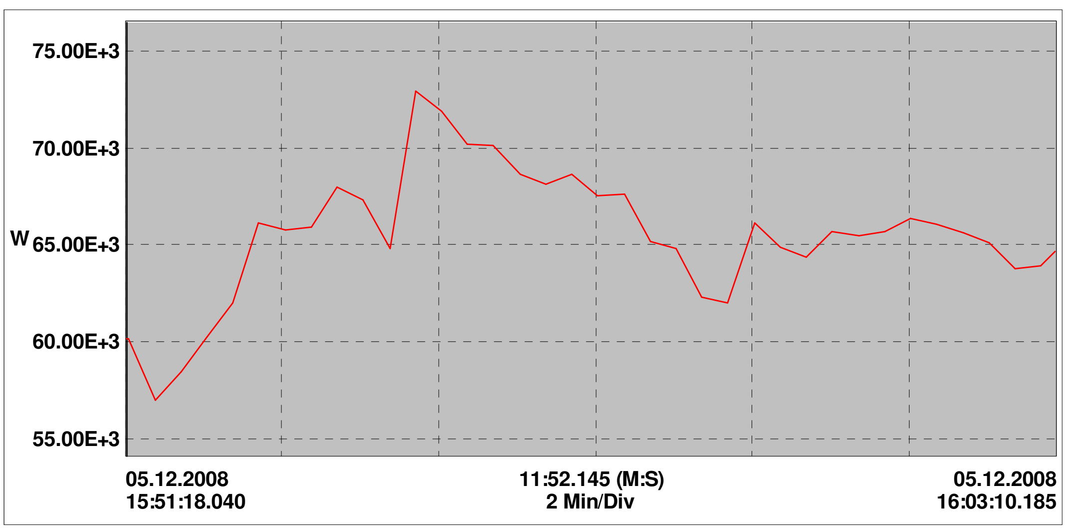

Figure 3.23 Active power of line1 before compensation

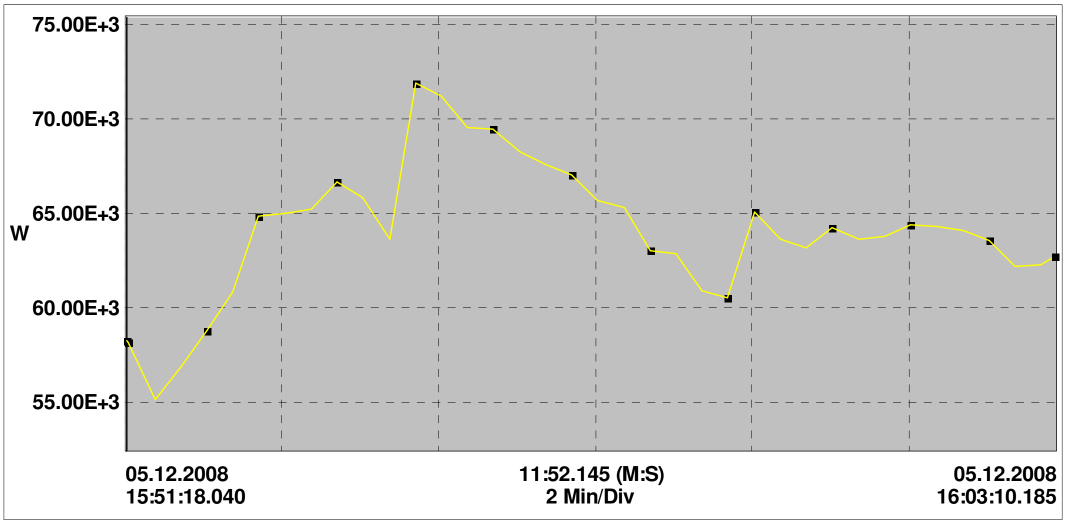

Figure 3.24 Active power of line2 before compensation

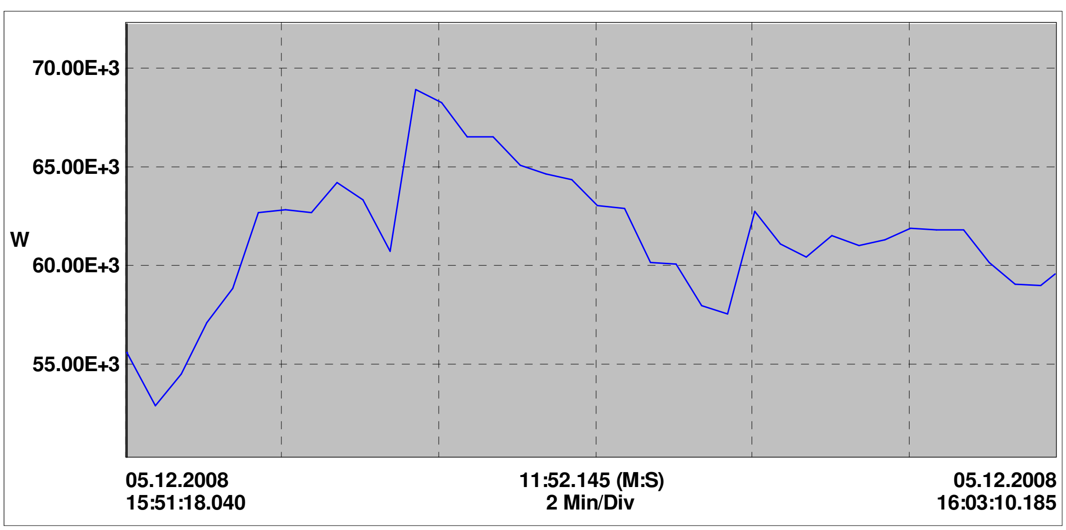

Figure 3.25 Active power of line3 before compensation

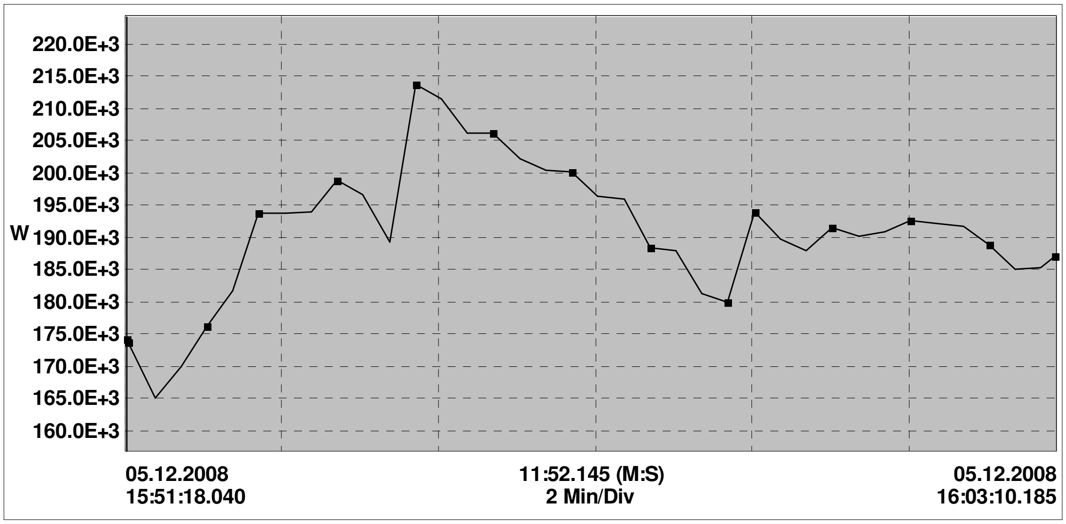

Figure 3.26 Total active power of phases before compensation

Results of apparent power analysis of line 1, line 2 and line 3 are shown in figure3.27, figure3.28 and figure3.29 respectively. It is obvious that apparent power reaches 100 kVA in each line when inductive loads are applied to power system. The total reactive power is approximately 330 kVA as shown in figure3.30.

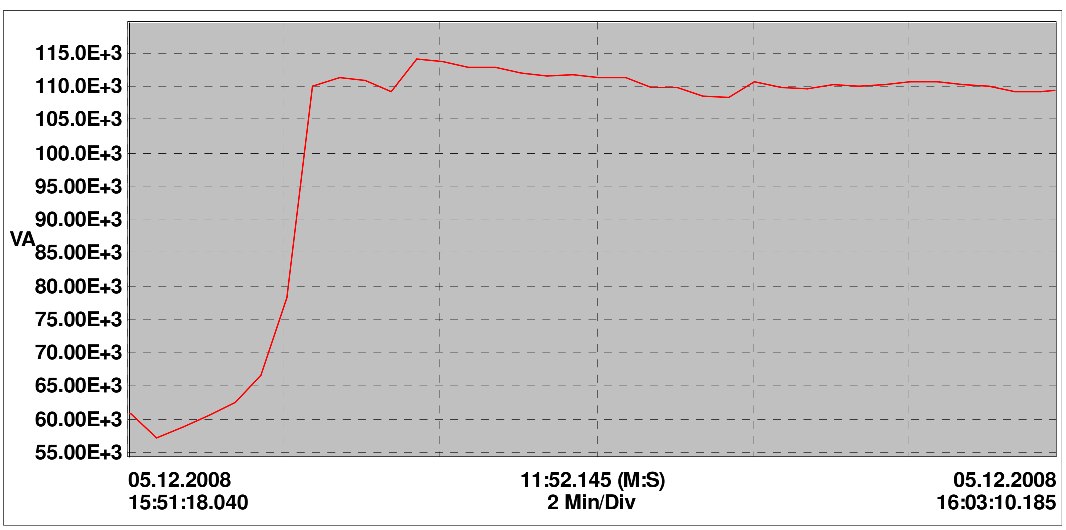

Figure 3.27 Apparent Power of line1 before compensation

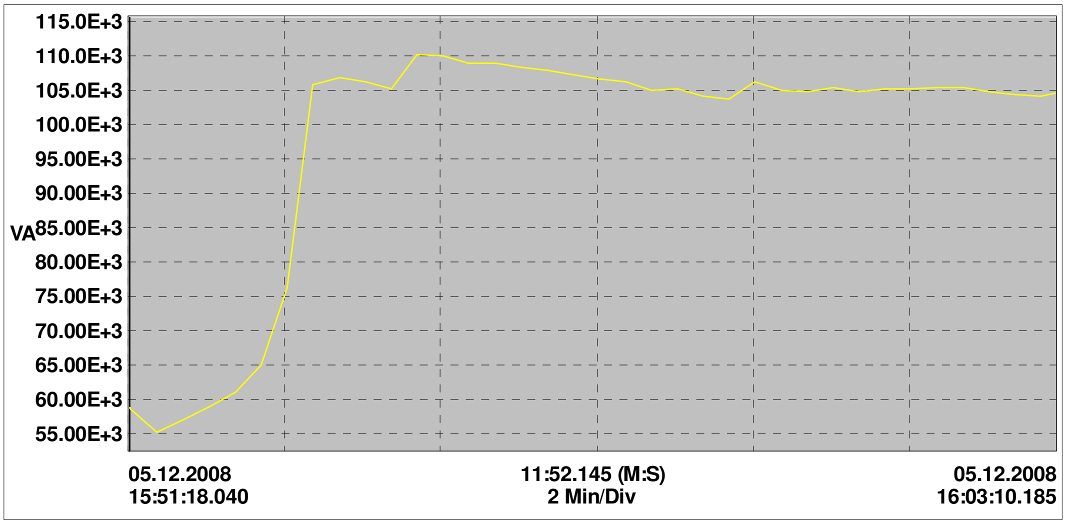

Figure 3.28 Apparent Power of line2 before compensation

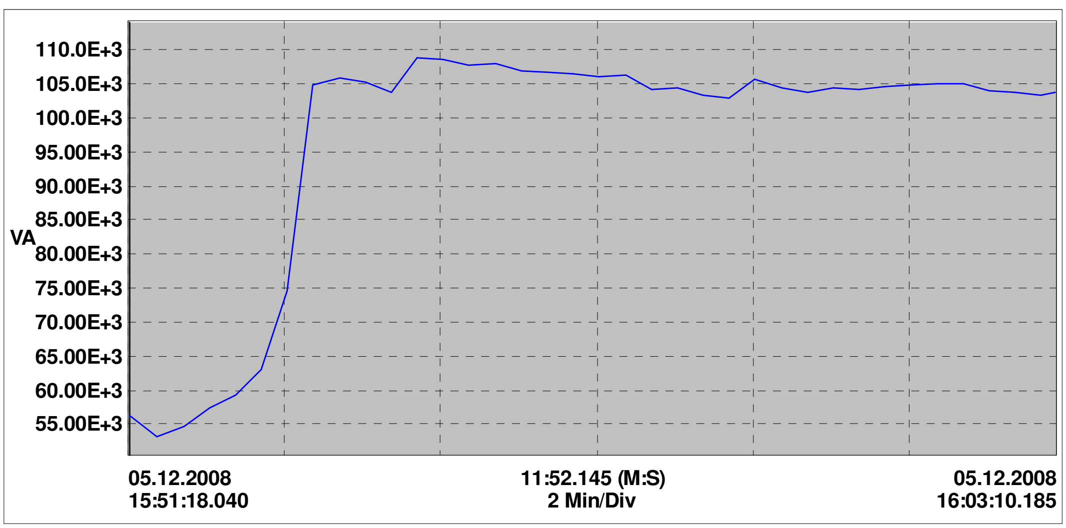

Figure 3.29 Apparent Power of line3 before compensation

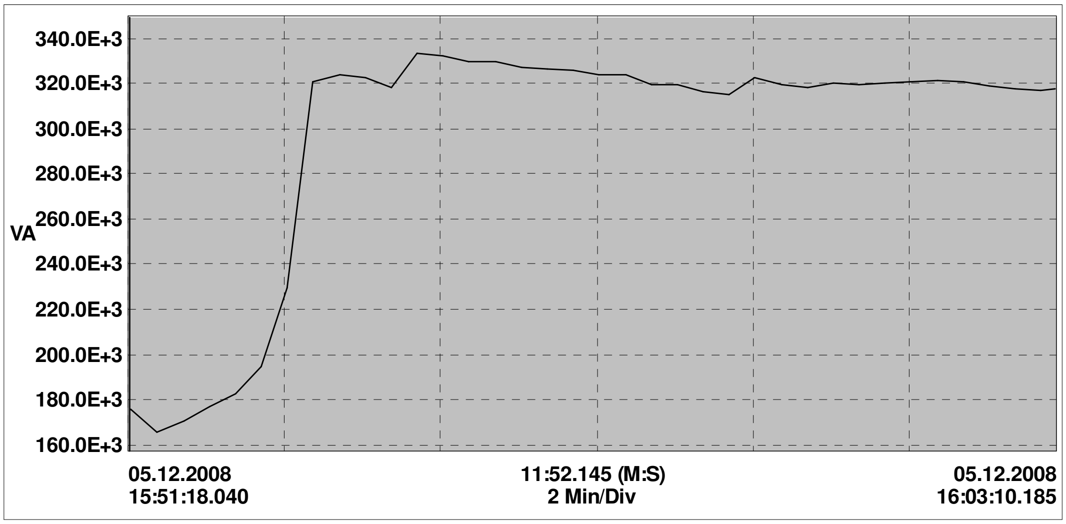

Figure 3.30 Total apparent Power of phases before compensation

Figure 3.31, figure 3.32 and figure 3.33 show measured reactive power of line1, line 2 and line 3 respectively. It is realized from aforementioned figures that reactive power reaches 90 kVAr for each when inductive loads are applied to power system. The total reactive power is 250 kVAr as shown in figure 3.34.

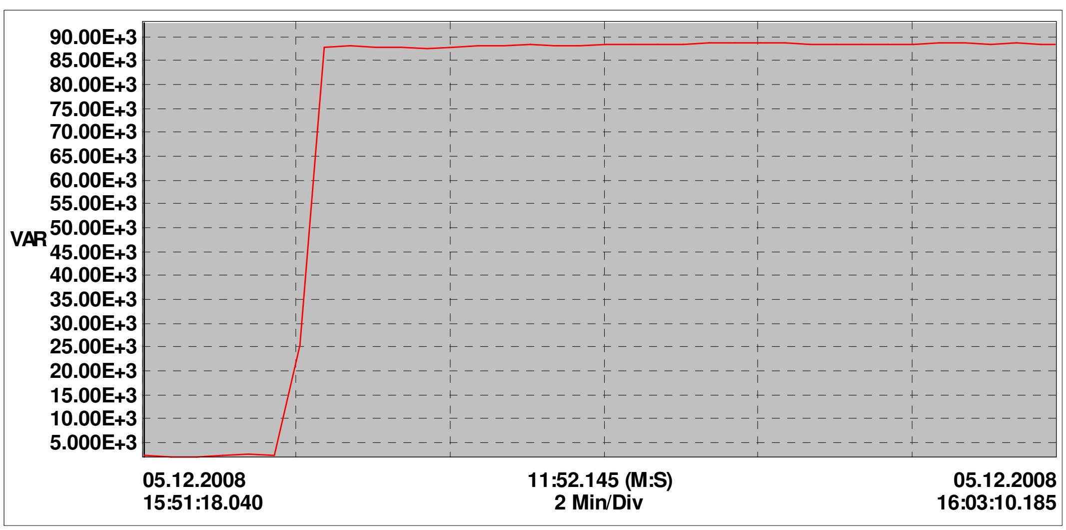

Figure 3.31 Reactive power of line 1 before compensation

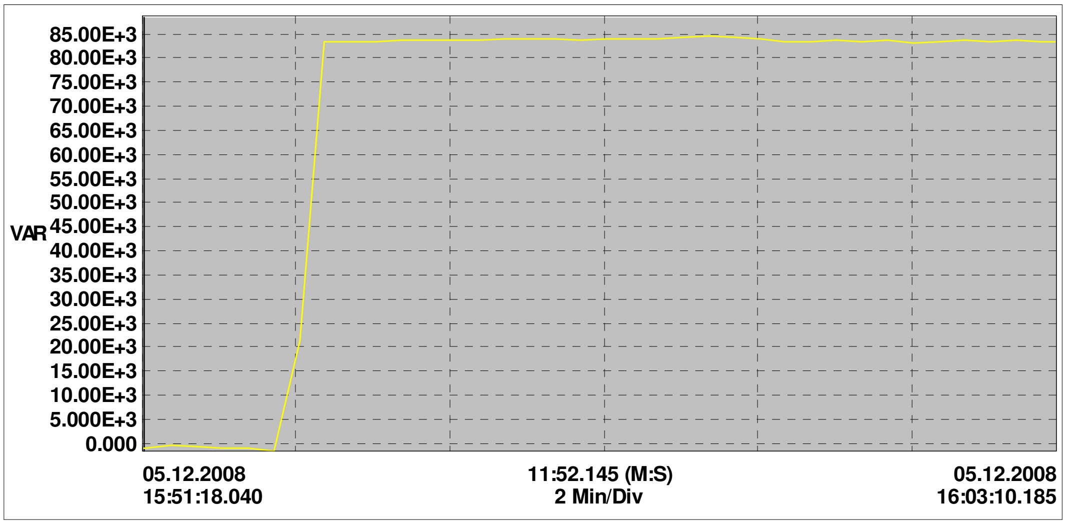

Figure 3.32 Reactive power of line 2 before compensation

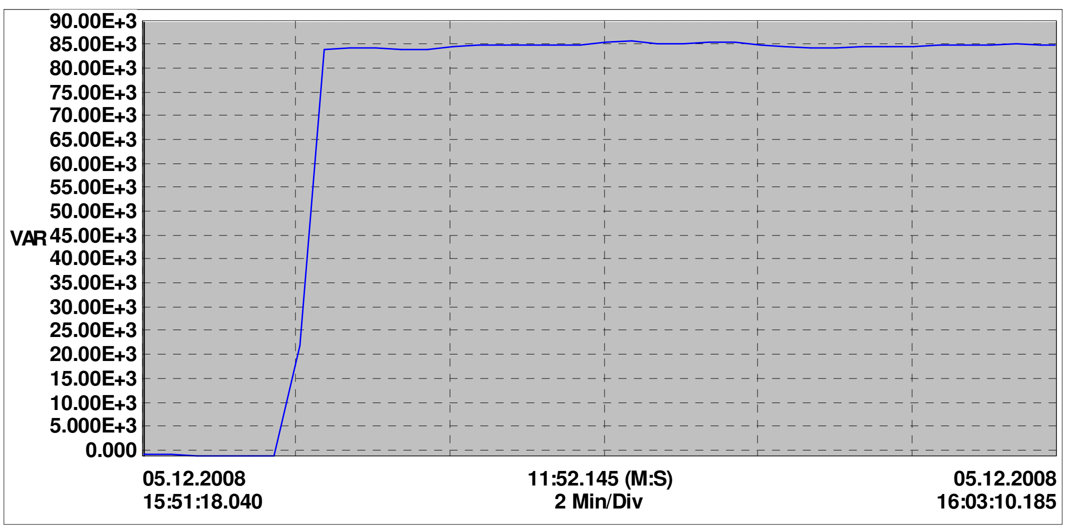

Figure 3.33 Reactive power of line 3 before compensation

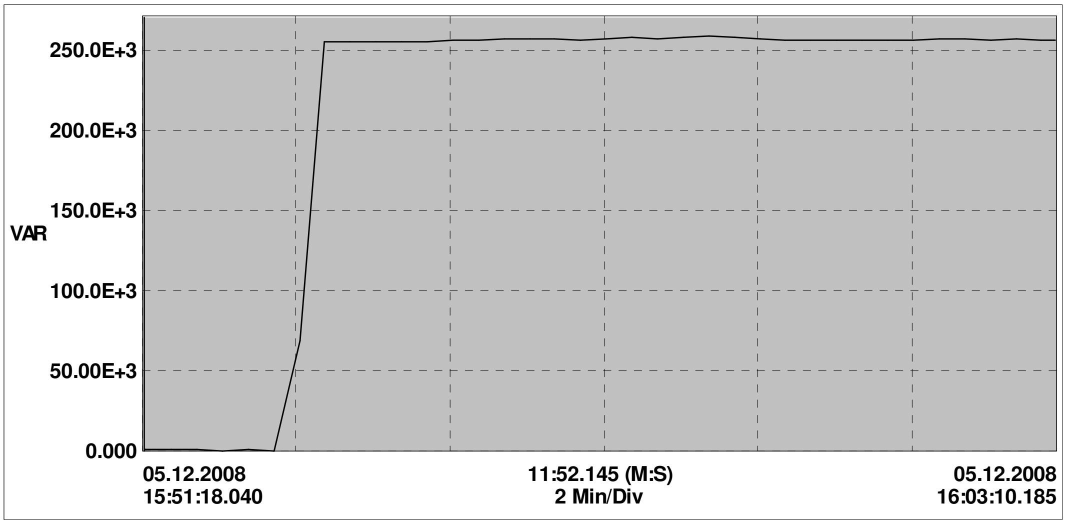

Figure 3.34 Sum of reactive power before compensation

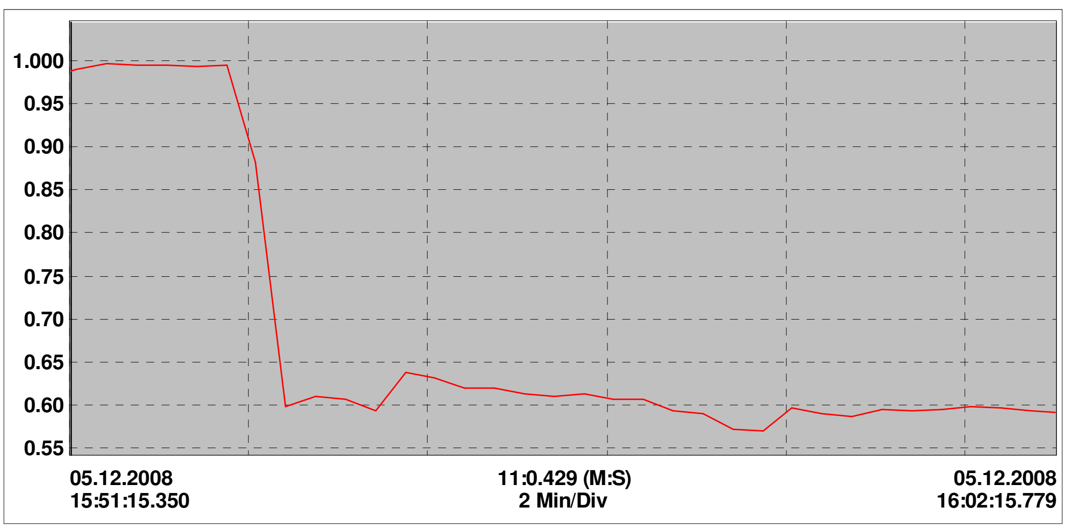

Figure 3.35 Power factor of line 1 before compensation

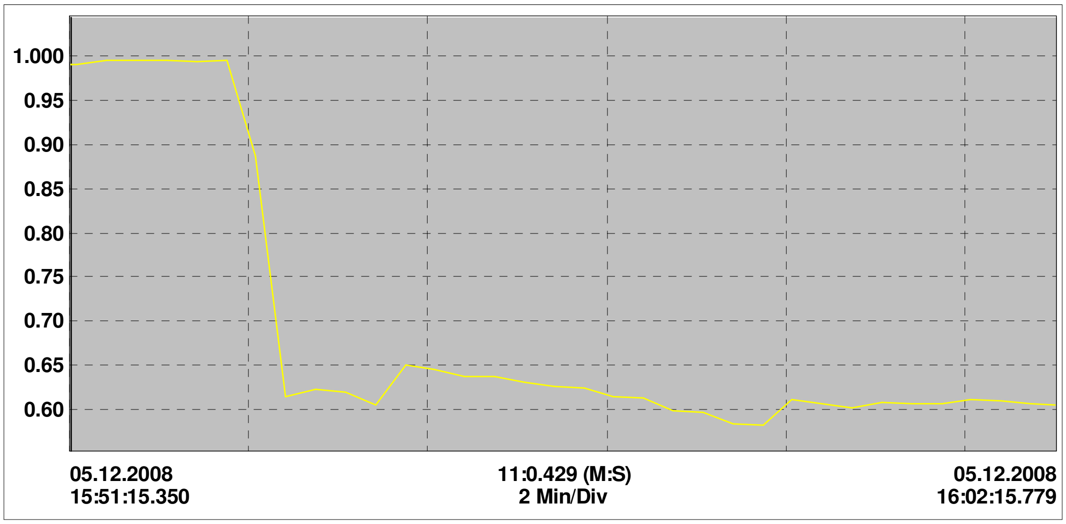

Figure 3.36 Power factor of line 2 before compensation

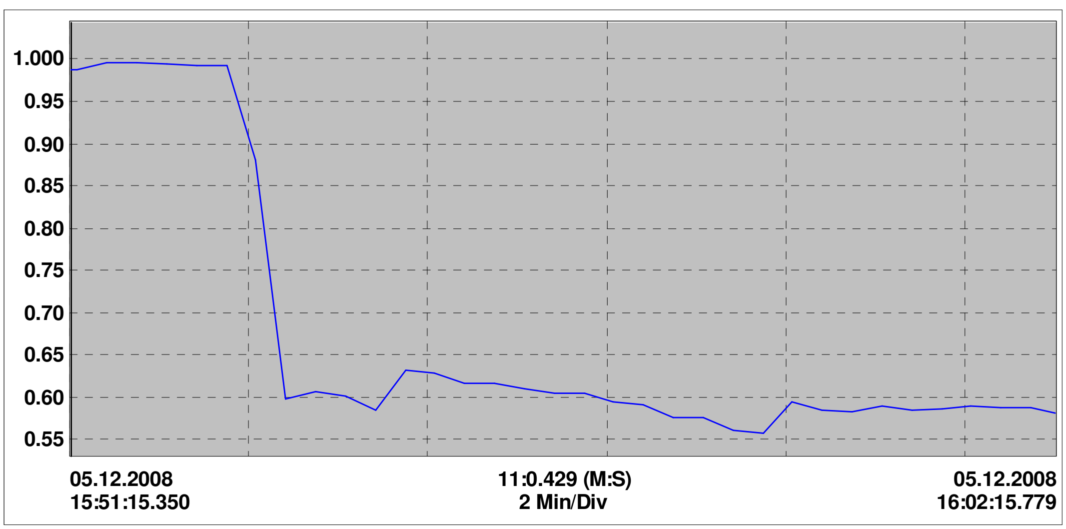

Figure 3.37 Power factor of line 3 before compensation

3.6 Data Collected During Compensation

At the beginning of compensation process, Fundamental frequency of power system is measured to insure that it remains stable. Frequency measurement shows a stable frequency of 50 Hz as shown in figure 3.38.

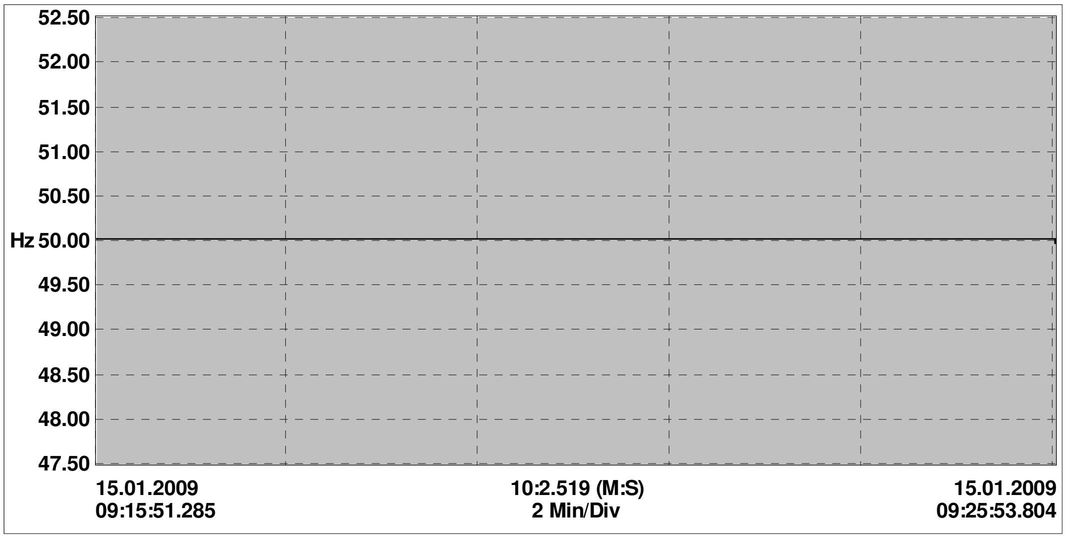

Figure 3.38 Frequency during compensation

Figure 3.39, Figure 3.40, and Figure 3.41 shows the voltage deviation can be 1 Volt when the system loaded.

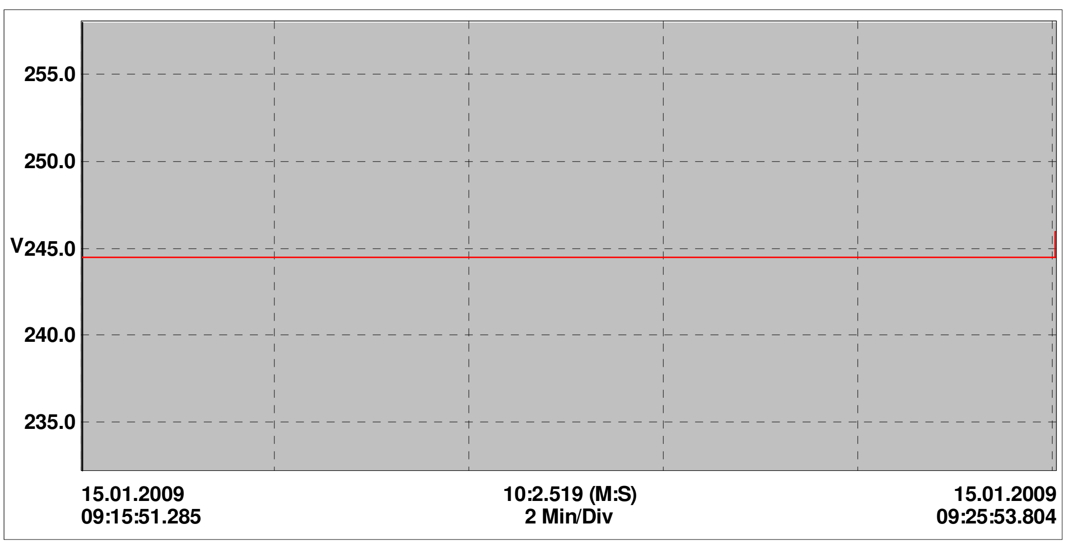

Figure 3.39 V_{rms} of line1 during Compensation

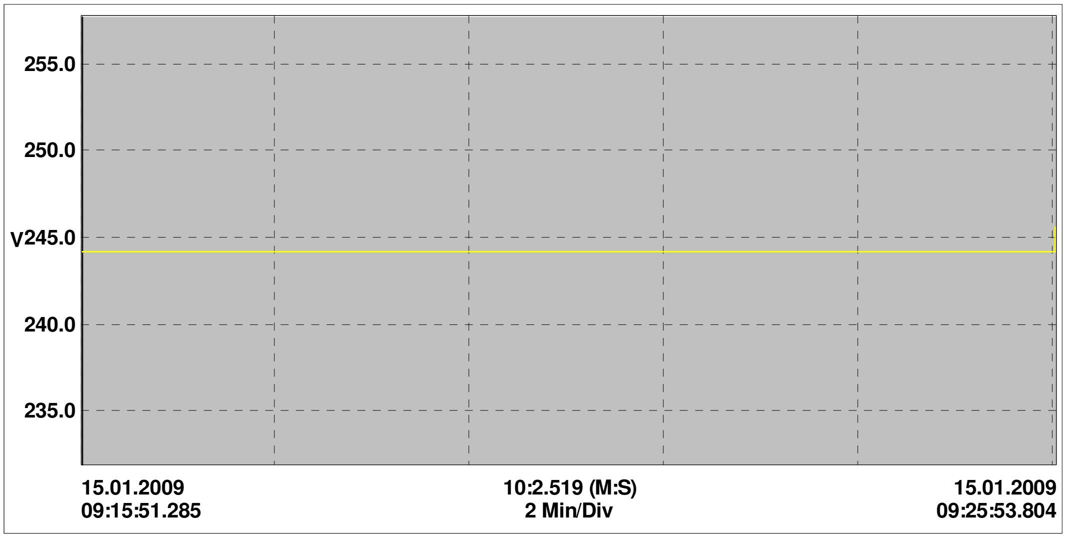

Figure 3.40 V_{rms} of line2 during Compensation

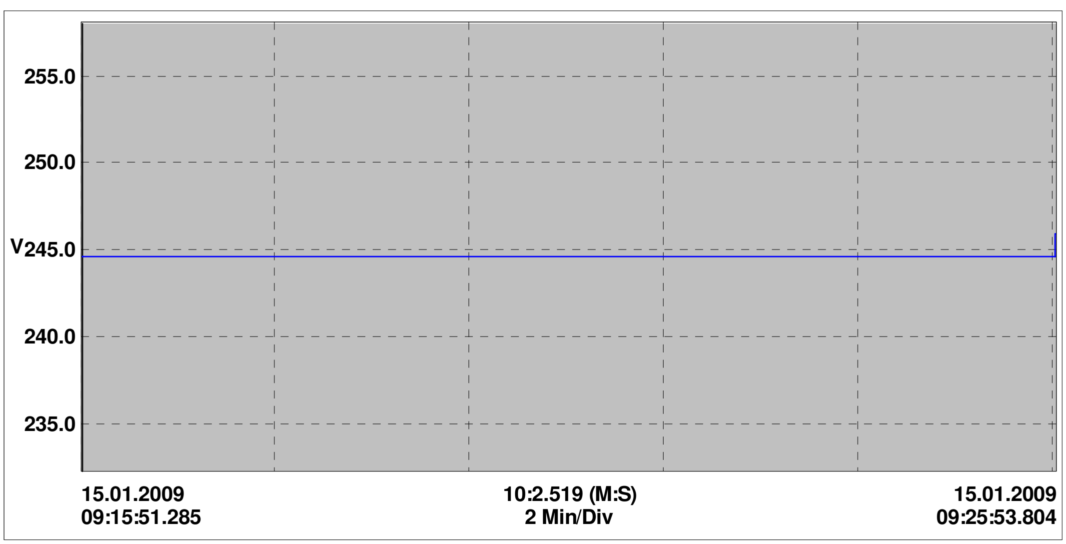

Figure 3.41 V_{rms} of line3 during Compensation

As seen from figures 3.42, 3.43 and 3.44 induction motors getting huge amount of current from network.

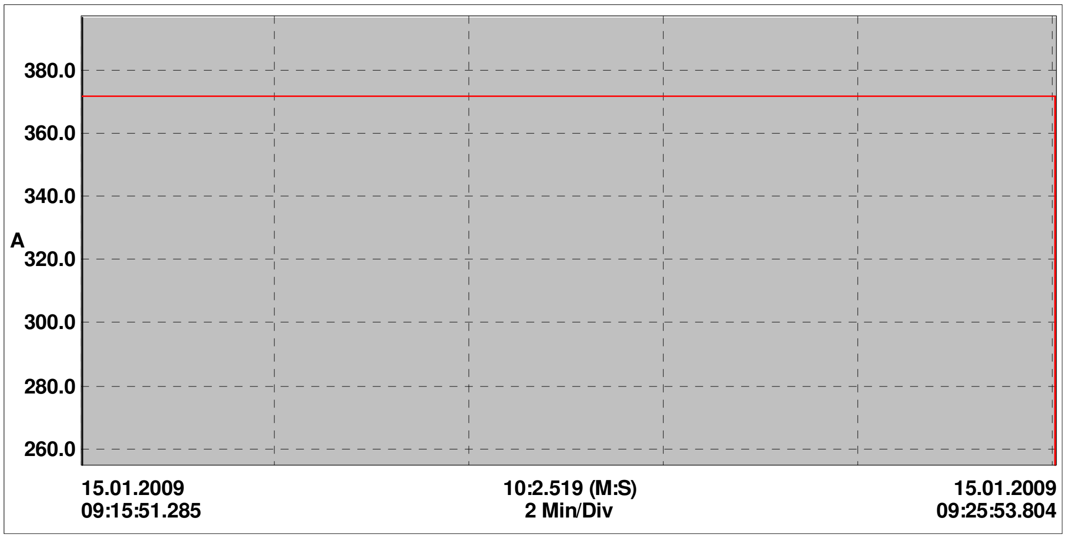

Figure 3.42 I_{rms} of line1 during Compensation

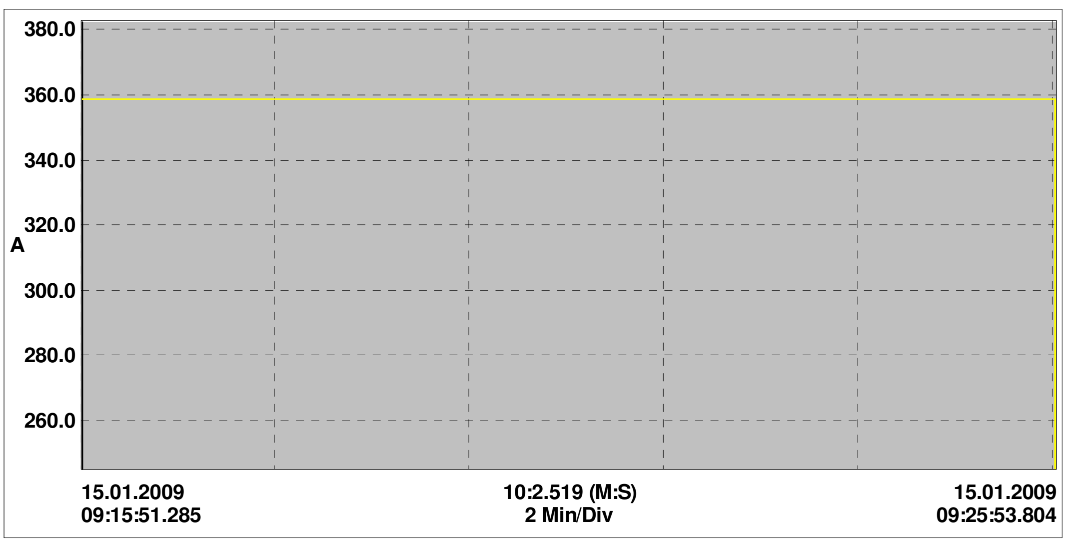

Figure 3.43 I_{rms} of line2 during Compensation

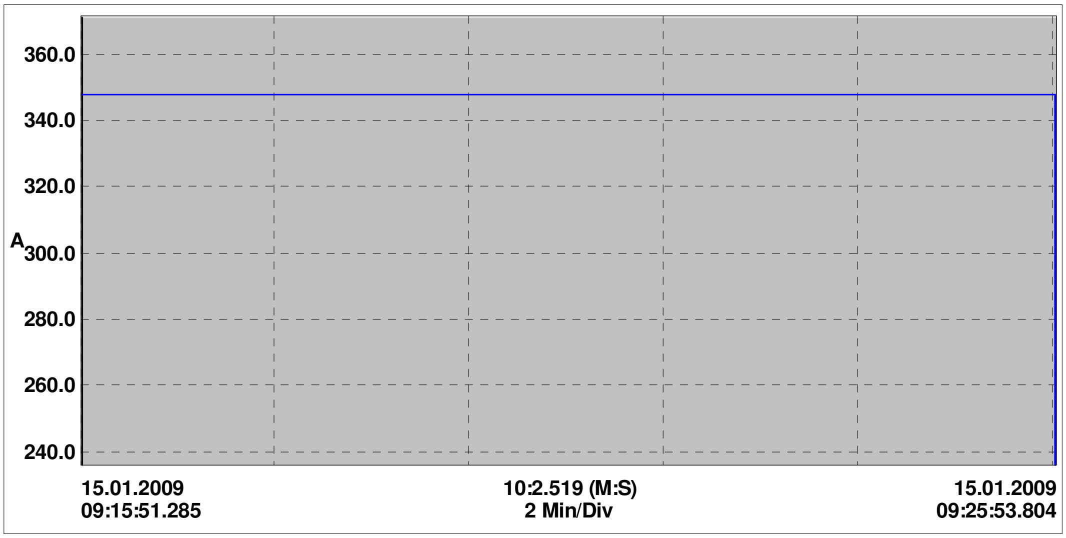

Figure 3.44 I_{rms} of line3 during Compensation

Figure 3.45 shows that three phase and single phase loads are balanced.

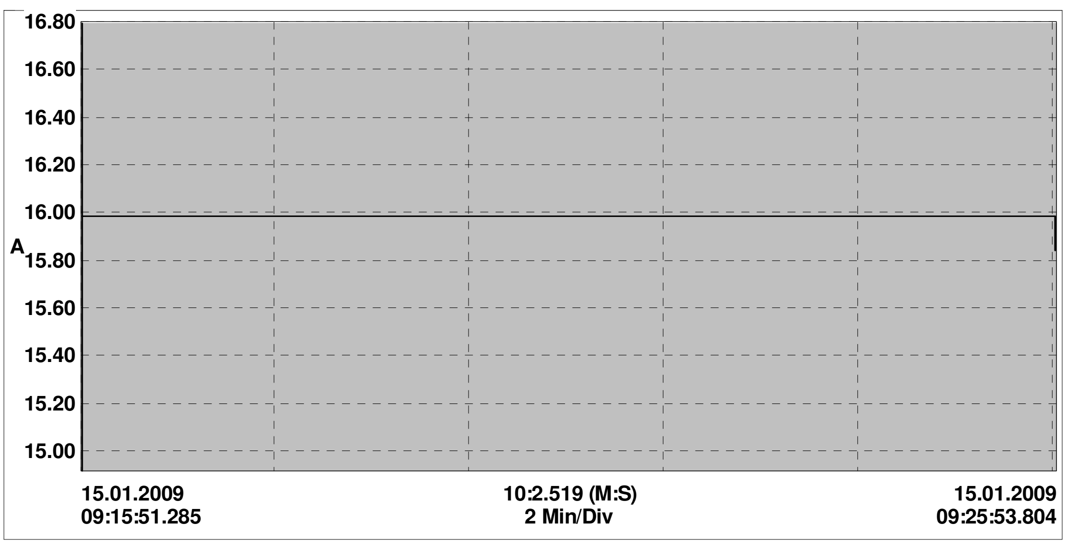

Figure 3.45 I_{rms} of neutral during Compensation

The Voltage and Current Total Harmonic Distortion trends were recorded and sample trends are given below. Total harmonic distortion trends in voltage are shown in figure 3.46, figure 3.47, figure 3.48 and Total harmonic distortion trends in Currents are shown in figure 3.49, figure 3.50, and figure 3.51.

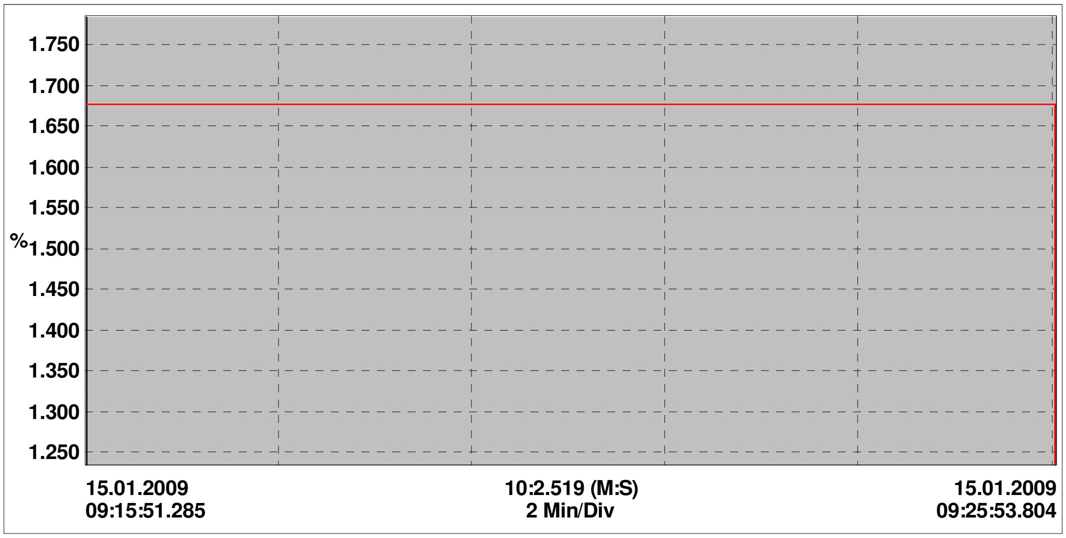

Figure 3.46 V_{thd} of line1 during compensation

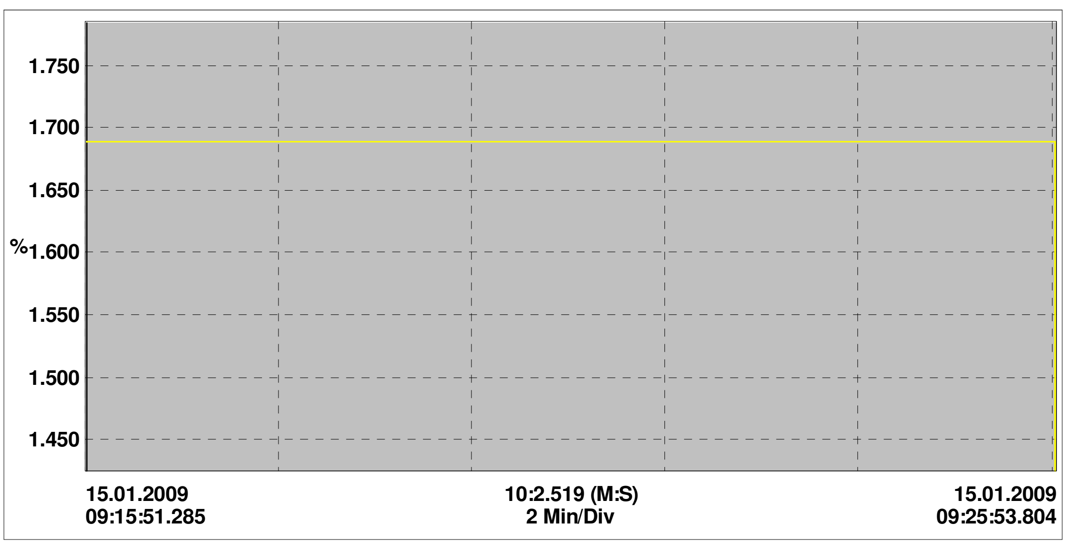

Figure 3.47 V_{thd} of line2 during compensation

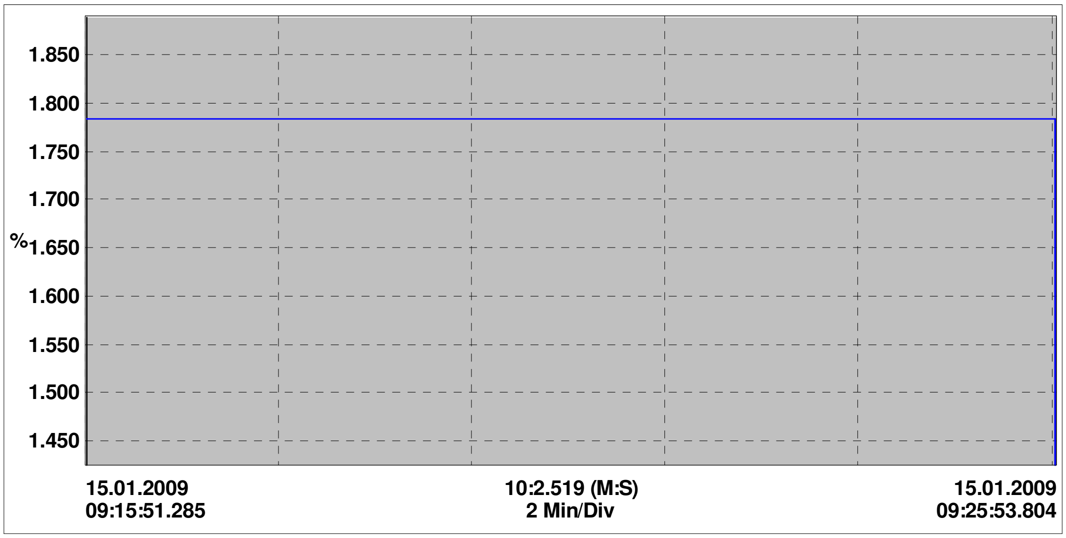

Figure 3.48 V_{thd} of line3 during compensation

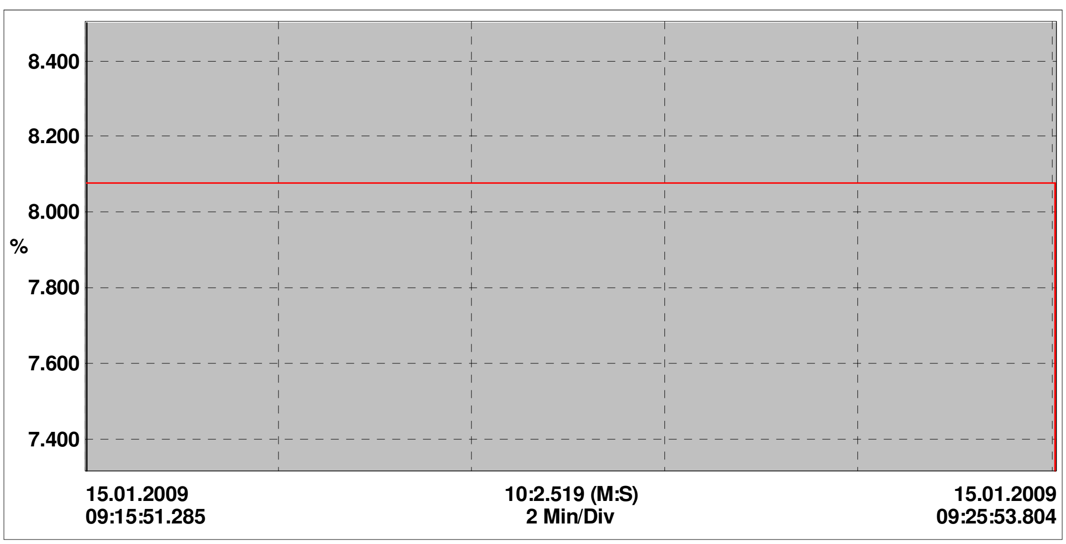

Figure 3.49 I_{thd} of Line2 during Compensation

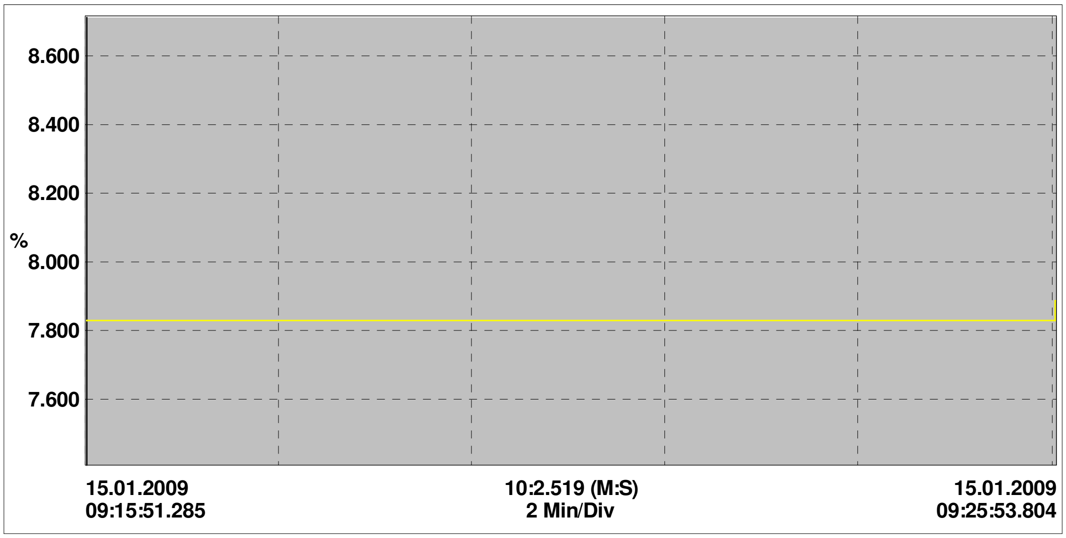

Figure 3.50 I_{thd} of line2 during compensation

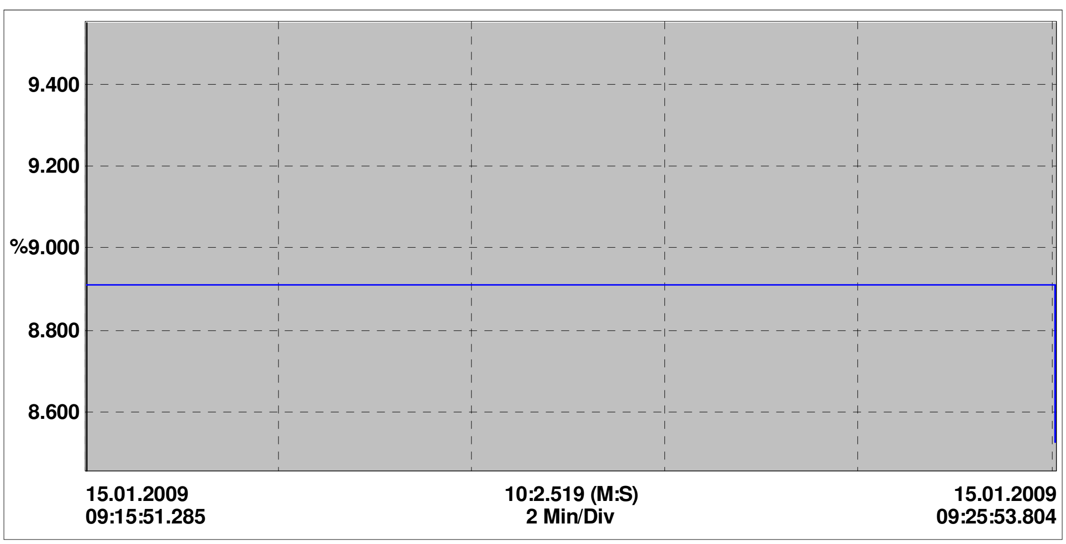

Figure 3.51 I_{thd} of line3 during compensation

Active power analysis during compensation shows that the average active power is around 87 kW for each line. This is shown in figure 3.52, figure 3.53, figure 3.54 and figure 3.59 show total active power.

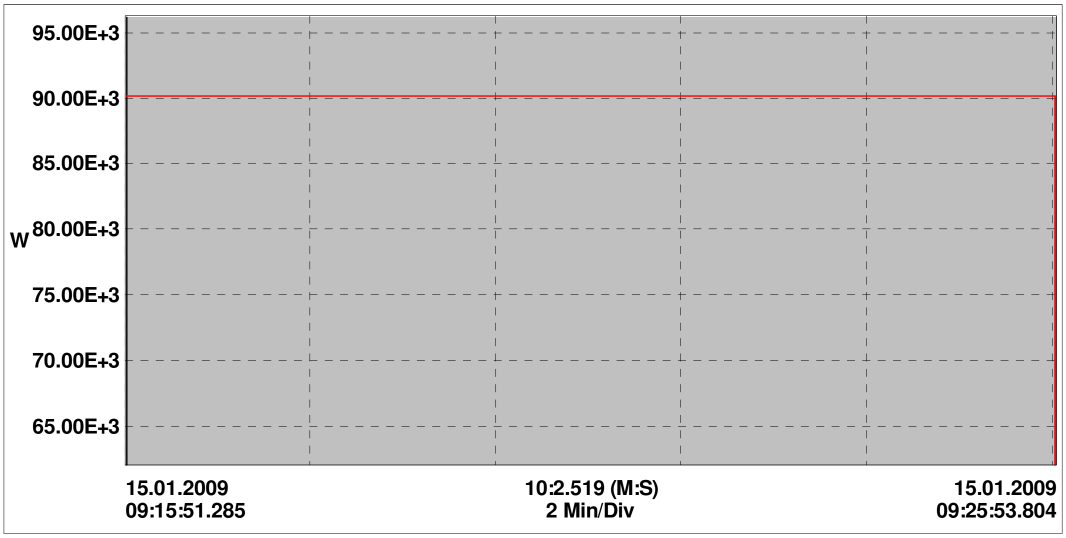

Figure 3.52 Active power of line1 during compensation

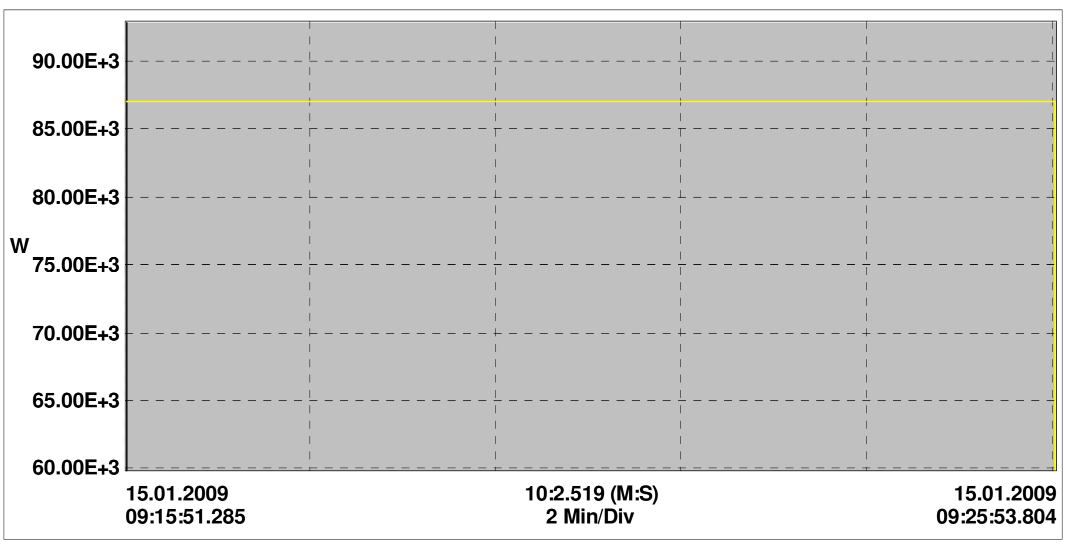

Figure 3.53 Active power of line2 during compensation

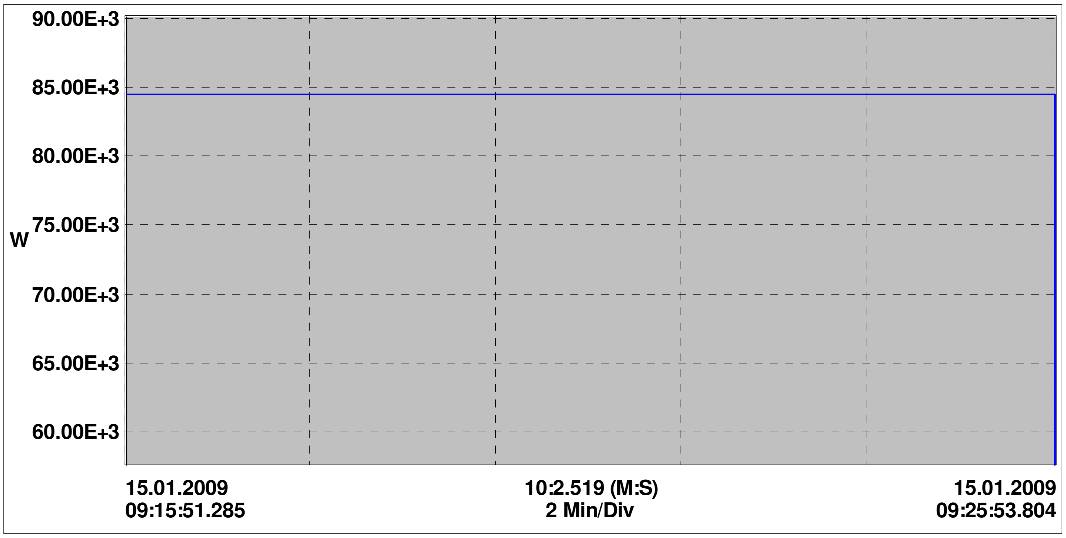

Figure 3.54 Active power of line3 during compensation

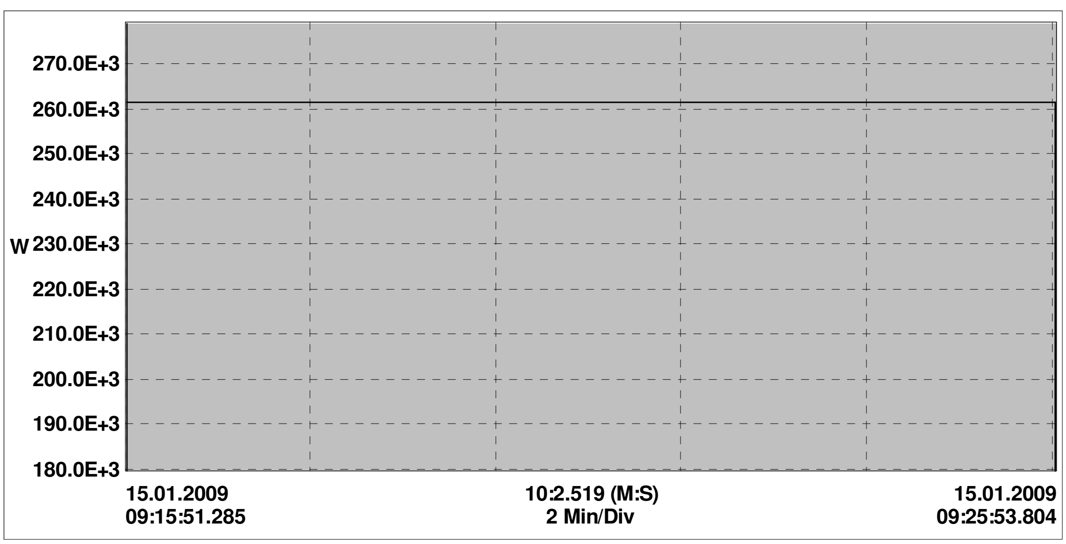

Figure 3.55 Total active power of phases during compensation

Results of apparent power analysis of line 1, line 2 and line 3 are shown in figure 3.57, figure 3.28, and figure 3.29 respectively. It is obvious that apparent power reaches around 90 kVA in each line when inductive and capacitive loads are applied to power system. The total reactive power is approximately 265 kVA as shown in figure 3.59.

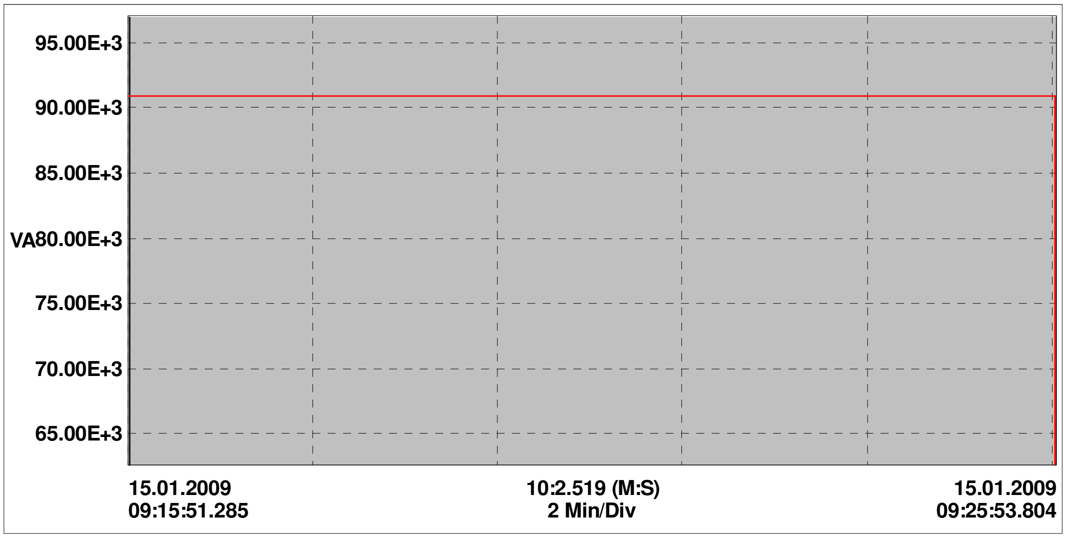

Figure 3.56 Apparent power of line1 during compensation

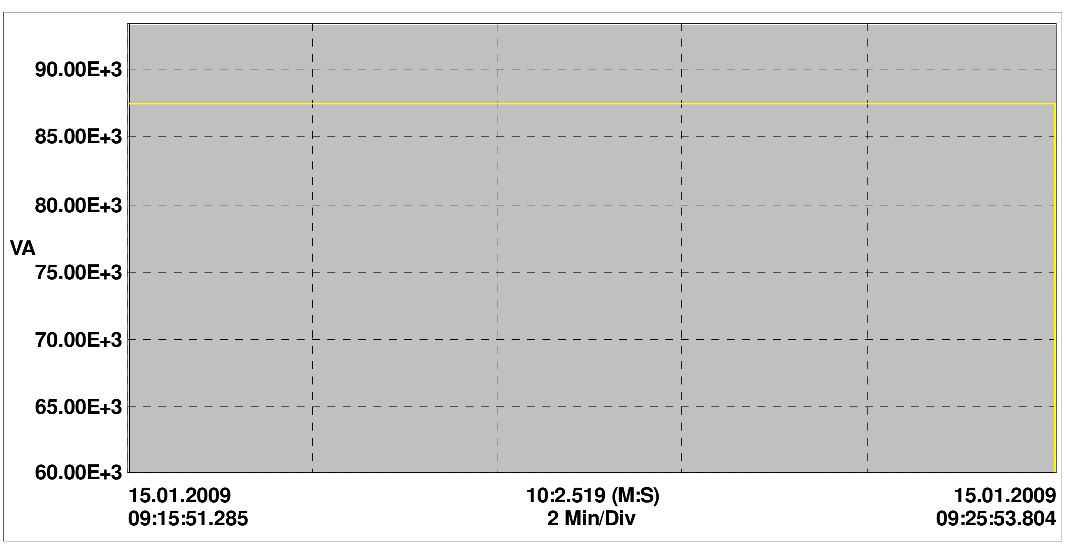

Figure 3.57 Apparent power of line2 after Compensation

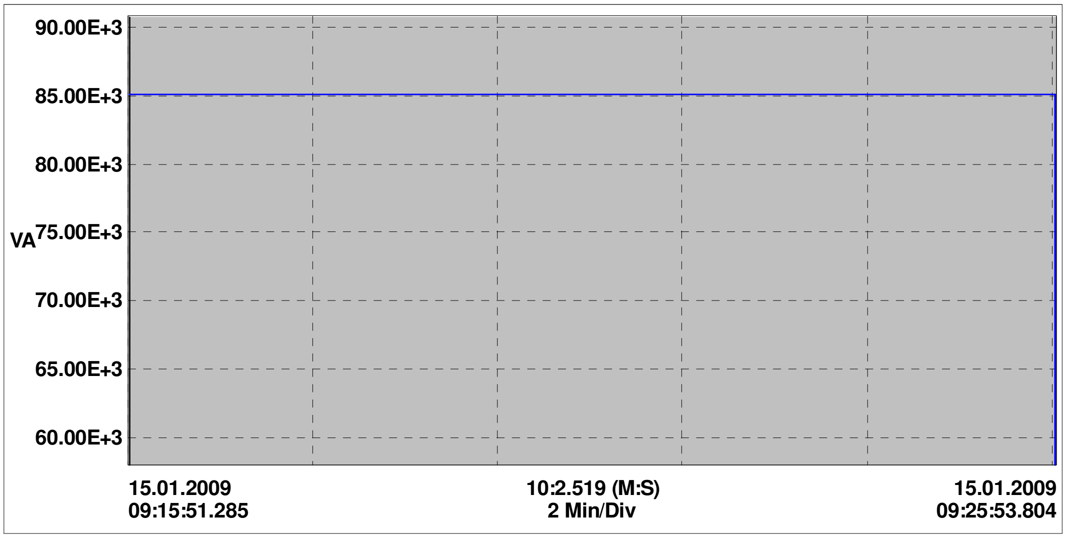

Figure 3.58 Apparent power of line3 during compensation

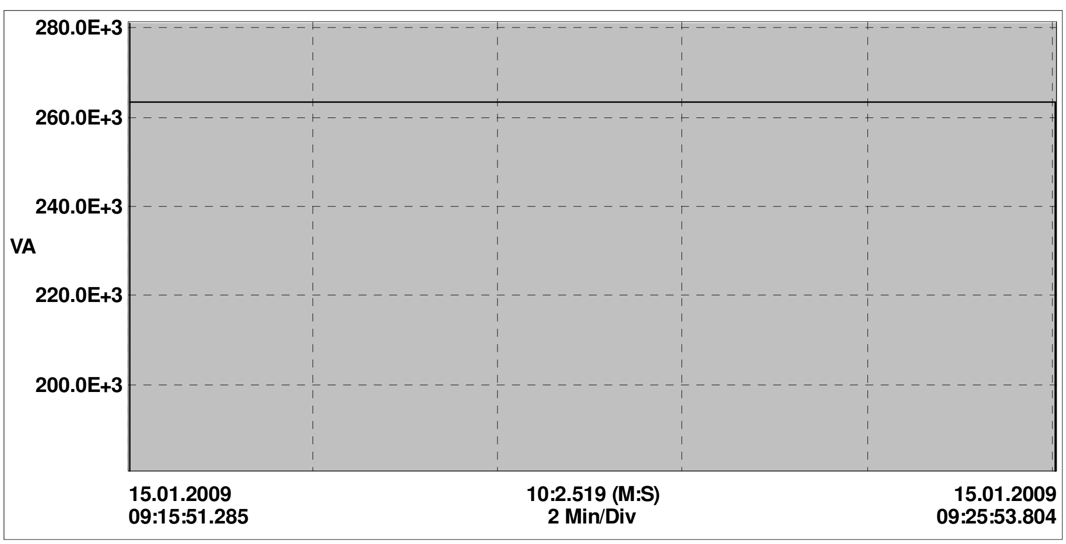

Figure 3.59 Total apparent power of phases during compensation

Figures 3.60, figure 3.61 and figure 3.62 show the measured reactive power of Line 1, Line 2 and Line 3. It can be seen that reactive power compensation works fine in steady state. The reactive power of each line is quite close to zero point. Figure 3.63 shows power factor of line1 during compensation.

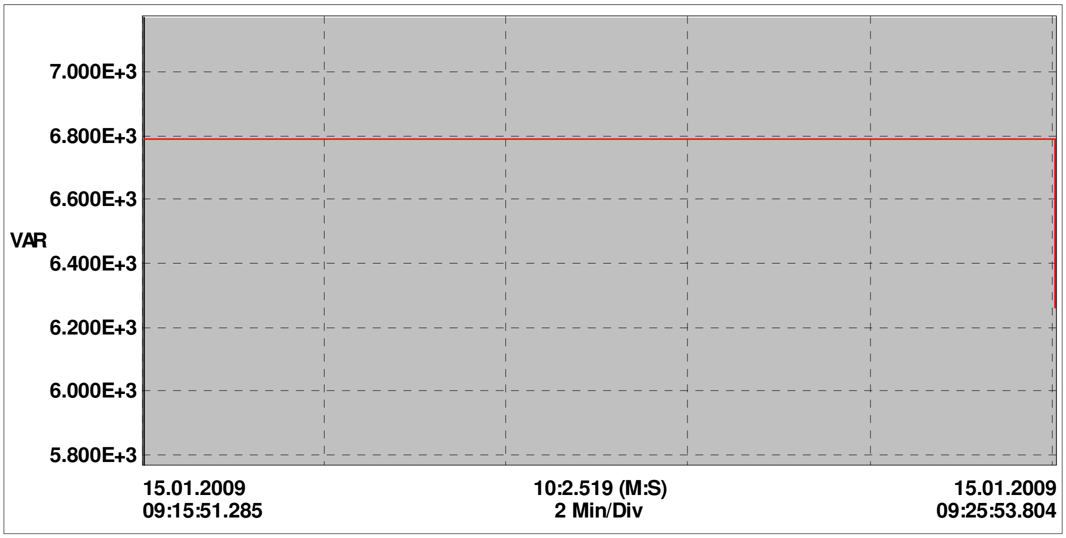

Figure 3.60 Reactive power of line1 during compensation

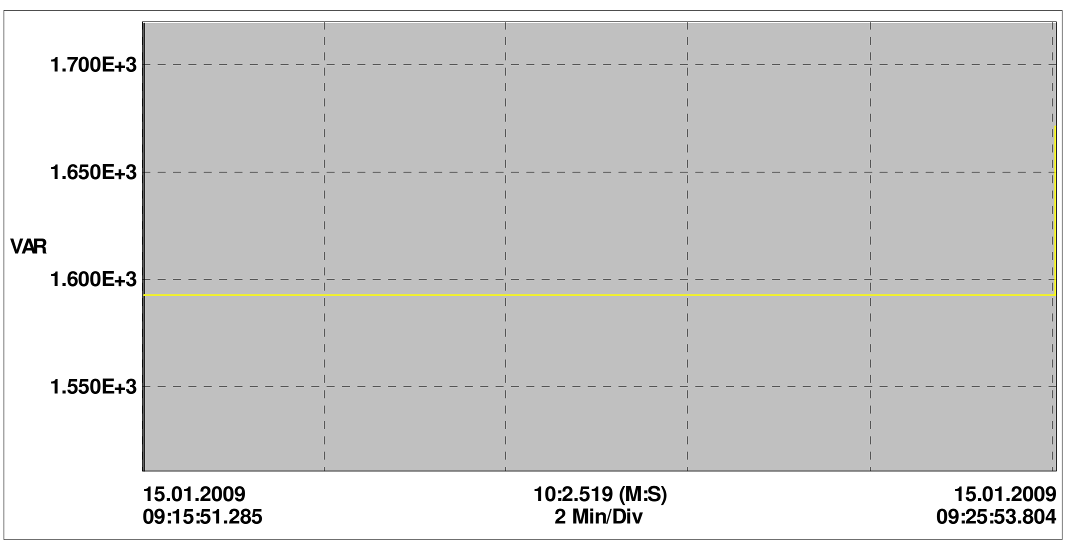

Figure 3.61 Reactive power of line2 during compensation

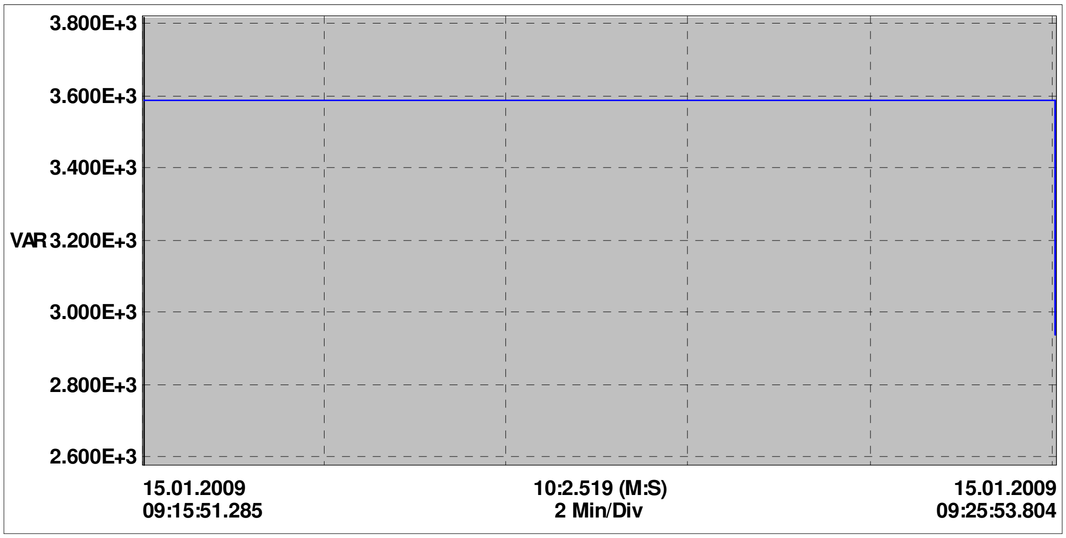

Figure 3.62 Reactive power of line3 during compensation

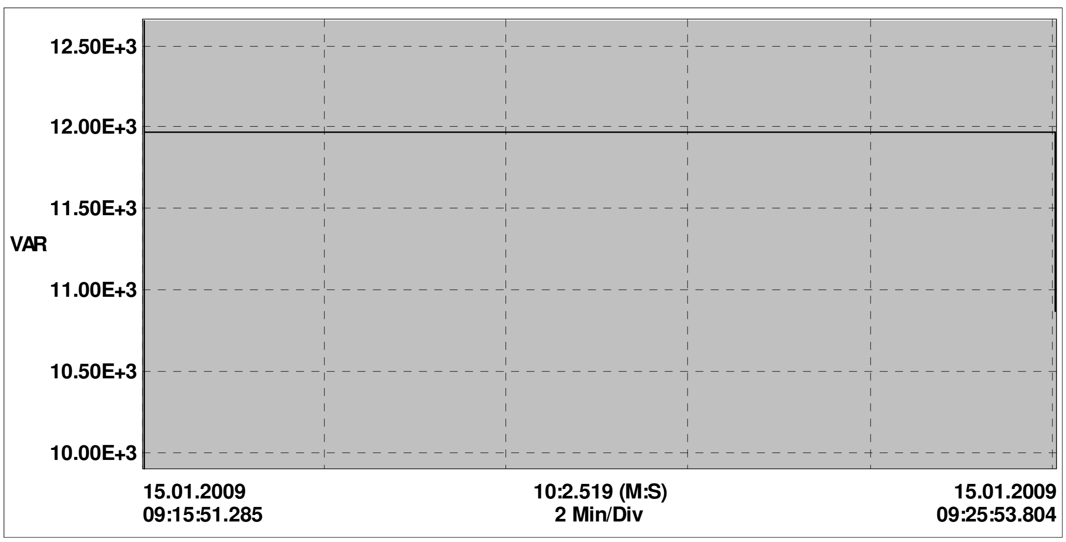

Figure 3.63 Total reactive power of Phases during compensation

The purpose of this work is to compensate the system at the load side and achieve a power factor of cosØ=1. It can be seen in figure 3.64 that the measured reactive power fluctuates close to the ideal reactive power.

If power factor is kept constant, the reactive power can be determined by:

$$Q = -P\sqrt{\frac{1}{(\cos\phi)^2} - 1} \qquad (3.1)$$

In figures 3.65, figure 3.66 and figure 3.67 gives the power factor of each transmission line which reached 0.99 as a result of compensation.

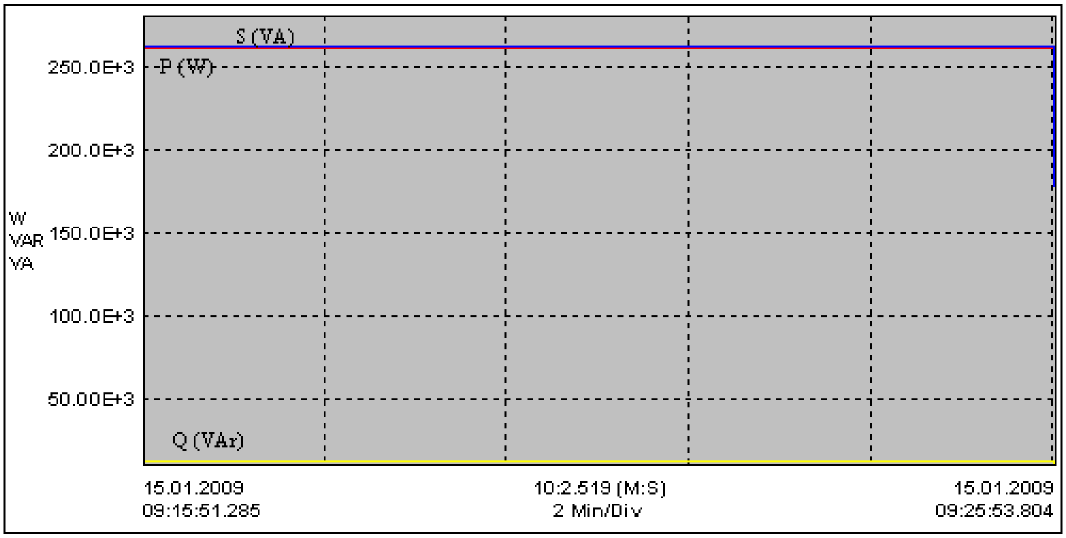

Figure 3.64 Active, Apparent and Reactive power at the system terminal with compensation cosØ =0.

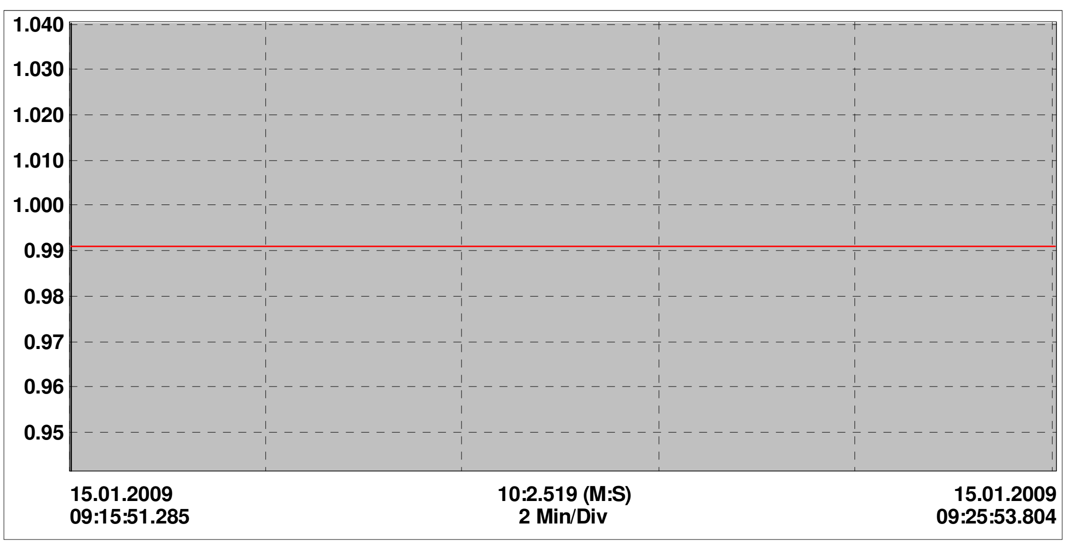

Figure 3.65 Power factor of line 1 during compensation

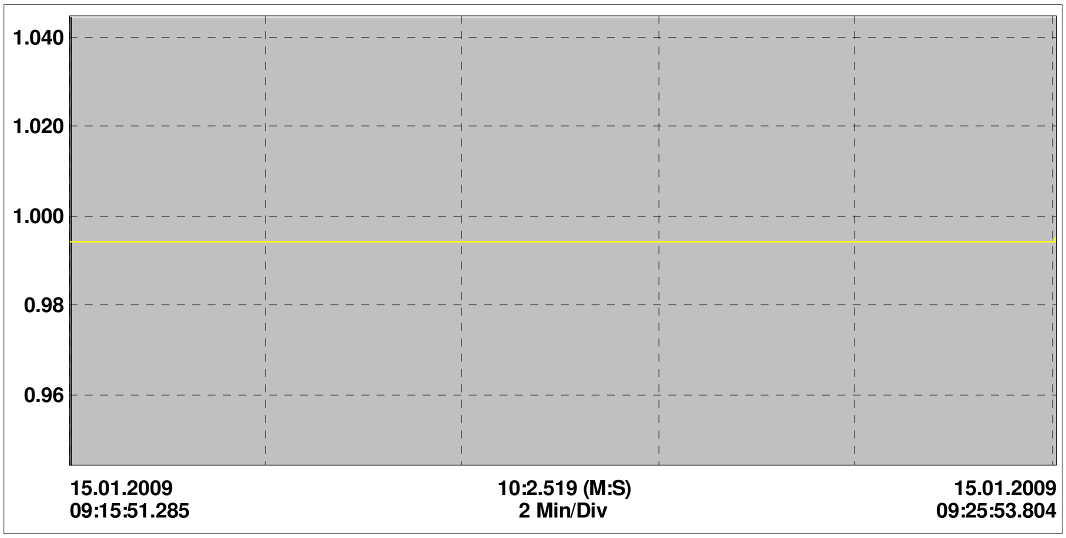

Figure 3.66 Power factor of line 2 during compensation

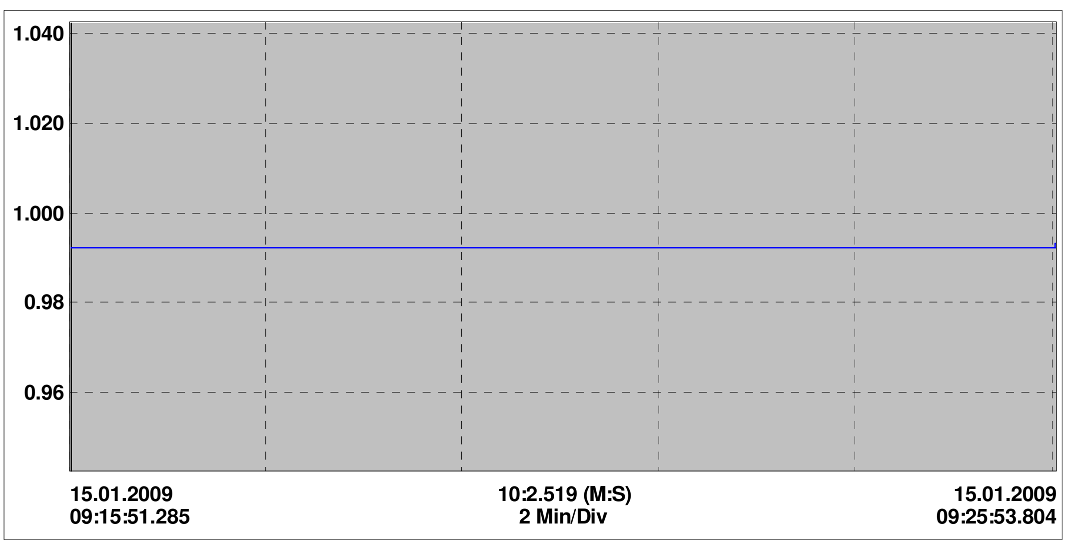

Figure 3.67 Power factor of line 3 during compensation

CHAPTER FOUR

StatCom Modeling by MATLAB and Simulation Results

4.1 Overview

The simulation is necessary to see the extent of the problems monitored at the Sag Mill bus by new FACTs technologies doing a simulation by MATLAB. Reactive Power was injected into the sag mil bus to see their propagation throughout the system and also motor starting were simulated. The duration arranged to 5 second. It was intended to see the behavior of the system and allow the steady sate conditions. The starting induction motor model in the simulation will show similar sags depths to the ones measured.

4.2 System

The voltage at the point of common coupling in a weak network is very sensitive to load changes. Mainly affect the voltage magnitude fluctuation in the bus voltage, whereas reactive load changes mainly affect the voltage magnitude. With the addition of energy storage to a StatCom, it is possible to compensate for the active power change as well as providing reactive power support. In this chapter, some effective power compensation schemes by showing that a StatCom with energy storage can significantly reduce phase jumps and magnitude deviations of the bus voltage. Simulation results are also presented showing the benefits of active power compensation to certain applications with phase sensitive loads.

As far as voltage quality is concerned, the focus has been on the magnitude whereas less attention has been paid to the impact of the phase angle jumps that might accompany the voltage magnitude fluctuations caused by faults, sudden active load changes, etc. However, a phase jump in the supply voltage may cause malfunction of certain phase sensitive loads such as ac motors, line commutated converters, etc. For instance, an induction motor will suffer large torque stresses when the supply voltage makes a phase jump. The phase jump in the induction motor supply voltage causes a fast change in the phase of the rotating stator flux. However, the rotor flux cannot follow the stator flux immediately due to the inertia and the rotor time constant. Typically it takes approximately 100 ms for the rotor flux to catch up with the stator flux. Therefore, during this transient, a large current and a large deviation of the motor electrical torque from its steady state value is inevitable. The torque deviation will in turn cause motor speed fluctuations, which might be harmful to certain industrial process. Utilization of series voltage sags with phase jumps has been studied in chapter 2, which show that keeping the load voltage as the pre-sag condition by injecting required voltage in series can protect the load from both magnitude sags and phase angle jumps.

The voltage sag mitigation techniques investigated by the aforementioned works aim to reduce the impact of voltage sags on some particularly protected loads. This work will instead describe control strategies for a StatCom with capacitor energy storage to reduce the voltage phase jump and magnitude fluctuation at the PCC. Simulations and experimental results will be presented showing the benefits of energy storage and verifying the proposed control strategies. The study is focused on the voltage fluctuations caused by changes in the load connected at the PCC.

4.3 StatCom Model

Figure 4.1 shows the basic model of a StatCom which is connected to the ac system bus through a coupling transformer. In a StatCom, the maximum compensating current is independent of system voltage, so it operates at full capacity even at low voltage. A StatCom's advantages include flexible voltage control for power quality improvement, fast response, and applicability for use with fluctuating loads.

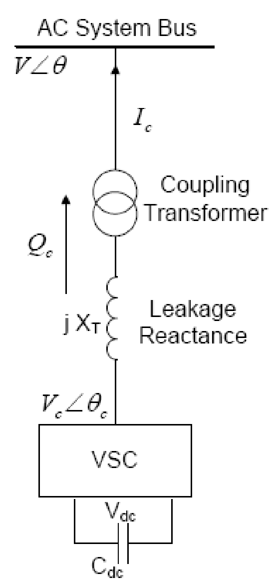

Figure 4.1 Basic model of a StatCom

The output of the controller Qc is controllable which is proportional to the voltage magnitude difference (*Vc-V*) and is given by (2)

$$Q_c = \frac{V(V_c - V)}{X} \quad (4.1)$$

The shunt inverter, transformer and connection filter are the major components of a StatCom. The control system employed in this system maintains the magnitude of the bus voltage constant by controlling the magnitude and phase shift of the voltage source converter's output voltage. By properly controlling iq, reactive power exchange is achieved. The DC capacitor voltage is maintained at a constant value and this voltage error is used to determine the reference for the active power to be exchanged by the inverter.

The StatCom is a static VAr generator whose output can be varied so as to maintain or control certain specific parameters of the electric power system. The StatCom is a power electronic component that can be applied to the dynamic control of the reactive power and the grid voltage. The reactive output power of the compensator is varied to control the voltage at given transmission network terminals, thus maintaining the desired power flows during possible system disturbances and contingencies.

StatComs have the ability to address transient event at a faster rate and with better performance at lower voltages than a Mechanical Switched Capacitor. The maximum compensation current in a StatCom is independent of the system voltage. Overall, a StatCom provides dynamic voltage control and power oscillation damping, and improves the system's transient stability. By controlling the phase angle, the flow of current between the converter and the ac system are controlled.

A StatCom was chosen as a source for reactive power support because it has the ability to continuously vary its susceptance while reacting fast and providing voltage support at a local node.

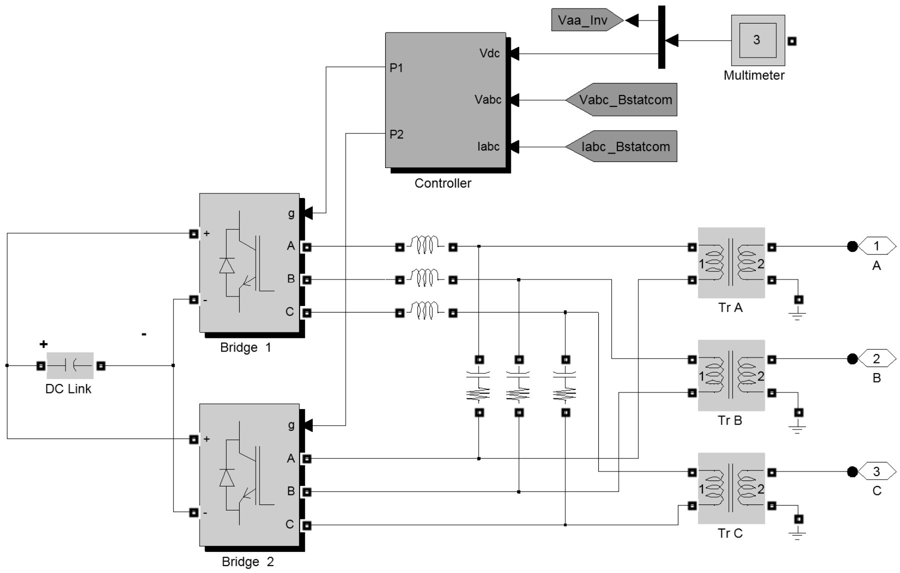

Figure 4.2 Control scheme of the StatCom

By controlling the phase and magnitude of the StatCom output voltage, the power exchange between the ac system and the StatCom can be controlled effectively. The outputs of the controller are id_ref and iq_ref which are the reference currents in the dq coordinates which are needed to calculate the power injections by the StatCom as in (3) and (4).

$$P_{\inf} = V_i(i_d \cos\theta_i + i_q \sin\theta_i) = v_d i_d + V_q i_q \qquad (4.2)$$

$$Q_{\inf} = V_i(i_d \sin\theta_i - i_q \cos\theta_i) = -v_d i_d + V_q i_q \qquad (4.3)$$

Where *d i* and *q i* are the reference d and q axis currents of the ac system. The Control variables are the current injected by the StatCom and the reactive power injected into the system.

The StatCom ratings are based on many parameters which are mostly governed by the amount of reactive power the system needs to recover and ride through typical faults on the power system and to reduce the interaction of other system equipment that can become out of synchronism with the grim. Although the final rating of the StatCom is determined based on system economics, the capacity chosen will be at least adequate for the system to stabilize after temporary system disturbances. The type of faults that the system is expected to recover from also determines the size of the StatCom. For example, a three phase impedance fault of low impedance requires a very high rating StatCom while a high impedance short circuit fault needs a lower rating device to support the system during the fault and help recover after the fault. The converter current ratings and the size of the capacitor also decide the capability of the StatCom.

The StatCom can be connected to the system at any voltage level by using a coupling transformer. The devices in a voltage source converter are clamped against over-voltages across the DC link capacitor bank to minimize losses and not have to withstand large spikes in reverse over-voltage.

4.4 Location of StatCom

Simulation results show that StatCom provides effective voltage support at the bus to which it is connected to. The StatCom is placed as close as possible to the load bus for various reasons. The first reason is that the location of the reactive power support should be as close as possible to the point at which the support is needed. Secondly, in the studied test system the location of the StatCom at the load bus is more appropriate because the effect of voltage change is the highest at this point.

The location of the StatCom is based on quantitative benefits evaluation. The main benefits of using a StatCom in the system are reduced losses and increased maximum transfer capability. The location of StatCom is generally chosen to be the location in the system which needs reactive power. To place a StatCom at any load bus reduces the reactive power flow through the lines, thus, reducing line current and also the I^2R losses. Shipping of reactive power at low voltages in a system running close to its stability limit is not very efficient. Also, the total amount of reactive power transfer. Available will be influenced by the transmission line power factor limiting factors. Hence, sources and compensation devices are always kept as close as possible to the load as the ratio $V_{nom} / \Delta V$ will be higher for the load bus under fault conditions.

4.5 Reactive Power Support from STATCOM

The amount of reactive power supplied by any compensating device depends on the voltage drop at the bus and its capabilities. For example, a StatCom can supply its maximum rated compensating current even at lower voltages. The rating of the StatCom also decides the maximum reactive power that can be supplied, but usually they have some extra capability called the transient capability which is available to the system for a short period of time. The reactive power supplied is also dependent on the immediate reactive power sources in the system.

4.6 Active Power Compensation Schemes with MATLAB

The following figure is a simple system drawn in MATLAB. The current through phases are monitored with a current meters, RMS meters are available to graph RMS voltage and power meters are also shown with scopes. Transmission lines can be modeled according to their tower configuration and other parameters.

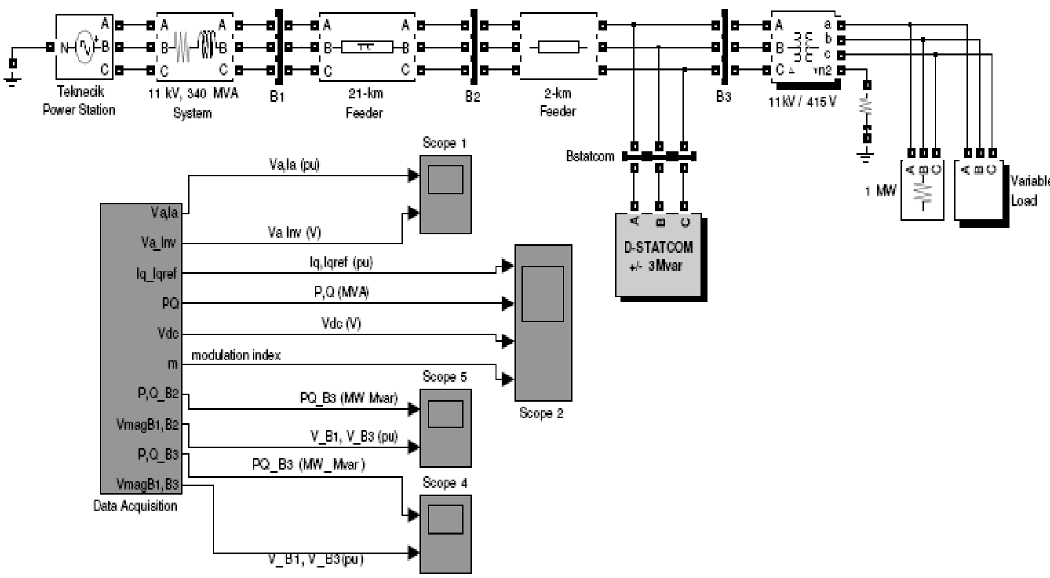

Figure 4.3 A simple system modeled in MATLAB

Runtime is initiated after a circuit is ready for simulation. The circuit is complied to check for errors and instantaneous plots are given. Flexibility in pausing a simulation and options for zoom are available. The following is an example of a plot from MATLAB.

Figure 4.4 shows the reactive power in the system with no compensation device. When the load occurs at = 0.02 sec, the synchronous generator immediately responds by supplying the maximum possible reactive power to support system.

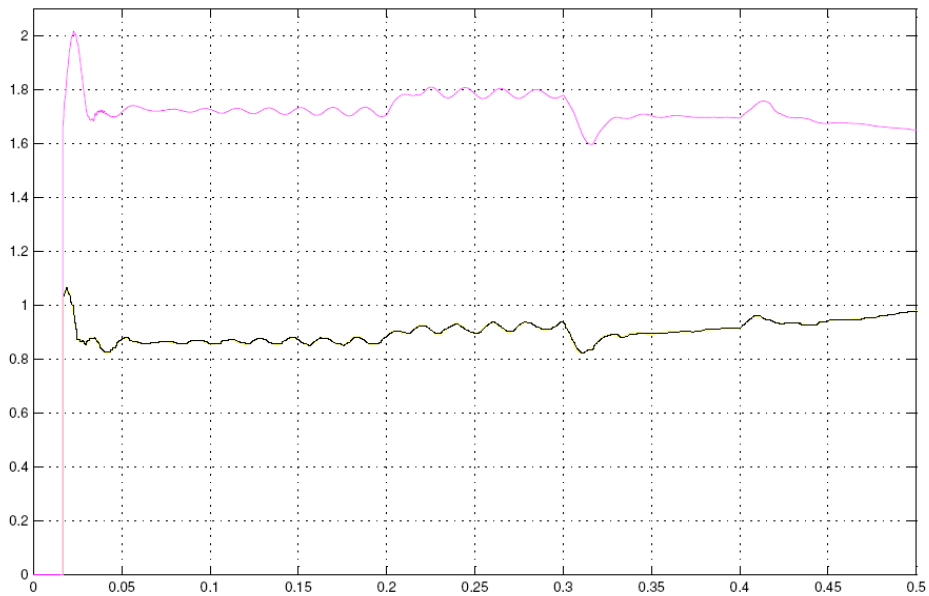

Figure 4.4 Reactive and active powers without StatCom

Figure 4.5 shows the reactive power in the system supported by StatCom compensation device. When the load occurs at= 0.02 sec, the StatCom immediately responds by supplying the maximum possible reactive power to load.

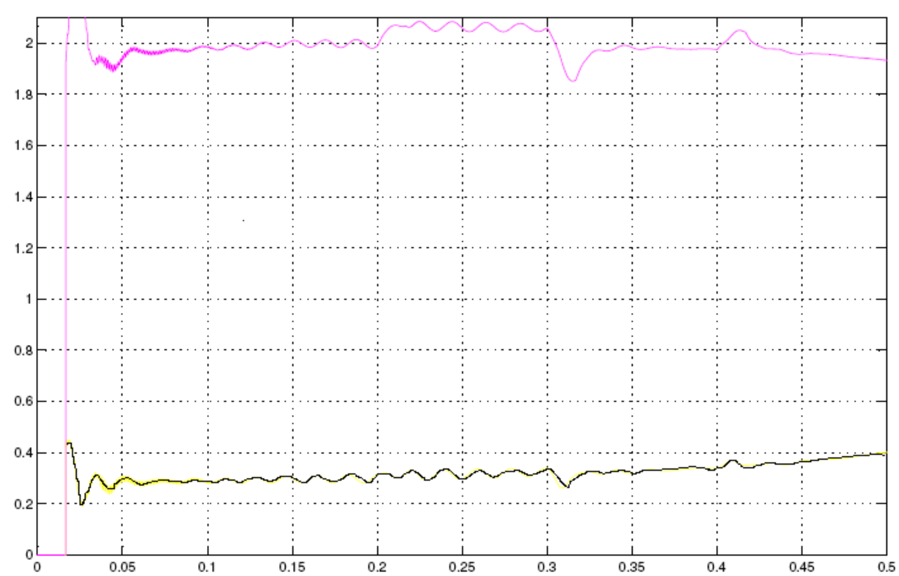

Figure 4.5 Reactive and active powers with StatCom

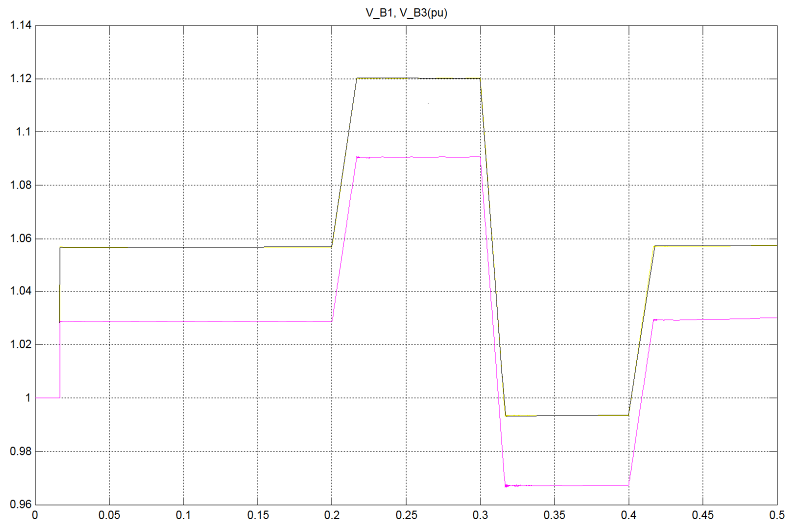

Figure 4.6 Load bus voltage without StatCom

Figure 4.6 show the load voltage for the system without StatCom. The load voltage response to this disturbance is oscillatory with about five times longer settling time than in the case with a StatCom.

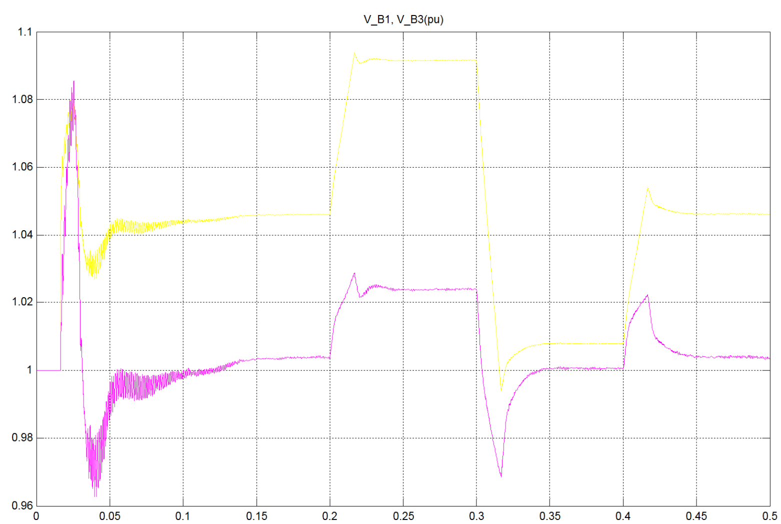

Figure 4.7 Load bus voltage with StatCom

Figure 4.7 show the voltage of the load bus in a system with the StatCom. The total reactive power supplied by the StatCom.

The StatCom supplies variable reactive power and supports voltage at the load bus thus reducing the oscillations in the load voltage. Also, the load has some wide power oscillations in the system without the StatCom that can be reduced with the help of a StatCom.

CHAPTER FIVE

Conclusion

5.1 Conclusions

In North Cyprus, the demand of electric energy keeps increasing. For this reason, electric energy prices increase. But in recent decades, the quality and price of electric energy should be in optimum level.

In power systems, active power should be supported by reactive power for power system's requirement. Reactive power is due to loaded generators and transmission lines. The technique of reactive power generation at load side is called Compensation. Unfortunately, electrical energy authorities in TRNC (Turkish Republic of Northern Cyprus) did not set rules or regulations for compensation. As a result of this, voltage drop, harmonics, over voltage, noises and unnecessary reactive power on lines often occur. In fact, these cause lack of quality on electricity. This work represents pilot design to overcome these problems in industries.

In this thesis, power system of Bozkaya Ltd was investigated. During the measurements and analysis, it is found out that voltage distortion is % 4 as shown in figure 3.9 which is too high when compared with international standards.

Figures 3.26 and 3.34 shows that 200 kW active power and 250 kVAr reactive power were used. Power factor was 0.56 as shown in figure 3.36, which is not an acceptable level.

As a proposed solution, mechanical switched capacitors are used. After reactive power compensation system was integrated to Bozkaya Ltd, the measurement was repeated. Figure 3.39 showing that voltage distorting were reduced. In figure 3.60 reactive power was reduced. Therefore, power factor increased up to 0.99, as shown in figure 3.65, which meets the international standards.

This work can be considered to be the first application of power factor compensation in North Cyprus industry. More modern techniques can be used for compensation. New modern techniques simulated in Matlab using StatCom. Figure 4.1 and 4.3 shows that the modern techniques are faster and adapting better to the load changes in a system.

By doing required regulations in Northern Cyprus and applying similar projects to other industrial areas, the energy efficiency could increase which will support economy.

5.2 Future Work

The investigations that have been performed by for only use conventional capacitors as energy storage, such as batteries, super-capacitors, etc, might be included in the future work.

The interface between energy storage and converter dc link should be studied. Large variations of the dc side voltage increase the rating of StatCom fact which is not desirable in most applications. In order to keep the dc side voltage at a reasonable and constant level, a certain kind of interface may be necessary. In additional, the protection of the converter dc side and the possibility of isolation between the energy storage and converter dc link might be studied in the future.

REFERENCES

[1] Dugan R.C., McGranaghan M.F., Santoso S., Beaty H. W., "*Electrical Power Systems Quality*", McGraw-Hill Companies, Inc., New York 2003.

[2] IEEE Standards Board, "IEEE std 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality", IEEE, Inc., New York June 1995.

[3] IEEE-SA Standards Board, "IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment", IEEE, Inc., New York 1998.

[4] Bollen M. H. J., Wang P., Jenkins N., "*Analysis and Consequences of the phase jump Associated With A Voltage Sag"*. Power System Computation Conference, Dresden, Germany, August 1996

[5] Mansoor A., Collin E. R., Morgan R. L., *"Effect of Unsymmetrical Voltage Sags on Adjustable Speed Drive" ,*Textile, Fiber, and Film Industry Technical Conference, 1997, IEEE 1997 Annual, 1997.

[6] Bollen M. H. J, "Understanding Power Quality Problems: Voltage Sags and Interruptions", IEEE, Inc., New York 2000.

[7] Wu J., Saha T. T., "*Simulation of Power Quality Problems on a University Distribution system",* Power Engineering Society Summer Meeting, 2000. IEEE, Volume: 4, 2000, Pages: 2326-2331 vol. 4.

[8] Lim P.K., "Understanding and Resolving Voltage Sag Related Problems for Sensitive Industrial Customers," Power Engineering Society Winter Meeting, IEEE, 2000.

[9] Yalçınkaya G., Bollen M. H.J. and Crossley P. A., *"Characterization of Voltage Sags in Industrial Distribution Systems,"* IEEE Transactions on Industry Applications, vol. 33 No. 4, July/August 1998.

[10] Stephen J. Chapman "Electric Machinery Fundamentals" , McGraw-Hill Companies, Inc., Fourth Edition

[11] Dugan R.C., McGranaghan M.F., Santoso S., Beaty H. W., "*Electrical Power Systems Quality*", McGraw-Hill Companies, Inc., 2004.

[12] M. McGranagham, D. Mueller, M. Samotyj M., "*Voltage sags in industrial systems*" Industrial and Commercial Power Systems Technical Conference, Pages 18-24, 6-9 May1991.

[13] K. Kobayashi, M. Goto, K. Wu, Y. Yokomizu, and T. Matsumura, “Power system stability improvement by energy storage type STATCOM,” in 2003 IEEE Power Tech Conference, Bologna, 2003.

[14] S. Samineni, B. Johnson, H. Hess, and J. Law, “Modeling and analysis of a flywheel energy storage system for voltage sag correction,” *IEEE Trans. On Industry Applications*, vol. 42, pp.42 – 52, Jan.-Feb. 2006.

[15] A. Arulampalam, J. Ekanayake, and N. Jenkins, “Application study of a STATCOM with energy storage,” in IEE Proc.-Gener., Transm., Distrib., pp. 373-384, 2003.

[16] J.E. Randolph Collins and A. Mansoor, ‘’Effects of voltage sags on AC motor drives,’’ in IEEE 1997 Annual Textile, Fiber and Film Industry Technical Conference, Greenville.,1997.

[17] J.D. Li, S. Choi, and D.M. Vilathgamuwa, “Impact of voltage phase jump on loads and its mitigation,” in *The 4th International Power Electronics and Motion Control Conference*, IPEMC 2004, pp. 1762-1766, 2004.

[18] K.Kahle and D. Jovcic, “Static Var Compensator or CERN’s Proton Synchrotron Particle Accelerator,” in *2nd International Conference on Critical Infrastructures*, Grenoble, France, October, 2004.