MODELING AND SIMULATING OF A WIND ENERGY SYSTEM WITH STATIC TRANSFER SWITCH USING PSCAD PROGRAM

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Ph.D. Dissertation

Graduate School of Sciences

Electrical and Electronics Engineering

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ABSTRACT

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Yusuf Alper KAPLAN

Anadolu University

Graduate School of Sciences

Electrical and Electronics Engineering Program

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In this thesis, classical power system stability, changes and challenges in the power system with installation of wind energy sources are given. An electromagnetic transient model of a system is composed by wind turbine system (WTS) and static transfer switch (STS). This system presents a technical review of power quality problems associated with the renewable based distributed generation systems and how STS plays an important role in power quality improvement. The highly developed graphic facilities available in PSCAD/EMTDC (Power System Computer Aided Design/Electromagnetic Transient including DC) were used to conduct all aspects of model implementation and to carry out extensive simulation studies. Recently, wind energy has attracted special interest because it is seen as a positive alternative to fossil fuels and many wind power stations are in service throughout the world. The output power of wind turbines fluctuates due to variations of wind speed. These power fluctuations cause frequency deviations, power outage and other power quality problem. In this thesis, a wind turbine system and grid system are connected with Static Transfer Switch and this system is developed by using PSCAD/EMTDC which contains powerful tools for the wind turbine simulation. A thyristor based STS provides a continuous supply for load with fast transfer between wind turbine system and grid system. The aim of the designed system is to improve the power continuity and power quality. A simulation model of wind turbine system and STS were developed, respectively and they were combined with simulation tool of PSCAD/EMTDC.

Keywords: Renewable Energy, Wind Energy, STS, Power Quality

ÖZET

Doktora Tezi

RÜZGAR ENERJI SISTEMININ STATIK ÇEVIRICI ANAHTARI ILE PSCAD PROGRAMINDA MODELLENMESI VE SIMÜLASYONU

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Bu tezde, güç sistemlerinde rüzgar enerji kaynağının kurulmasıyla birlikte klasik güç sistem kararlılığı, değişiklikleri ve sorunları verilmiştir. Rüzgar türbin sisteminden (RTS) ve statik transfer anahtarından (STA) oluşan bir sistemin elektromanyetik geçici modeli oluşturulmuştur. Bu sistem yenilenebilir tabanlı dağıtım üretim sistemlerine teknik bir bakış sunmuştur ve güç kalitesini iyileştirmekte STA'nın nasıl önemli rol aldığını sunmuştur. Model uygulamasının tüm yönlerini ve benzetim çalışmalarını yürütmek için PSCAD/EMTDC (Güç Sistemi Bilgisayar Destekli Tasarım / DC içeren Elektromanyetik Geçici durum) programının mevcut yüksek geliştirilmiş grafik özellikleri kullanılmıştır. Son zamanlarda rüzgar enerjisinin fosil yakıtlara pozitif bir alternatif olarak görülmesi ve bir çok rüzgar güç istasyonlarının tüm dünyada hizmette olmasından dolayı rüzgar enerjisi özel bir ilgi çekmektedir. Rüzgar türbininin çıkış gücü rüzgar hızındaki değişikliklerden dolayı dalgalanır. Bu güç dalgalanmaları frekans sapmalarına, elektrik kesintisine ve diğer güç kalite problemlerine neden olur. Bu tezde, rüzgar türbini sistemi STA ile şebekeye bağlanmıştır ve bu sistem rüzgar türbini simülasyonu için güçlü elemanlara sahip olan PSCAD/EMTDC programı ile geliştirilmiştir. Bir tristör tabanlı STA, rüzgar türbini ve şebeke sistemi arasında hızlı transferi ile yük için sürekli bir kaynak sağlar. Tasarlanan sistemin amacı güç sürekliliğini ve kalitesini iyileştirmektir. Rüzgar türbini sisteminin ve STA'nın benzetim modeli sırasıyla geliştirilmiştir ve bunlar PSCAD/EMTDC programında birleştirilmiştir.

Anahtar Kelimeler: Yenilenebilir Enerji, Rüzgar Enerjisi, STA, Güç Kalitesi

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I would also thank to my family and friends for their patience and moral support throughout this exhausting work. I want to express my gratitude to my father and my mother for their confidence and support.

Yusuf Alper KAPLAN

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

STS	: Static Transfer Switch
WT	: Wind Turbine
WTS	: Wind Turbine System
CPP	: Custom Power Park
WTG	: Wind Turbine Generator
PMSG	: Permanent Magnet Synchronous Generator
DFIG	: Double Fed Induction Generator
IG	: Induction Generator
WPP	: Wind Power Plant
WECS	: Wind Energy Conversion System
PQ	: Power Quality
ρ	: Density of air
λ	: Tip speed ratio
β	: Blade pitch angle
θ	: Pitch angle
C_p	: Power Coefficient
E	: Energy
P	: Power
V_w	: Wind Speed
W_R	: Rotor speed
R	: Radious of blade
τ	: Time constant

T_W : Turbine torque

T_E : Electrical torque

Va, b, c : Phase voltages

$Vd, q, 0$: Park transformation voltages

Ia, b, c : Line currents

Vp : DC reference voltage

$Etot$: Tolerance limit

1 INTRODUCTION

1.1 Objectives of the Thesis

As the price of the fossil fuels is rising and risk for their availability is appearing worldwide; and above causes as the environmental problems and climate change due to excessive use of fossil fuels are being considered seriously by countries, renewable energy, especially the wind energy is becoming more and more important [1]. There is a strong rate of increase for wind energy installations in all developed countries. Due to the fact that wind energy has become such an important electric power source, stable operation also during grid disturbances is needed [2, 3]. Currently, wind energy is seen as a positive alternative to fossil fuels and also a way to assist the expansion of local economies in future. The world will use renewable energy instead of using fossil fuels in order to meet the demands of the world's energy. Energy planning and management are necessary to promote wind energy which has a vital importance for the development and future of all countries.

Recent technological improvements on wind energy systems and the incentives provided by the governments have increased the penetration level of wind power into the grid. This phenomenon forces the transmission and distribution system operators to revise their grid codes. Moreover, these developments force the wind turbines stay connected to the grid during the disturbances in order to enhance system stability. This work is devoted to the modeling of variable speed wind turbines and the investigation of fault-ride through (FRT) capability of wind turbines for grid integration studies [4].

Hence, more renewable energy sources, especially the wind power plants are being installed in power systems, both as new additional units and as replacement of custom power parks (CPP). As discussed above, CPPs, which are based on synchronous generators directly connected to the grid, have inherent capabilities to provide stable power system operation and participate in the balancing act. The replacement of CPPs with wind power plants (WPPs) has influence on the security of the supply since the WPPs do not exactly replace the functional behavior of the CPPs, due to the specific characteristics of the WPPs.

The increasing use of sensitive loads makes it necessary to solve power quality problems and to use custom power devices. This study presents electromagnetic transient models of a system which is composed by wind turbine system and static transfer switch.

The main purpose of proposed system is to supply specified power quality for customers, which includes an acceptable combination of following features.

- Power must be continuous.
- Duration and magnitude of the voltage reductions must be in specified limits.
- Duration and magnitude of the overvoltage must be in specified limits.

Until recently, voltage reductions and short term outages were not an issue, the number of cumulative hours of interruptions per year has been the benchmark measure for reliability has been changing, and the pace of change has accelerated. Studies of cumulative monitoring of events at a large number of distribution substations show that most of the sag events are of short duration of a few cycles and less than 40% voltage reduction and only 1% of events with voltage reduction of less than 80%. With the availability of two independent feeders which are WTS and alternate feeder at the distribution substation, and high speed solid state transfer switches, a large percentage (70–90%) of the events can be eliminated in a much more efficient and economical manner than the customers own solutions.

1.2 Outline of the Thesis

In this thesis, we focus on mainly increasing demands for power quality and fail-safe operation of WTS. Simulation study of the proposed system is presented. Two different feeders are used to protect the sensitive load terminal voltage. Additional issues such as the load transfer through a static transfer switch, detection of sag/fault etc. are also discussed. The concepts are validated through PSCAD/EMTDC simulation studies on a sample distribution system.

In Section 2, the wind turbines are briefly explained. The structure and the characteristics of the wind turbines are given in detail. Then power system connection issues of wind energy conversion systems and the control systems of wind turbines are explained. The wind turbine's generators and subroutine of generators are mentioned. Finally the all component of wind turbine in PSCAD/EMTDC program are given in detail. The wind turbine which is used in proposed system is composed in PSCAD/EMTDC program.

In Section 3, power quality terms and definitions, types of the power quality problems, overview of sources of the power quality problems, negative impacts of the power quality problems and power quality standards are described. The impacts of wind farms on power quality are presented.

In Section 4, the characteristics of STS and principle of operation are explained in detail. An effective way to improve power quality and reliability of sensitive customers is to use a static transfer switch. This device enables a very fast change in the supply of the customer to an alternate feeder providing adequate power conditioning for several power quality problems, such as voltage sags, swells, and interruptions. In this study, an analytical model of STS is modeled and its performance is simulated for different faults scenarios using the PSCAD/EMTDC program. The performance of static transfer switch for feeder reconfiguration has been assessed and evaluated. Static transfer switch restores the voltage to pre-fault conditions.

In Section 5, the proposed system which is the combination of STS and wind turbine is completely modeled in PSCAD/EMTDC program. Simulation results for different case studies are given and evaluated. In these cases, the performance of the proposed system for different fault type, sag/swell and interruption are analyzed; dynamic response of system is also investigated.

In Section 6, finally the importance of wind turbines which is connected to the network has been indicated. The simulation results are generally evaluated and the advantages of the proposed system are emphasized.

1.3 Literature Survey

In this chapter a literature survey of the proposed system operation, modeling and control will be studied. The WTS is composed by wind turbine and STS. There are many articles regarding the modeling of STS and wind turbines, respectively. The basic aim of this thesis is to develop simulation models of WTS. This thesis deals with the modeling of Custom Power topologies for WTS in PSCAD/EMTDC. The related survey studies are presented under the following heads.

1.3.1 Literature Review of WTS

Koc and Guven [4] have generally assessed the current system of wind turbine systems and they presented different variable speed wind turbine models in detail. Also requirements of grid codes for wind power integration were be discussed regarding active power control, reactive power control and fault ride through (FRT) capability. Investigation of the wind turbine FRT capability is the main focus of this study. Some methods were used for different types of wind turbines to overcome these power quality problems. These methods were also explained in detail. Permanent magnet synchronous generator (PMSG) and doubly-fed induction generator (DFIG) were modeled in PSCAD/EMTDC. Grid-connected models of them were also implemented. Bahandare et. al. [5] presented the relation of power (P) and power coefficient (C_p) with reference to variable wind speed. Also the wind connected information collection for study of this idea and manufacture of generator. In wind framework comprises of wind turbine, gear box, generator, and control electronic apparatus and lattice or standalone load. Power depends on many variables in wind system one of them is power coefficient. A mathematical equation of the alternative energy tested those changes in power & power coefficient with relevancy variable speed wind system. The related information was collected from SUZLON wind power plant. Tahani et. al. [6] initially briefly introduced different types of wind turbine power control systems, and then they mentioned advantages and disadvantages of them. They evaluated the turbines in practical and theoretical aspects. At the following, governing generated power formulation was proved briefly, then the effective parameters on power, e.g. wind velocity, wind temperature were studied and simulated in MATLAB software. Then they investigated practical data from an actual stall control wind turbine entered and related curves. Based on these data, performance of an actual pitch control wind turbine was estimated and related curves were investigated. At the following, using Weibull theory, real power-time curve and estimated power-time curve, monthly produced energy of turbines were estimated. And finally they defined Specific Power Performance (SPP) and showed that pitch control system produced energy more than stall control system at the same rotor swept area. Liserre et. al. [7] generally mentioned and reviewed the most-adopted wind-turbine systems, the adopted generators, the topologies of the converters, the generator control and grid connection issues, as well as their arrangement in wind parks. Kadam and Kushare [8] provided an overview of different wind turbine concepts and they explained possible different generator types. They also described the basic configurations and characteristics of different wind generator systems based on contemporary wind turbine concepts with their advantages and disadvantages. Also Critical Power Quality issues & problems related with Grid connections were also discussed. Kenneth [9] presented a permanent magnet synchronous generator (PMSG) variable speed wind turbine connected to an electrolyzer and a battery model system. Hydrogen gas could be produced from the model system, when a variable wind speed is applied to the PMSG driven variable wind turbine. He presented the simulation results and showed the nature of some of the variables of the PMSG wind driven turbine and the hydrogen gas produced as the wind speed varies with time. Simulations were run in PSCAD/EMTDC. Cabral and Zita [10] presented a study concerning the expansion of an already existent wind farm, located in Praia, the capital of Cape Verde Republic. This study includes results from simulation studies that have been undertaken using PSCAD software and some economic considerations. Nirmala et. al. [11] generally explained electric grid effects of WTS. The effects of the power quality measurements are the active power, reactive power, variation of voltage, flicker, harmonics, and electrical behavior of switching operations. The installation of wind turbine with the grid causes some power quality problems which were generally mentioned by studying this paper. The grid connected wind energy generation system for power quality improvement by using STATCOM-control scheme was simulated using SIMULINK in power system block set. This relives the main supply source from the reactive power demand of the load and the induction generator (IG) in this proposed scheme. The improvement in power quality on the grid has been presented here according to the guidelines specified in IEC-61400 standard (International Electro-technical Commission) provides some norms and measurements.

1.3.2 Literature Review of Power Quality

Teke et. al. [12] described the several types of the more common power quality disturbances which are current harmonics, flicker, imbalance, voltage sag, voltage swell and interruption. They presented the causes, effects and mitigation techniques for each disturbance. They also explained the concept of custom power and mentioned possible solutions to PQ disturbances. With the increasing number of power quality disturbances, the custom power devices such as STS, APF, and DVR. Both power suppliers and customers can satisfy the standard limits such as IEEE, IEC, ANSI, EN, CIGRE, and BNS using custom power devices. Almeida et. al. [13] presented the main Power Quality (PQ) problems with their associated causes and consequences. They characterized these PQ problems and gave economic impacts of them. Finally, some solutions to mitigate the PQ problems were presented. Yuvaraj et. al. [14] simulated The FACTS Device (Static Compensator) control scheme for the grid connected wind energy generation system by using MATLAB/SIMULINK program to improve the power quality. The intended result of the proposed scheme relives the main supply source from the reactive power demand of the load and the induction generator. They have consolidated the feasibility and practicability of the approach for the applications considered from the obtained results. Muljadi et. al. [15] gave different aspects of power quality which were described within the wind power generating plant. They have also shown that the reactive power compensation, strategically placed, affects the voltage behavior of a very large area consisting of many wind power plants. Finally, they showed that capacitor compensation used by induction generators in a wind power plant can lead to self-excitation and harmonics.

1.3.3 Literature Review of STS

Meral et. al. [16] presented extended custom power park and they described some CPP devices such as STS. They explained high power quality and improved power services which were achieved with CPP. The loads of CPP receive superior quality power compared to the regular power of ordinary loads. Therefore, more sensitive load gets more power quality in the CPP. Mahmood and Choudhry [17] have generally assessed the performance of static transfer switch for feeder reconfiguration and they evaluated the simulating results of STS. Static transfer switch restores the voltage to pre-fault conditions. The simulation results of various case studies showed that the quality of power is poor for preferred network feeder, without STS. Also, the value of voltage sag, at critical nodes is greater than that of the permissible limits (5%). However, in this area of deregulation and restructuring environment, it is a challenging task for utilities to provide uninterruptible power to the consumers. Sannino [18] mentioned the various PQ problems. An application of a Static Transfer Switch in an industrial plant containing many induction motors has been treated. He briefly emphasized operating principle and structure of the STS. Factors which determine the actual transfer time have been explained. Problems that may arise in plants with high amount of induction motor load have been illustrated by means of an example realized with ATP (Alternative Transients Program) simulation. Results demonstrate the improvements achieved with the installation of a STS. Moreover, it has been pointed out that the time needed for completing the transfer becomes higher with induction motor, as compared with static load. Mokhtari and Iravani [19] showed that the system for symmetrical disturbances, when the main source leads the backup source. From the obtained results the load transfer time decreased compared to the other two cases (i.e., in-phase or lagging main source), for the same operating conditions. The results also showed that the effect of phase difference on load transfer time can be neglected when the main source is subjected to unsymmetrical faults. It is also shown that the phase difference can affect the cross current phenomenon during a transfer process. Sannino [20] explained the operation of the Static Transfer Switch for protection of sensitive loads against voltage sags. He calculated maximum detection times for various types of events. Conditions for fast switching have been evaluated analytically, depending on amplitude and phase of the two source voltages and on the load to be protected. Results, also validated by simulation, show that the often claimed transfer time lower than 4 ms cannot be guaranteed in any condition: rather, the transfer time depends on the type of disturbance and on the actual operating conditions of the power system when transfer is initiated. Shu-jun et. al. [21] presented a new effective solid static transfer switching (SSTS) control strategy. Through SSTS, thyristor current's polarity was determined by detecting the thyristor voltage's polarity. And then the corresponding thyristor's switch was controlled. This new strategy overcomes some defects of traditional control strategy based on the current polarity detection and shortens the SSTS system's switching time. Simulation results based on EMTDC / PSCAD show that: the switching control strategy fast, secure. Using this strategy, dual power supply SSTS device's switching time can be less than 5ms. Loop current between the main and backup power supply does not appear in the switching process. Iravani [22] evaluated time-domain simulation results of two thyristor based STS systems and from obtained results, he described this system. The objectives are to provide guidelines for digital simulation of STS systems and to provide a basis for accuracy evaluation of simulation studies used for STS performance analysis. He used the PSCAD/EMTDC simulating program to show the performance of system.

2 WIND TURBINE SYSTEMS

2.1 Overview of Wind Energy

Recently, due to the reduction of available energy resources and the continuous increase in energy demand; many countries in the world, especially EU countries, trend toward using renewable energy resources in energy production. Wind energy is currently one of the most cost-competitive renewable energy technologies in the world when its technical, geographical and social issues are considered. It offers a virtually unlimited, clean and emissions free energy supply. Hence, using wind as a source of power is essential in energy production. Many developed countries identify long-term plans and implement the policies depend on these plans to exploit wind energy potential more efficiently.

Figure 2.1 shows the installed wind power capacity in the world from 2004 to 2013. The total installed wind energy capacity of the World is 318.137 GW, this value is 121.474 GW for Europe. At the end of 2013, nearly 36 GW new wind power installed and the total capacity reached 318.137 GW in the world [23]. This figure shows that there is a very large and growing global demand for emissions-free wind power almost everywhere in the world.

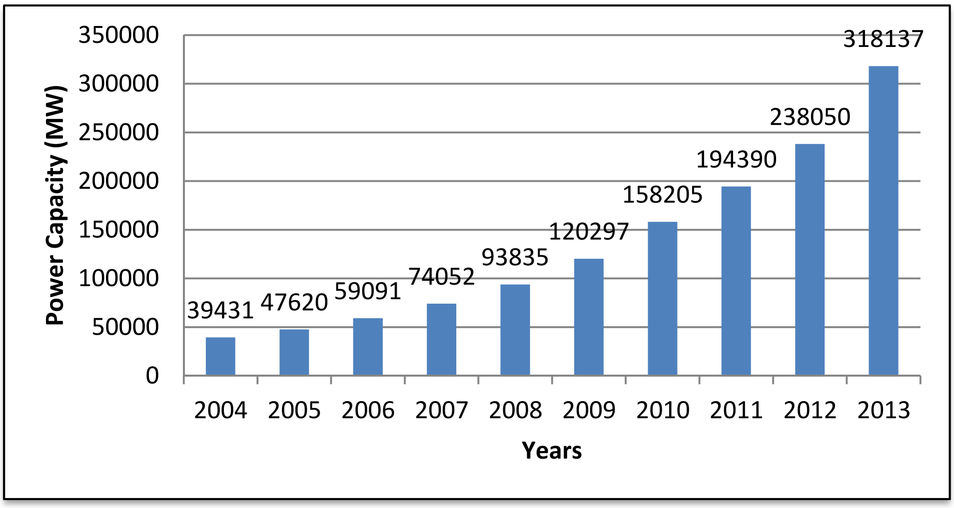

Figure 2.1 Installed wind power capacity in the World [23].

It is clearly seen in Figure 2.2 that installed wind power capacity is very small for our country. Owing to the unstable condition of energy system and the lack of renewable energy policies in our country, existing wind energy potential has not been efficiently used. Although wind energy potential of Turkey is 48.000 MW, installed wind power is only 2.959 GW until 2014.

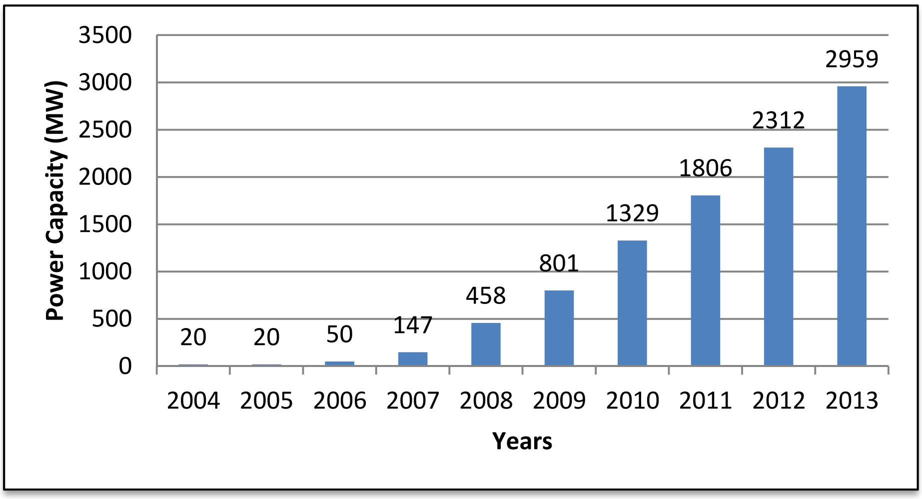

Figure 2.2 Installed wind power capacity in Turkey [23].

2.2 Wind Turbine Characteristics

In the wind turbine, wind energy can be efficiently captured by the variable speed control. In a recent wind power generation, synchronous generator with the inverter system is almost adopted. The variable speed control and the power factor control are executed in the wind power generation.

The kinetic energy of the air through the rotor blades is given by

$$E_{wind} = \frac{1}{2}\rho V v_w^{\ 2} \tag{2.1}$$

Where, ρ is the density of air (kg/m^3), V is the volume of air and V_w is the velocity of wind (m/s).

$$P_{wind} = \frac{1}{2}\rho A_R v_w^{\ 3} = \frac{1}{2}\rho \pi R_t^2 v_w^{\ 3} \tag{2.2}$$

Where, A_R is the swept area of the blades (m^2), R_t is the length of blades (m).

It is impossible to extract all the kinetic energy from the wind. The fraction of power harnessed by the wind turbine is given by its coefficient of performance, C_p. In practice, the power is smaller because the wind speed behind the hub is not 0. This efficiency is characterized by the Betz coefficient (given by Bernouilli's equations), also called the Power Coefficient C_p:

$$C_p = \frac{p_{real}}{p_{th}} \tag{2.3}$$

$$C_p = \frac{1}{2}\left(1-a^2\right)\left(1+a\right) \tag{2.4}$$

a is the tip speed ratio which is the ratio of wind speed behind the rotor to wind speed in front of the rotor.

$$P_{mec} = c_p\left(\lambda,\beta\right).P_{wind} \tag{2.5}$$

The power coefficient expression can be obtained from empirical expressions deduced from experimental tests, or derived analytically from fluid dynamics theory applied to a certain turbine type. where $C_p(\lambda,\beta)$ is the power conversion coefficient expressed as a function of the blade pitch angle β and the tip-speed ratio λ. The tip-speed ratio is defined as:

$$\lambda = \frac{W_r.R_r}{V_w} \tag{2.6}$$

where, R_r is the radius of the blade .

$$C_p\left(\lambda,\beta\right) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{18.5}{\lambda_i}} \tag{2.7}$$

Where, $$\lambda_i = \frac{1}{\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.085}{\beta^3 + 1}} \tag{2.8}$$

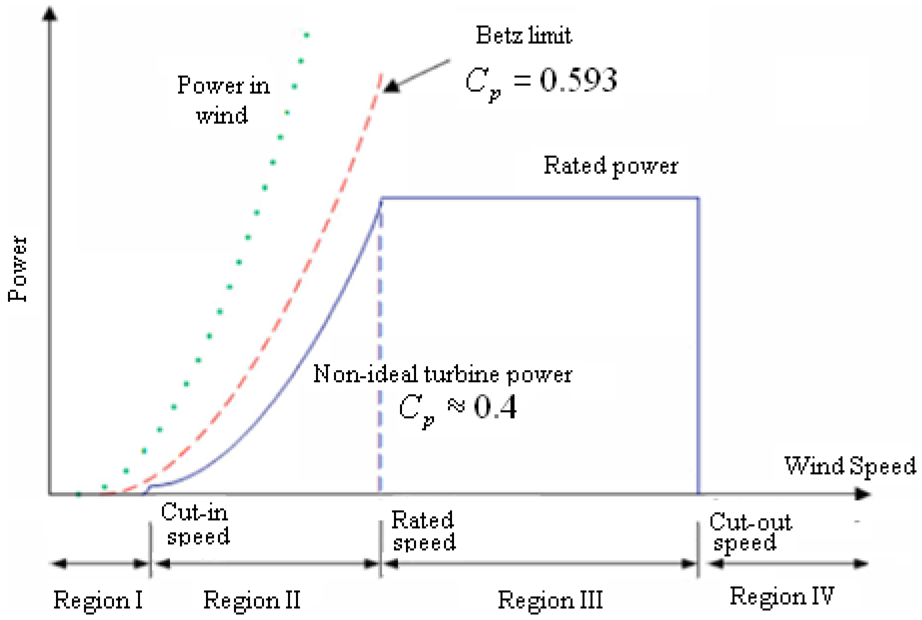

Figure 2.3 Wind Turbine Characteristics.

Figure 2.3 shows that totally different completely wind speed generates different power, when cut-out speed power goes to constant.

- Region I : $V_{wind} < V_{cut\text{-}in}$, it means that turbine does not turn P = 0.
- Region II : Cut-in speed, the wind speed at that the turbine begins to get power for this system $V_{cut\text{-}in} = 4$ m/s.
- Region III : Rated speed, the wind speed at that the wind turbine arrives at appraised turbine Control. Ordinarily this could be frequently, nonetheless not consistently, the maximum power.
- Region IV : Cut-out speed, the wind speed at that the turbine is pack up to stay masses and generator control from arriving at harming levels for this system $V_{cut\text{-}out} = 25$ m/s [5].

2.3 Power control systems of WTS

2.3.1 Stall control systems

Blade design of this type of turbines is so that they naturally control the power generated by turbine. These rotors with constant pitch are designed to operate near the optimal tip speed in moderate winds. Passive stall control relies on inherent machine characteristics in the way that the aerodynamic power is limited when the wind speed increases. In stall control used turbines, an asynchronous generator is generally used by which the rotor rotational speed is kept nearly constant. A rotating tip which is located at the end of the rotor is generally used as the aerodynamic brake. This device which limits the rotor momentum by applying the opposite torque due to the drag force is activated by centrifugal force and it is subjected against the wind flow with a 90° angle [6].

2.3.2 Pitch control systems

In pitch control used turbines, all blades of turbine can about the root and also angle can change instantly throughout the rotor length. One of the most conventional mechanical mechanisms of the rotor pitch control comprises a piston inserted in the main shaft. This piston arranges the rotor pitch angle by its reciprocating movement using a mechanism installed forward the turbine hub. Clearly, the lift coefficient has a direct relation with the attack angle. Therefore, we can say that if we decrease the attack angle lift force and the power reduces at the same time. Thus, the output power of the turbine can be controlled by pitch control system with rotating the rotors. The generator torque of the wind turbine with pitch control is controlled to obtain constant electrical output power above the rated wind speed. The blade pitch is controlled to keep the rotor speed close to the rated rotor speed. As an example, Figure 2.4 depicts the dependency of the aerodynamic efficiency C_p on the tip speed ratio λ and the blade pitch angle θ. For this blade, maximum energy capture from the wind is obtained for θ =0 and λ. To keep C_p at its optimum value over the wide range of wind speeds, the rotor speed should be proportional to the wind speed. Between the cut-in wind speed and rated wind speed, the wind turbine of this concept is operated at fixed pitch with a variable rotor speed to maintain an optimum tip speed ratio. When the rated power is reached, the generator torque controls the electrical power output, while the pitch control is used to maintain the rotor speed within acceptable limits. During gusts the generator power can be maintained at a constant level, while the rotor speed increases. The increased energy in the wind is stored in the kinetic energy of the rotor. If the wind speed decreases, the aerodynamic torque decreases, which results in a deceleration of the rotor blade while the generator power is kept constant. If the wind speed remains high, the rotor blade pitch can be changed to reduce the aerodynamic efficiency and torque, once again reducing the rotor speed. Therefore when the pitch control concept is used in the wind turbine, the power can be limited to the designed power by pitching the blades, so that the power ratings of generator, converter and cables are all same with the designed power [24].

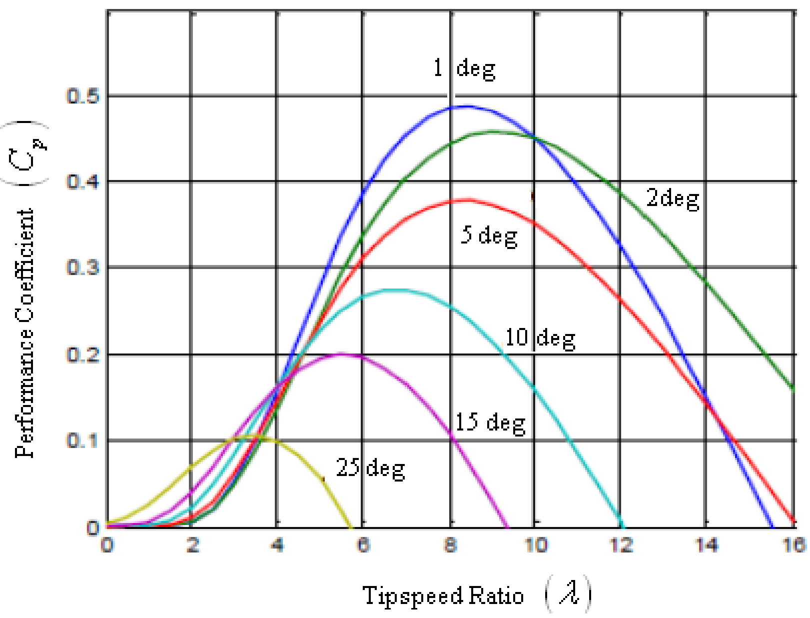

Figure 2.4 C_p-λ characteristics of a typical wind turbine.

2.3.3 Active stall control systems

The active speed stall control concept is a kind of passive stall control, in which rotor blades are directly fixed on the hub without a pitch mechanism. Therefore the pitch angle of the rotor blades of this concept is zero. There is another method which uses the combination of pitch and stall control systems. In this system, to achieve the maximum efficiency at low wind speeds the rotors are repositioned like a wind turbine controlled by pitch. At high speeds, the rotors are rotated slowly against the wind to get stall. With this type of control, a smoother limited power is achieved compared with pitch control turbines. Combining both systems facilitates the required stops in emergency cases and restarting wind turbines compared with stall control. Aerodynamic power and torque of the wind turbine with this concept are limited by reducing the rotor speed at wind speeds above rated. The rotor speed is controlled by regulating the generator torque. Therefore the turbine with this concept can be operated at any desired tip speed ratio within the design limits of the generator and rotor blades. The rotor speed is accelerated by decreasing the generator torque below the aerodynamic torque. The rotor speed is decelerated by increasing the generator torque over the aerodynamic torque. However, it is a disadvantage of this concept that the generator must reduce the rotor speed even if the wind speed increases in order to force the rotor blades into stall. This means that the maximum torque of generator must be larger than the torque produced at rated power [24].

2.3.4 Yaw control systems

In this control system, instead of limiting the output power using pitch or stall controls, the turbine yaw is controlled. The yaw system located in the junction of the nacelle and the tower; is used to make the yaw angle and wind direction equal. The wind turbines which use pitch and stall control systems generally have yaw control system. These type systems receive the data related to wind flow direction from the turbine wind gauge and tries to turn the nacelle, therefore the maximum air flow rate enters the rotor disk. In a wind turbine which is controlled by yaw system, at too high wind speeds, the rotor turns against the wind direction to reduce the effect of the air flow rate in rotor, and thus, the output power of the turbine decreases [6].

2.3.5 PI control of the System

PI (proportional and integral) and PID (proportional, integral and derivative) controllers are widely used throughout industry and are a good starting point for many wind turbine control applications. A PID controller can be written in terms of the Laplace variables (similar to a differentiation operator).

$$y = \left(\frac{Ki}{s} + Kp + \frac{K_d s}{1 + s\tau} \right) x \tag{2.9}$$

Where x is the input error signal to be corrected and y is the control action. K_i, K_p and K_d are the integral proportional and derivative gains. The time constant τ prevents the derivative term from becoming large at high frequency, where it could respond excessively to signal noise. K_d is zero in a PI controller.

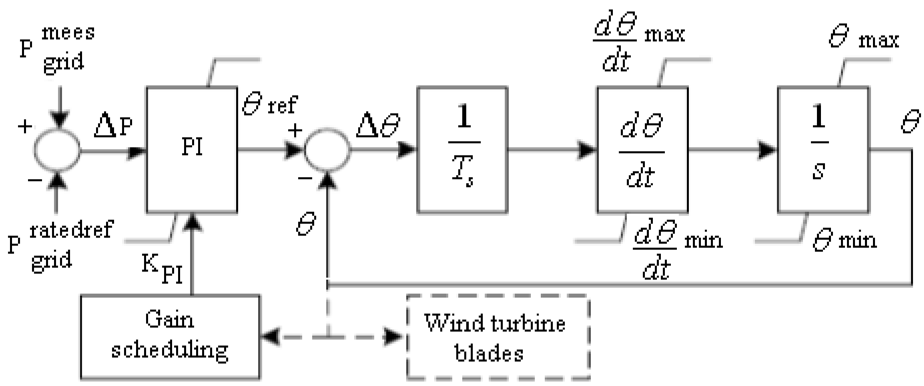

Figure 2.5 The power limitation control loop.

The block diagram of power limitation control loop is shown in Figure 2.5. The task of the power limitation controller is to increase or decrease the pitch angle in the power limitation strategy, i.e. in order to limit the generated power at rated value. The error signal ΔP which is the difference between measured power and the rated reference value of grid power, is sent to a PI controller, so the PI controller generates the reference pitch angle θ_{ref}. This reference is further compared to the actual pitch angle θ and then the error Δθ is obtained and then it is corrected by the servomechanism. In order to get a realistic response in pitch angle control system, the servomechanism model accounts for a time constant Ts and the limitation of both the pitch angle and its gradient. The pitch angle of the blades is the power limitation controller [25].

These Equations reveal that the power absorbed by the wind turbines depends upon the operational speed of the turbine and the blade pitch angle. In a variable speed wind turbine, the turbine speed can be controlled to achieve an optimal tip speed ratio (λ), and therefore maximum efficiency can be achieved over a range of wind speed. When the wind speed varies, the turbine rotor and generator speed vary, while the torque remains fairly constant. Thus, the mechanical stress is reduced. Maximum power point tracking over a wide speed range enables increased energy capture, improved power quality, and reduced mechanical stress on the wind turbine. Apart from this, the turbine speed should be limited within safe design limits in presence of strong wind conditions. Stall control has been used for fixed speed wind turbines. Fast pitch control mechanism is used to regulate the power in variable speed wind turbines [26]. The blades can be turned out or into the wind as the power output varies. Such a fast control provides good power control, assisted start-up and emergency stop.

2.4 Grid Connection of WTS

Moving mass of wind possesses kinetic energy. For a long time wind mills and sails have been used for harnessing the wind energy. Nevertheless, conversion to electrical energy is a recent development of the twentieth century. Depleting fossil fuel reserves and the focus on sustainable development through the use of renewable energy sources have been the key motivators for the rapid development of wind energy conversion systems (WECS) in the last couple of decades. Large wind turbine generators of the order of 2–6 MW have been developed and the units of 10 MW sizes are under development [7]. Tens or hundreds of wind turbine generator units are installed and connected together through a network of medium voltage cable systems forming the collector system network, thereby forming a large wind farm. A growing penetration of wind energy into power system demands that the wind farms behave more like a power plant, and they comply with the rules of grid connection, or the grid code requirement (GCR). Hence, these days the wind farms are referred to as wind power plants.

Last technological improvements on wind energy systems and the incentives provided by the governments have increased the penetration level of wind power into the grid. This phenomenon forces the transmission and distribution system operators to revise their grid codes. Moreover, these developments force the wind turbines stay connected to the grid during the disturbances in order to enhance system stability [27].

2.5 Wind Turbine Generators (WTG)

A wind turbine generator comprises of a wind turbine for harnessing the kinetic energy of the wind into the mechanical energy of the rotating shaft which drives the generator. The three-blade, upwind horizontal axis wind turbine (HAWT) is the most popular turbine. It has three air-foils or blades connected to a central hub assembly mounted on the top of a high tower. The drive train, generator and the transformers are usually housed in the nacelle on the tower. A gear box assembly may be used to rotate the generator at a sufficiently high speed for electrical power generation. The electrical generator transforms mechanical energy into electrical energy. Commercially available wind generators installed at present are squirrel cage induction generator, doubly fed induction generator, wound field synchronous generator (WFSG), and permanent magnet synchronous generator. Based on rotational speed, in general, the wind turbine generator systems (WTGS) can be split into two types:

- Fixed speed WTGS
- Variable speed WTGS

2.5.1 Fixed Speed WTGS

The wind turbines of early installations operate at near constant speed. This means that regardless of the wind speed, the angular speed of the rotor is fixed and determined by the frequency of the grid, the gear ratio, and the generator layout. They are designed to achieve maximum efficiency at one particular wind speed. Induction generators and the wound rotor synchronous generators have been applied, where the majority has been based on the induction generator. In order to operate the fixed speed systems at low and high wind speeds efficiently, pole changing is generally employed. Smaller number of pole pairs is used at high wind speeds and higher number at lower wind speeds. This allows the generator to operate at a different mechanical speed without affecting its electrical frequency [28]. A fixed speed WTGS has some advantages because of it has superior characteristics such as brushless and rugged construction , which consists of a conventional, directly grid coupled squirrel cage induction generator, low cost, maintenance free, and operational simplicity. The amount of the generated power changes the slip and hence the slip changes the rotor speed. The variations of the rotor speed which are nearly 1 to 2 % of the rated speed is very small. Therefore, this type of wind energy conversion system is normally referred to as a constant or fixed speed WTGS. We can say that it has many advantages because it has constant speed system. Therefore, the list price of fixed speed wind turbines tends to be lower than that of variable speed wind turbines. However, constant speed wind turbines must be more mechanically robust than variable speed wind turbines. Because the rotor speed of turbine cannot be varied with wind speed change, fluctuations in wind speed translate directly into drive train torque fluctuations, causing higher structural loads than with variable speed operation. This partly cancels the cost reduction achieved by using a relatively cheap generating system.

2.5.2 Variable Speed WTGS

Variable speed wind turbines with power electronic converters which is in using variable speed wind turbine (VSWT) driving a doubly fed induction generator, wound field synchronous generator or PMSG has become more common than traditional fixed speed wind turbines. In order to maintain the suitable aerodynamic efficiency for turbine, variable speed wind turbines used more. Therefore maximum power can be obtained from the actual wind at different speed and this power can be delivered to the grid system. There are many advantage of variable speed wind turbines we can say that the most important one of them is more energy can be generated for a specific wind speed regime [29]. Although the electrical efficiency decreases due to the losses in the power electronic converters that are essential for variable speed operation, the aerodynamic efficiency increases due to variable speed operation. As a result of a higher overall efficiency, the aerodynamic efficiency gain can exceed the electrical efficiency loss. Moreover, the mechanical stress is less because the rotor acts as a flywheel (storing energy temporarily as a buffer), reducing the drive train torque variations. Because the wind turbine runs at low speed noise is also reduced. The main disadvantage of variable speed wind turbines is that these turbines are more expensive. However, using a variable speed wind turbines can also give major savings in other subsystems of the turbine such as lighter foundations in offshore applications, limiting the overall cost increase.

There are three main types of wind turbines currently in use: the fixed speed wind turbine with Squirrel Cage Induction Generator, the variable speed wind turbine with Doubly Fed Induction Generator, and the variable speed wind turbine with Permanent Magnet Synchronous Generator. A brief distinction of the 3 types of wind turbine driven generators is given below.

2.5.3 Squirrel Cage Induction Generator

A wind power system (WPS) with squirrel cage induction generator is shown in Figure 2.6. The stator winding is connected to utility through a four-quadrant power converter comprised of two Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) connects back-to-back trough a DC link. The control system of the stator side converter regulates the electromagnetic torque and supplies the reactive power to maintain the machine magnetized. The supply side converter regulates the real and reactive power delivered from the system to the utility and regulates the DC link. The uses of squirrel cage induction generator have some advantages [30]:

- The squirrel cage induction machine is extremely rugged; brushless, reliable, economical and universally popular,
- Fast transient response for speed is possible,
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available,

This generator consumes reactive power and cannot contribute to voltage control. For this reason, although static capacitor control may allow wind farms with this type of generators are doomed to disappear from wind turbines. Below are the schematic diagram and the equivalent circuit of the fixed speed squirrel cage induction generator used in wind turbine technology as shown in Figure 2.6 and Figure 2.7, respectively.

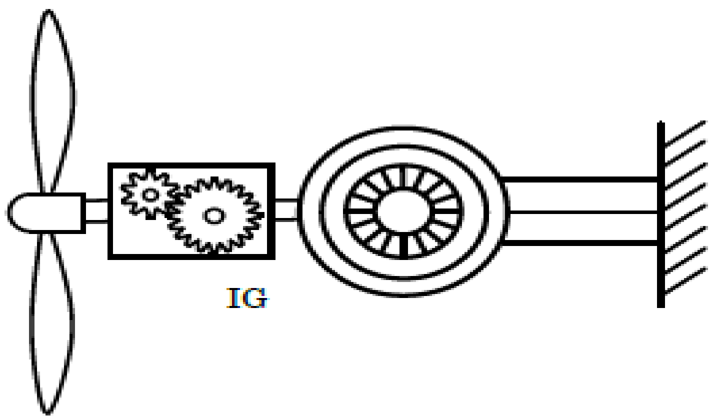

Figure 2.6 Induction Generator Schematic Diagram.

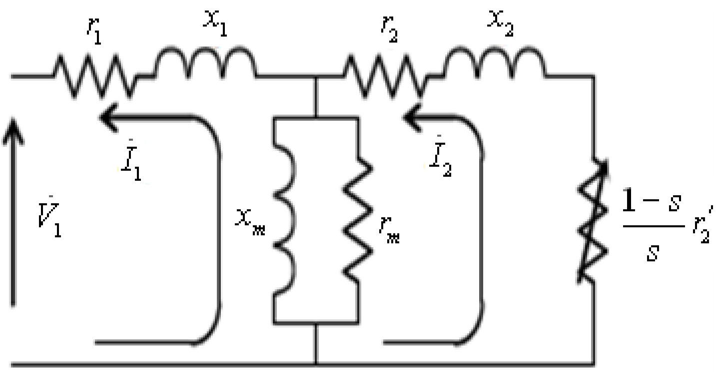

Figure 2.7 Induction Generator Equivalent Circuit per Phase.

2.5.4 Doubly Fed Induction Generator

The wind power system shown in Figure 2.8 consists of a doubly fed wound-rotor induction generator, where the stator winding is directly connected to the utility and the rotor winding is connected to the grid through a four quadrant power converter comprised of two back-to-back PWM-VSI. The SCR based converter can also be used but they have limited performance [30]. This generator can be controlled to provide frequency and voltage control with a back-to-back converter in the rotor. This type of generator presents some difficulties to ride-through voltage dips, because voltage dip generate high voltages and currents in the rotor circuit and the power converter could be damaged. This is the most extended variable speed wind turbine technology and manufacturers already offer this type of wind turbines with fault ride-through capabilities. The schematic diagram and the equivalent circuit of the DFIG are shown in Figures 2.8 and Figure 2.9, respectively.

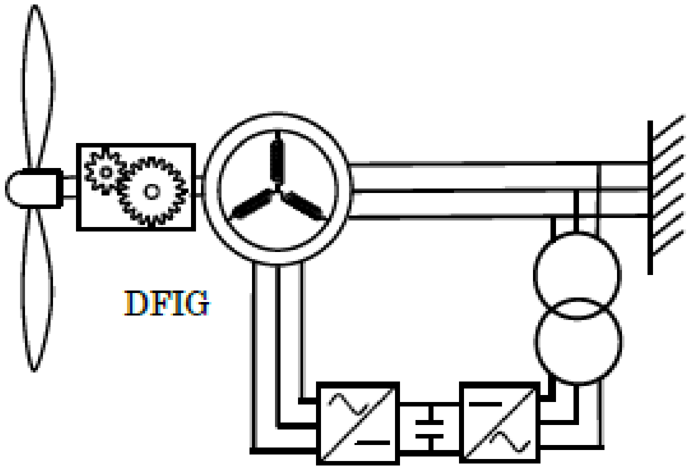

Figure 2.8 DFIG Schematic Diagram.

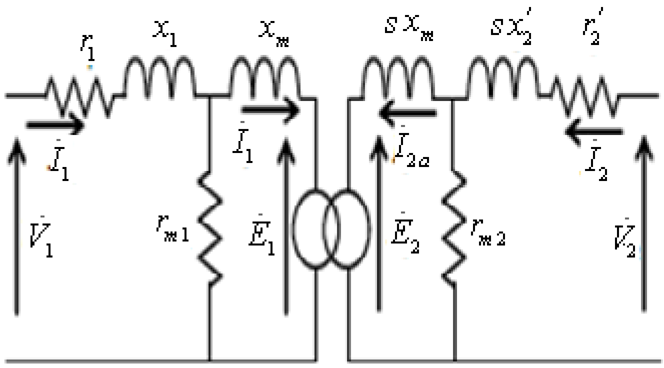

Figure 2.9 DFIG Equivalent Circuit.

2.5.5 Permanent Magnet Synchronous Generator

Figure 2.10 shows a WPS where a permanent magnet synchronous generator is connected to a three-phase rectifier followed by a boost converter. In this case, the boost converter controls the electromagnetic torque. The supply side converter regulates the DC link voltage as well as control the input power factor. One drawback of this configuration is the use of diode rectifier that increases the current amplitude [30]. This generator is connected through a back-to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips. The schematic diagram and the equivalent circuit of PMSG are shown in Figure 2.10 and Figure 2.11, respectively. PMSG has a better efficiency and it can be brush less. The grid fault ride through capability is less complex [8].

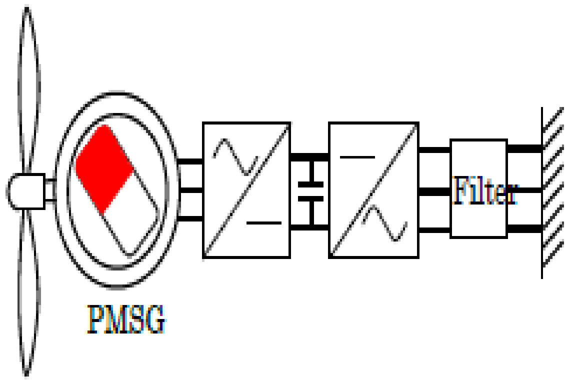

Figure 2.10 PMSG Schematic Diagram.

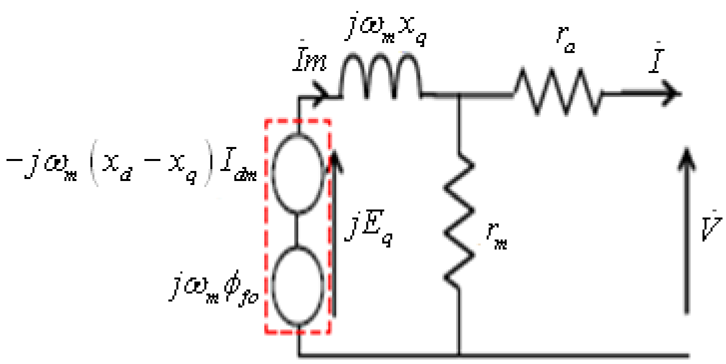

Figure 2.11 PMSG Equivalent Circuit [9].

2.5.6 WTGS-Subroutine

Two probable cases have been considered for calculating the initial conditions of a wind turbine generator system.

Case I: This case is shown in Figure 2.12. In this case, we consider that the wind speed, V_W, is equal or less than the rated wind speed. So that the pitch angle, β , is set to zero. We need to know the exact wind speed value to get a desired output power from an induction generator. The all step of this case is generally described in flowchart which is shown in Figure 2.12. Firstly, we need to set two input value. They are desired the IG output power PIG-OUT and the IG terminal voltage V_T. These values can be obtained from the power flow calculation. We also need the initial values of the wind speed, V_W, and rotor speed, ω_R.

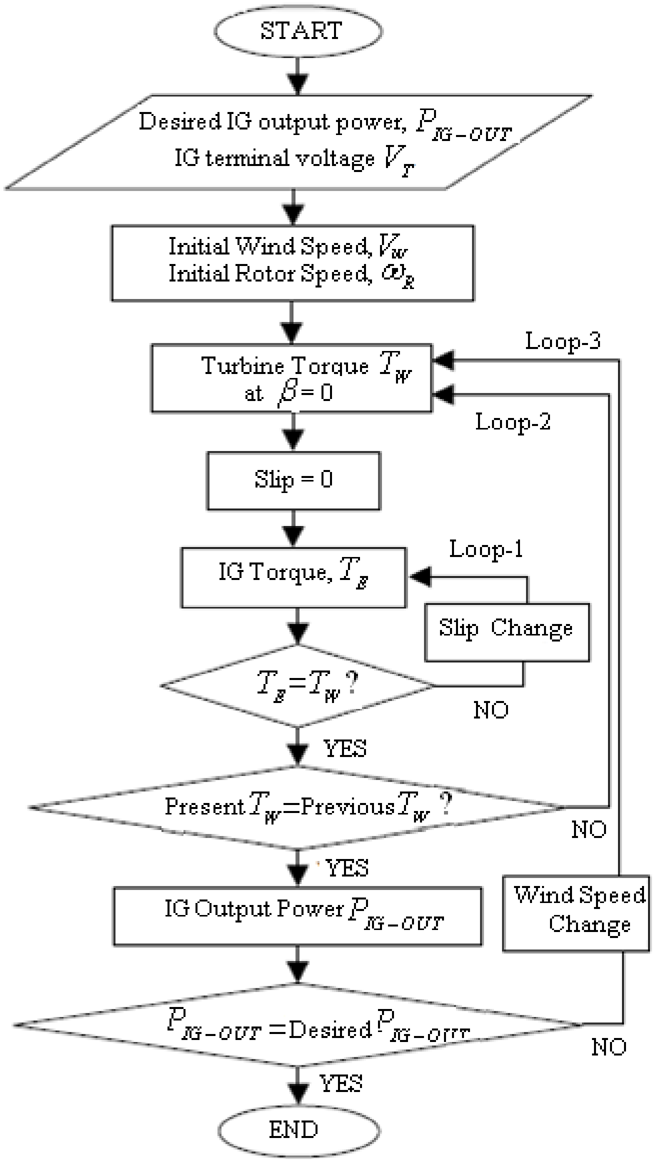

Figure 2.12 Flowchart for initial value calculation (Case I).

Case II: This case is shown in Figure 2.13. In this case, we consider that the wind speed V_W is higher than the rated wind speed. So that the pitch angle β is increased to maintain the rated induction generator output power. All step of this process has been demonstrated in flowchart which is shown in Figure 2.13. It is assumed that wind speed V_W and terminal voltage V_T are known. Firstly the pitch angle β has been set to zero, and the rotor speed, ω_R, has also been known. For a particular slip, when the previous T_W and the present T_W become equal, the IG output power PIG-OUT is calculated. If it is higher than the rated output value of power, then β is increased, and loop-3 will be continued until PIG-OUT becomes equal to the rated output value of power. Finally, we will get a different β for any wind speed over the rated speed, at which the induction generator output power becomes the rated output value of power.

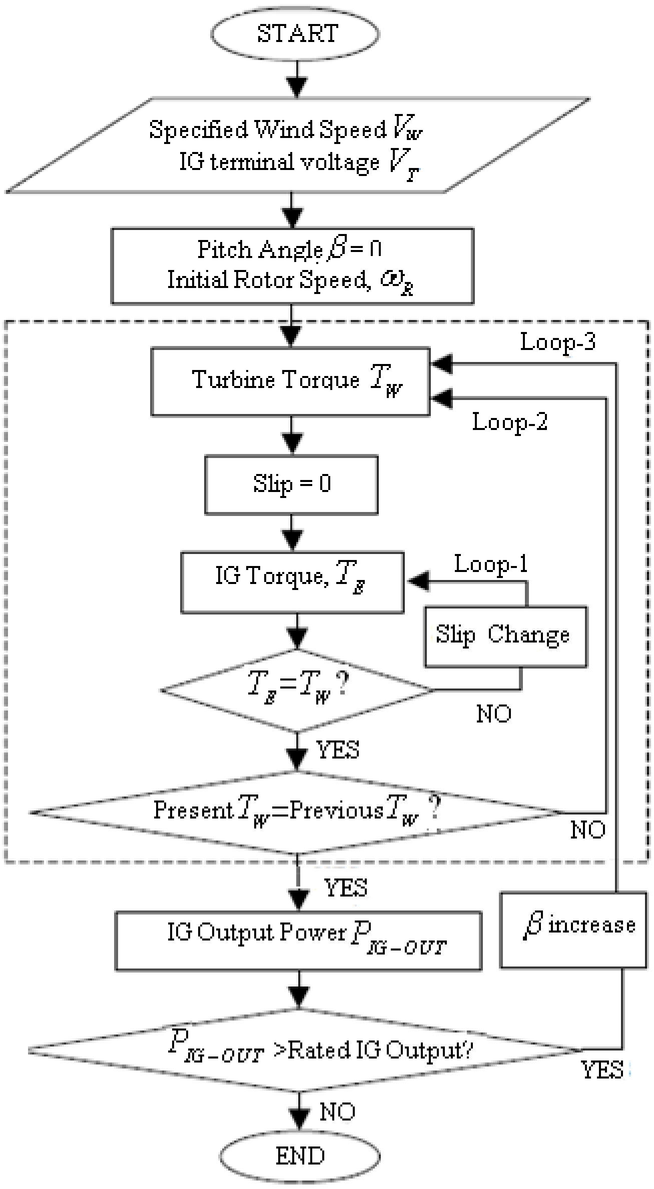

Figure 2.13 Flowchart for initial value calculation (Case II) [31].

2.6 PSCAD Model of Wind Turbine

Recently, wind power generation has attracted special interest, and many wind power stations are in service throughout the world. In wind power stations, induction machines are often used as generators, but the development of new permanent magnet generators, the improvement of the AC-DC-AC conversion and its advantages for output power quality make other solutions possible. A recent solution is to use a permanent magnet generator with variable speed and a conversion stage, which is the case studied in this technical study. We used the PSCAD/EMTDC program to simulate the system. This tool is a general-purpose time domain simulation program for multiphase power systems and control networks. It is mainly dedicated to the study of transients in power systems. A full library of advanced components allows a user to precisely model interactions between electrical networks and loads in various configurations. A graphical user interface and numerous control tools make PSCAD a convenient and interactive tool for both analysis and design of any power system [10]. Using the proposed model, comprehensive simulation study was carried out to observe the dynamic behaviors of STS and WTS with varying wind conditions and its response to network fault conditions. Wind turbine system is an example of such dynamic systems, containing subsystems with different ranges of the time constants: wind, turbine, generator, power electronics, transformer and grid. PSCAD provides a powerful graphical interface for building and verifying new mathematical models as well as new control strategies for the wind turbines systems. As wind energy is increasingly integrated into power systems, the stability of already existing power systems is becoming a concern of utmost importance [32].

In PSCAD, the complete wind generator cycle is composed of:

This study makes the choice to define a wind turbine connected to a permanent Magnet Synchronous Generator with 100 pole pairs.

In the first sections, the following components will be described and dimensioned:

- Wind Source Component
- Wind Turbine Component
- Wind Governor
- Synchronous Generator

The wind source component:

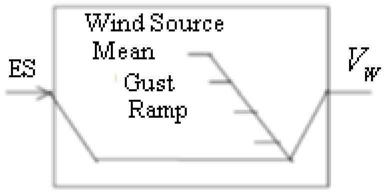

Table 2.1 Wind source component parameters.

I/O	Definition	Description
ES	Input External Value	An external value created by the user can be added to the value internally generated.
V_W	Output Wind Speed	Wind Speed in m/s

The mechanical turbine, represented by a component called "wind turbine".

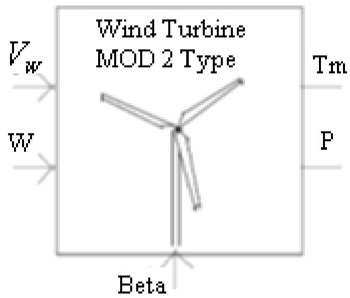

Table 2.2 Wind turbine component parameters.

I/O	Definition	Description
W	Input	Mechanical rotation speed of the turbine (rad/s)
Beta	Input	Angle of the blades (deg)
V_W	Input	Wind Speed in m/s
Tm	Output	Torque of the turbine (p.u.)
P	Output	Power of the turbine (p.u.)

The regulation governor of the turbine's output power. This regulation can be passive (passive pitch control) or dynamic (dynamic pitch control). The difference is whether or not the blades turn around their longitudinal axis. Both kinds of regulation can be simulated by a component called “Wind turbine governor”.

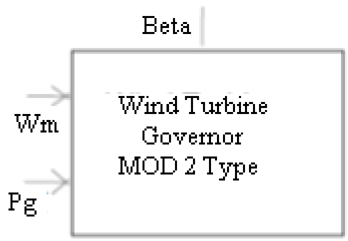

Table 2.3 Wind turbine governor parameters.

I/O	Definition	Description
Wm	Input	Mechanical rotation speed of the turbine (rad/s)
Pg	Input	Output power of the turbine (p.u.)
Beta	Output	Angle of the blades (deg)

The synchronous generator is described with the following component:

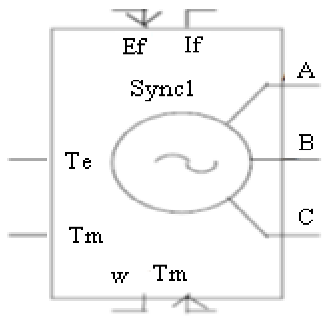

Table 2.4 Synchronous generator parameters.

I/O	Definition	Description
Ef	Input	The exciter voltage (p.u.)
Tm	Input,Output	The mechanical torque (p.u.)
If	Output	The exciter current (p.u.)
Te	Output	The electrical torque (p.u.)
w	Output	The speed of the generator (p.u.)
A,B,C	Output	The voltage (KV)

The other components are standard ones: synchronous machine, transformer, rectifier, inverter, Control System, Modeling Functions (CSMF),…. This study makes the choice to define a wind turbine connected to a Permanent Magnet Synchronous Generator with 100 pole pairs.

The following components were described and dimensioned in Figure 2.14:

- Wind Source Component
- Wind Turbine Component
- Wind Governor
- Synchronous Generator

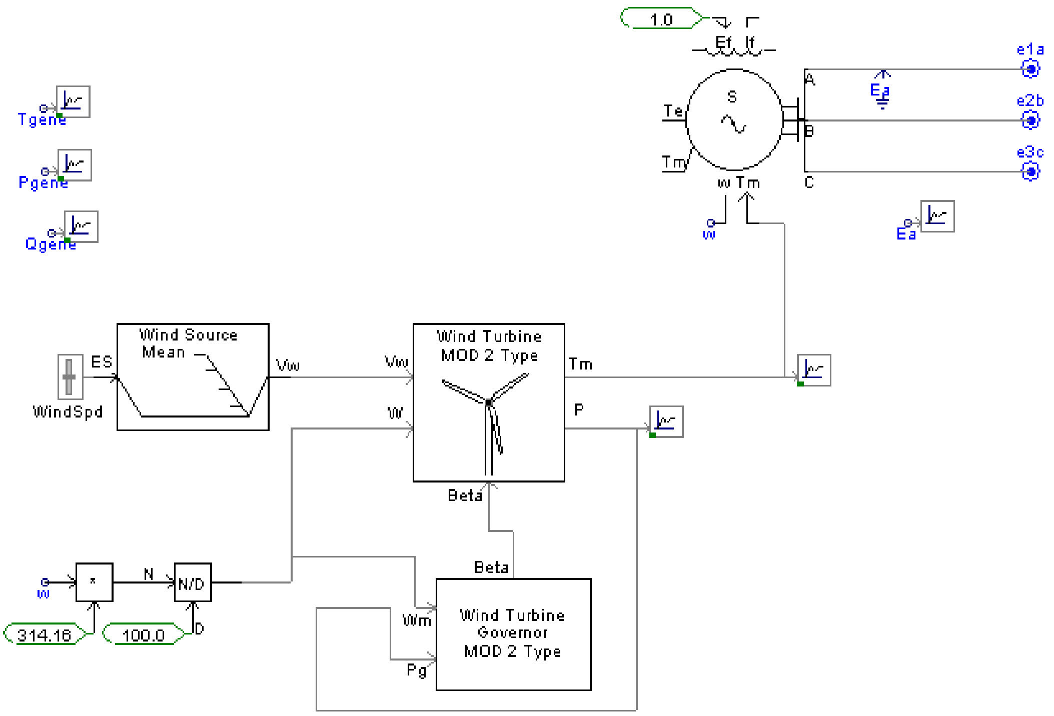

Figure 2.14 WTS implemented in PSCAD/EMTDC.

3 POWER QUALITY

3.1 Power Quality Description

Power quality of any system can be defined as having a bus voltage that closely resembles a sinusoidal waveform of required magnitude. The importance of power quality increases day by day because of increasing number of sensitive devices. Therefore, losses are reduced and behaviors of interconnected networks are made more appropriate. Recently power quality problems in the industry are increasing because power quality polluting loads are increasing day by day. The main reasons for concern with PQ are as following [12, 33]:

- End user devices which are very sensitive to PQ due to many microprocessor based controls.
- Industrial processes have very complex system; the re-startup is very costly.
- Large computer systems which are used in many businesses facilities.
- Power electronics equipment used for enhancing system stability, operation and efficiency. They are major source of bad PQ and are vulnerable to bad PQ as well.
- Power industry deregulation.
- Systems have complex interconnection structure, which results in more severe consequences if any one component fails.
- Some technological development which supply high performance equipment; Such equipment is more susceptible to power disturbances.

The many users demand more power quality to use their sensitive loads to automate processes and improve quality. Some basic criterions can be defined for power qualities which are constant magnitude of rms value, pure sinusoidal wave shape, constant frequency, symmetrical three-phases, and limited total harmonic distortion (THD). These values should be maintained between specified limits determined by standards if the power quality level is considered to be high. Power quality covers several types of problems of electrical supply and power system disturbances. The cost of power interruptions and disturbances can be quite high as a result of the important processes controlled and maintained by the sensitive devices. It is observed that the source current on the grid is affected due to the effects of nonlinear load and wind generator, thus purity of waveform may be lost on both sides in the system [11].

The power quality issues are vital concerns to the majority of industries today. The power quality is an index to quality of current and voltage available to industries, commercial and household consumers of electricity. The quality of voltage waveform at the entry point of a consumer premise depends upon the types of loads within that premise. These loads may be linear (nonharmonics producing) and nonlinear (harmonics producing) in nature. For linear loads, any distortion in the voltage waveform should be responsibility of the supply authority. Contrary to this, for nonlinear loads, any deviation from no load to full load voltage waveform is responsibility of consumer itself. Therefore, the quality of current exactly depends upon the quality of voltage with the non-harmonics producing loads.

3.2 Costs of Power Quality Problems

The costs of PQ problems are highly dependent of several factors, mainly the business area of activity. Other factors, like the sensitivity of the equipment used in the facilities and market conditions, among other, also influence the costs of PQ problems. Some of these PQ problems effected costs directly or indirectly. PQ problems can cause the damage in the equipment and loss of production. Moreover, this result can affect loss of raw material, salary costs during non-productive period and restart costs. We must subtract the costs which are achieved during the non-productive period, such as energy savings. We can obviously say that these costs are very small relative to cost which is resulted PQ problems. However, some of electrical disturbances do not imply production stoppage, they may have other costs associated, such as reduction of equipment efficiency and they can reduce the equipment lifetime. Indirect costs are very hard to evaluate for example the investment to prevent power quality problems may be considered indirect cost [13].

3.3 Main Sources of Power Quality Problems

A power quality problem is defined as an occurrence manifested in voltage, current, or frequency deviations, which results in failure or misoperation of end-use equipment. Commercial customers have become more exact in their demand for relative quality of power they purchase; variations in flow or voltage can actually damage and disrupt sensitive electronics, computers, and microprocessors. As modern society relies more heavily on high tech-processes, power quality has become even more critical [34].

Recent studies conducted show that 80-90 % of all power quality issues result from onsite problems, rather than utility problems. But, more importantly, the studies indicate that power quality problems are on the rise for industrial and commercial customers. Main sources of power quality problems can be summarized below:

- Load Switching
- Power Electronic Devices
- Information Technology and Office Equipment
- Arcing Devices
- Embedded Generation
- Large Motor Starting
- Storm and Environment Related Damage
- Wiring and Grounding
- Saturated Transformers
- Other Sources of Power Quality Problems [16].

3.4 Power Quality Standards

Standards are needed to achieve coordination between the characteristics of the power supply system and the requirements of the end use equipment. This is the role of power quality standards. International Electrotechnical Commission

(IEC) and Institute of Electrical and Electronic Engineers (IEEE) have proposed various power quality standards as it is seen from Table 3.1.

Table 3.1 Some power quality standards of IEC and IEEE.

Phenomena	Standards
Classification of Power Quality	IEC 61000-4-30-2008, IEEE 1159-2009 IEEE 1409-2012
Transients	IEC 61000-4-4-2012 IEEE C62.41-1991, IEEE 1159-2009
Voltage Sag/Swell and Interruptions	IEC 61009-1-2012,IEEE 1159-2009
Harmonics	IEC 61000-4-7-2002 IEC 61000-3-14-2011, IEEE 519-1992
Voltage Flicker	IEC 61000-3-3-2008

Similar power quality standard and some practices are determined in our country. This standard is TS EN 50160 (December 2011) which is prepared by the TSE. The decision issued in 13 December 2011 really entered into force. The standard determines low voltage, medium voltage and high voltage supply characteristics. The purpose of the standard is to describe and explain the supply voltage characteristics; frequency, magnitude, wave format, in terms of symmetry of the line voltage. International Electro Technical Commission Guidelines are provided for measurement of power quality of wind turbine. The International standards are developed by the working group of Technical Committee-88 of the International Electro-technical Commission (IEC), IEC standard 61400-21, describes the procedure for determining the power quality characteristics of the wind turbine.

The standard norms are specified.

- IEC 61400-21: Wind turbine generating system, part-21. Measurement and Assessment of power quality characteristic of grid connected wind turbine.
- IEC 61400-13: Wind Turbine—measuring procedure in determining the power behavior.
- IEC 61400-3-7: Assessment of emission limits for fluctuating load IEC 61400-12: Wind Turbine performance. The data sheet with electrical

characteristic of wind turbine provides the base for the utility assessment regarding a grid connection [14].

Although terms of power quality are valid for transmission and distribution systems, their approach to power quality has different concerns. An engineer of transmission system deals with the control of active and reactive power flow in order to maximize both the loading capability and stability limits of the transmission system. On the other hand, an engineer of distribution system deals with load compensation (by means of individual or group compensation) in order to maintain power quality for each load in the distribution system, for example achieving nearly sinusoidal bus voltage at rated magnitude for every load. These interests on power quality have also brought the solution by utilizing power electronic based power conditioning devices.

3.5 General Electrical Disturbances

3.5.1 Voltage sag and swell

Voltage sag and swell are shown in Figure 3.1. The voltage quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a sine wave of constant frequency and constant magnitude. The term voltage quality can be interpreted as the quality of the product delivered by the utility to the customers. Voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal.

Voltage sag is a fundamental frequency decrease in the supply voltage for a short duration (5 cycles to one minute). Voltage swell is defined as the increase of fundamental frequency voltage for a short duration. The definitions of sags and swells have evolved over the past fifteen years, as have the power quality instruments that measure them. Voltage sags, or voltage dips as they are referred to in the European communities, were initially any reduction in voltage below a user- defined low limit for between one cycle and 2.55 seconds.

Voltage swells, originally referred to as voltage surges, were similar to voltage sags, except that the voltage exceeded a user defined high limit. While various definitions relative to the amplitude and duration are still in use, the IEEE 1159-1995 Recommended Practice on Monitoring Electric Power Quality has defined them as follows; Voltage sag (dip) is a decrease to between 0.1 and 0.9 pu in rms voltage or rms current at the power frequency for durations of 0.5 cycles to 1 minute. Voltage swell is an increase to between 1.1 pu and 1.8 pu in rms voltage or rms current at the power frequency durations from 0.5 to 1 minute.

3.5.2 Interruption

An interruption occurs when the supply voltage (or load current) decreases to less than 0.1 per unit for a period of time not exceeding 1 minute. When the supply voltage is zero for a period of time in excess of 1 minute, the long duration voltage variation is called sustained interruption. Human intervention is required during sustained interruptions for repair and restoration. The mentioned common voltage disturbances are shown in Figure 3.1.

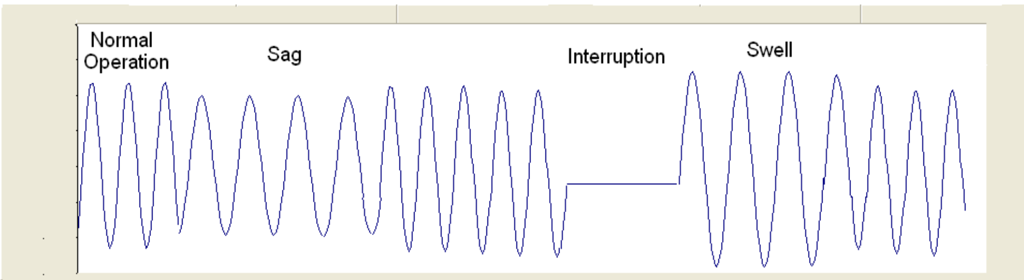

Figure 3.1 Voltage Disturbances.

3.5.3 Voltage Flicker

A very rapid change in the supply voltage is called voltage flicker. This is caused by rapid variations in current magnitude of loads such as arc furnaces in which a large inrush current flows when the arc strikes first causing a dip in the bus voltage.

3.5.4 Notching

Notch which is shown in Figure 3.2 occurs when current commutates from one phase to other causing a momentary short circuit between two phases. The maximum voltage during notches depends on the system impedance. The frequency components that are associated with notches are usually high.

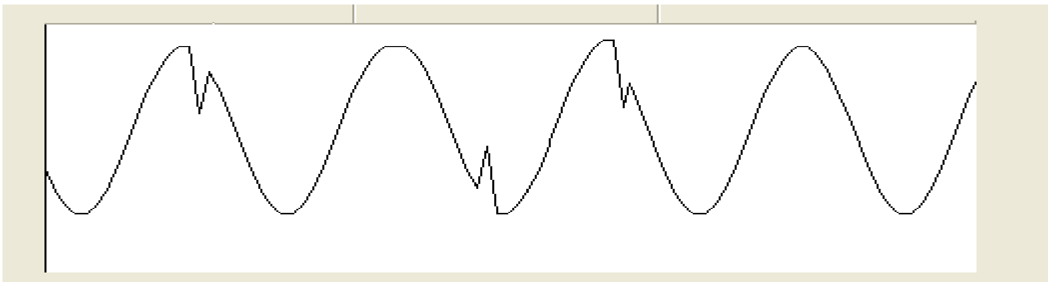

Figure 3.2 Notching.

3.6 Impacts of Wind Farms on Power Quality

Until recently there were no standard procedures for determining the power quality characteristics of a wind turbine, and simplified rules like; requiring a minimum short-circuit ratio of 25 or that the wind farm should not cause a voltage increment of more than 1%, were often applied for dimensioning the grid connection of wind turbines. This approach has proved generally to ensure acceptable voltage quality; however, it has been costly by imposing grid reinforcements not needed and has greatly limited the development of wind farms in distribution grids. On the local level, voltage variations are the main problem associated with wind power. This can be the limiting factor on the amount of wind power which can be installed. With the increasing share of wind energy sources and also due to other reasons discussed below, power systems are becoming less strong, i.e. weak grid. Critical power quality issues related to integration of wind farms in weak grids which is as follows to characterize the power quality:

- Grid availability and capacity
- Reactive power
- Voltage unbalance
- Voltage ranges
- Frequency range
- Harmonics and interharmonics
- Voltage fluctuations

Of these, reactive power is at present the most important parameter for the electricity boards while grid availability, frequency range, voltage unbalance and voltage range are the primary parameters influencing the wind turbine operation [35, 36]. Fortunately, many new wind power plants are equipped with state of the art technology, which enables them to provide good service while producing clean power for the grid. The advances in power electronics have allowed many power system applications to become more flexible and to accomplish smoother regulation. [15].

4 STATIC TRANSFER SWITCH

4.1 The Characteristics of STS

Static Transfer Switches are used to provide energy to a specific load with the highest possible quality by fast switching between two or more alternative power sources [17]. Energy reliability is especially important for critical and sensitive loads. Therefore, any deviation from acceptable levels should be detected very quickly and load should be transferred to an alternative source. STS, can easily fulfill this job by means of the sensing circuits, controllers and thyristor power stages it includes. The STS contains two or more switches that allow transferring a load from a preferred feeder to an alternate feeder, as in Figure 4.1. STS is connected in the bus tie position when a sensitive load is supplied by two feeders. It protects the load from sag by quickly transferring it from the faulty feeder to the healthy feeder.

The design and application of a STS takes into account numerous considerations including:

- Correct measurement of applied voltages and currents,
- Thyristor firing control under the condition of non-sinusoidal load current operation,
- Transfer operation with up-stream/down-stream fault discrimination,
- Protection functions to avoid producing power quality problems for connected loads and to afford protection for the STS from additional failure,
- Thyristor cooling methods,
- Main circuit design.

Due to the control and monitoring point-of-view, we can say that the STS is a very complex device. In spite of complexity and the large number of components which are used in a STS, the fact remains that there are many years of experience with thyristor applications where reliability issues were previously addressed in order to deliver viable products. The development of thyristor applications supplies many advantages to use of STS. The principal contribution to thyristor application technology in the STS are the algorithms that make firing control possible without delays at current zero crossings, and the near instantaneous detection of fault direction to inhibit transfer of downstream faults.

Primarily, sensitive loads are fed by WTS. In case of voltage sag or interruption, the control circuit of STS transfers the sensitive loads to alternate feeder. Hence, the reliability and quality of electric power can be significantly improved for sensitive loads. PSCAD/EMTDC program has been used for modeling and analysis of the considered system. The STS is used in uninterruptible power supply systems and in distribution networks to provide connection to alternate sources of ac power for critical loads when WTS fails. The STS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances. The STS ensures continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. To ensure continuity of electrical power supply with process controls, a sensitive load is normally supplied from two independent sources, one being the primary selection which is WTS. Traditionally, the sources are often connected to mechanical switches incorporating controls that can recognize loss of the WTS power source and then automatically transfer to the second source, thus maintaining a highly reliable source of power. However, as processes and process controls have become increasingly sensitive not only to loss of the power source but also to fluctuations in the voltage supplied (i.e. voltage sags and swells), Mechanical transfer switches can not transfer quickly enough to eliminate customer interruptions when such interruptions occur [16].

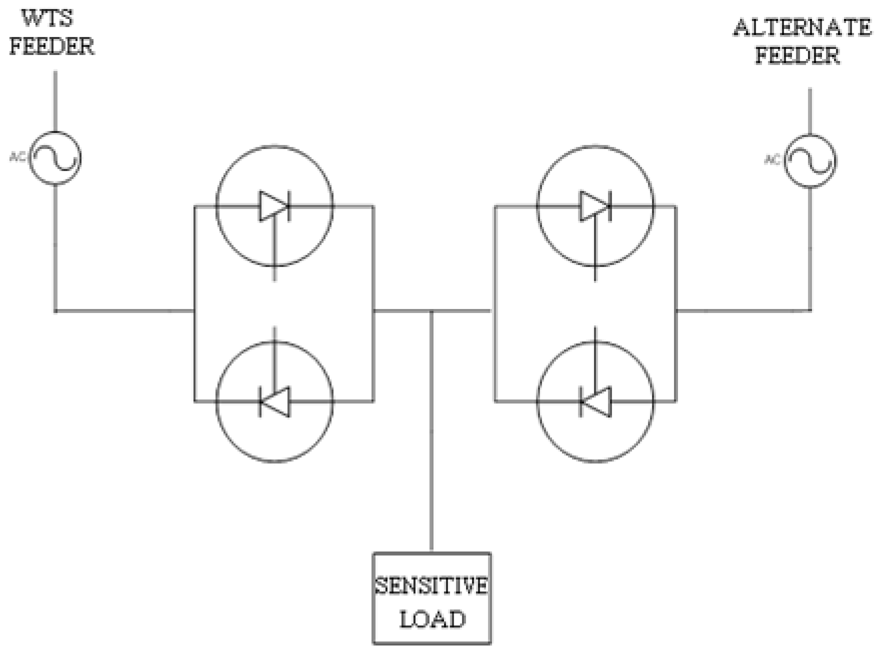

Figure 4.1 Structure of a STS.

The STS is used to transfer the load from the WTS to alternate source (AS) during the voltage disturbance. This process is very effective way of mitigating the effects of both interruptions and voltage disturbances by limiting their duration as seen by the sensitive load. There are many advantages of using STS one of them is mainly due to its rather low cost compared with other solutions.

The main considerations for the control system of a STS include:

- Sag detection of STS.
- Transfer and gating strategy of thyristors.

The principal contribution to thyristors application technology in the STS are the algorithms that make firing control possible without delays at current zero crossings, and the near instantaneous detection of fault direction to inhibit transfer of downstream faults (caused to sag or interruption) [37].

Therefore, the STS must meet the following requirements:

- It must detect voltage fluctuations in the system as fast as possible.
- In case the preferred source fails, it must perform a fast load transfer to the alternative source.

- The gating strategy, which controls the transfer process, must prevent paralleling the two sources.
- Detection and transfer logic must function properly for all possible operating conditions.
- Detection scheme must not be sensitive to temporary voltage transients, e.g., capacitor switchings.

4.2 Static Transfer Switch Operation

The block diagram of operation logic of the STS which is shown in Figure 4.2 is composed of four sections. There are;

- Voltage detection
- Gating enable generator
- Phase locked loop (PLL)
- Gating signal generator

The STS operation is responsible for monitoring the quality of the WTS and performing the transfer of the load from the WTS to the alternate source, and vice versa. The required input signals to the control circuit are the three phase voltages from each source and phase currents from the load. The outputs of the control circuit are the gating patterns for the main and alternate source thyristor switches.

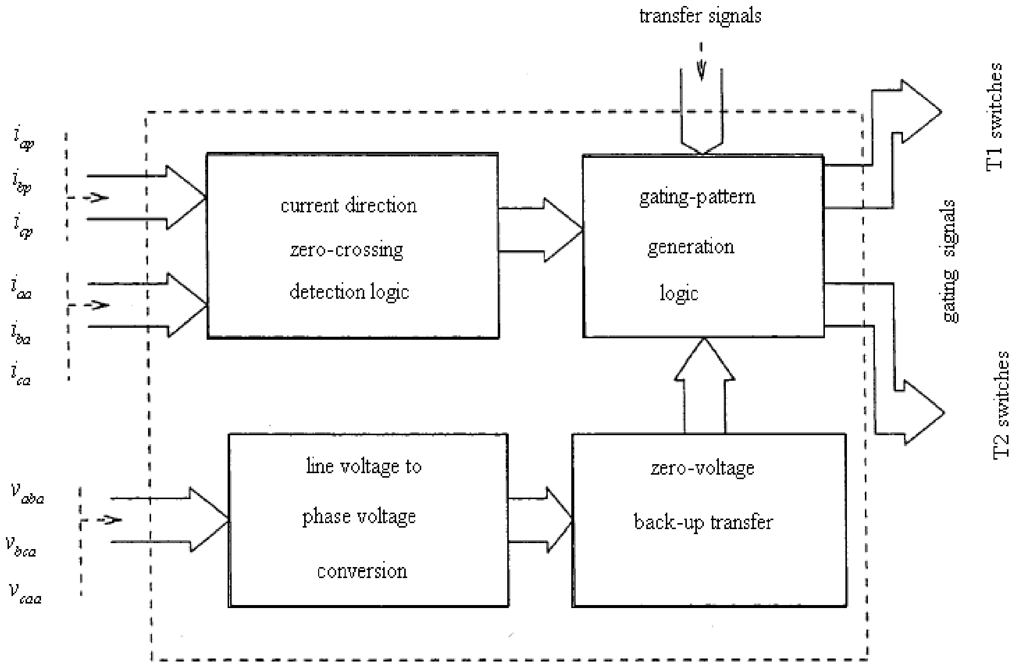

Figure 4.2 Operating logic of STS.

The operating time of the STS is given by the sum of the detection time and the time needed for the actual transfer of the load (thyristor switching time), as fault detection and transfer initiation are sequential [18].

4.3 PSCAD Model of STS

Under normal conditions, the control logic triggers only the thyristors of WTS (Preferred Feeder). If the WTS can not meet voltage requirements, the control unit will detect the disturbance and will transfer the load to the alternate feeder if it is in a better condition than the preferred one.

We modeled STS in PSCAD Simulating program which is shown in Figure 4.3. We analyzed our simulating results based on theoretical results and also we compared the simulating results to the previous studies for this modeled system.

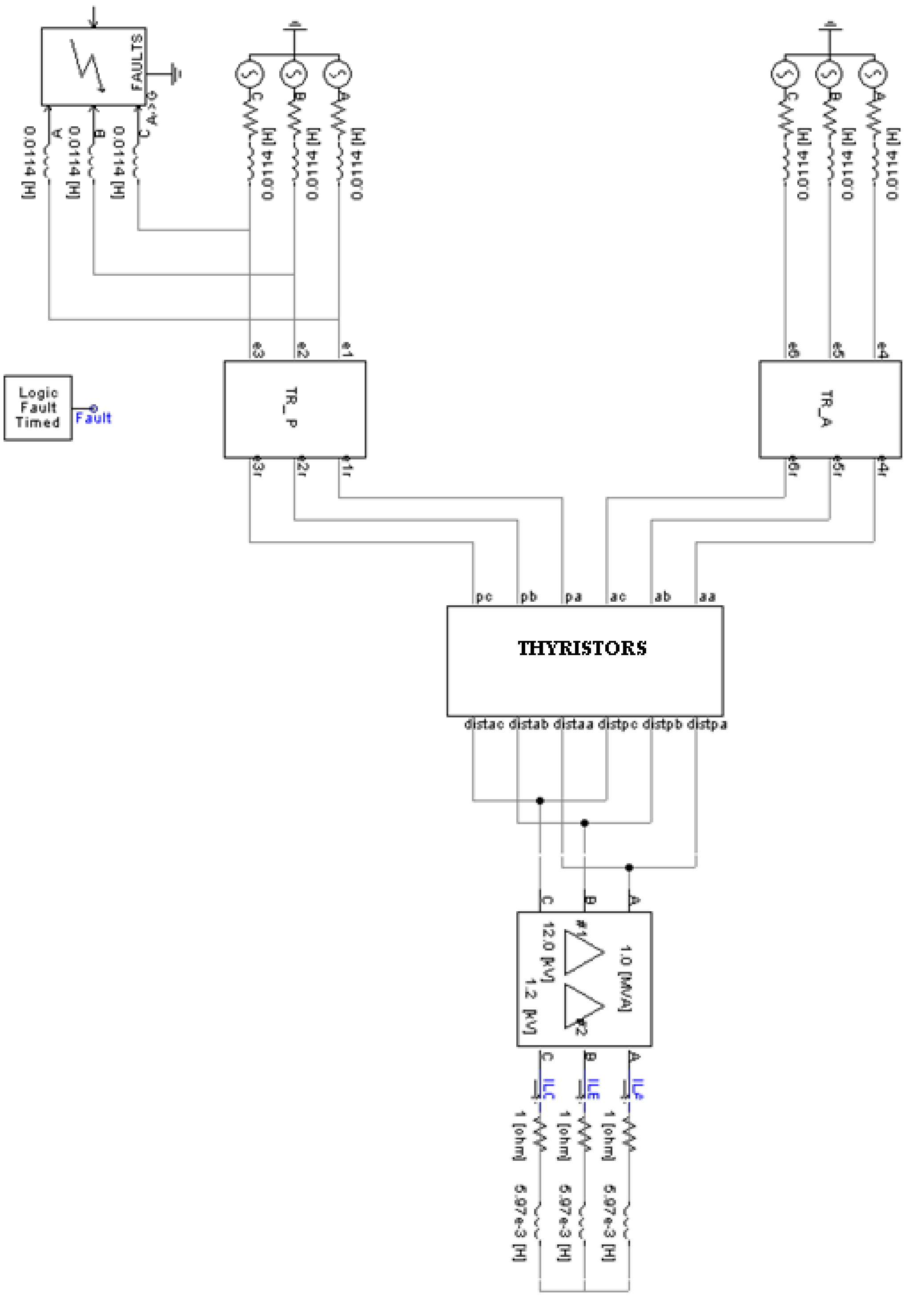

Figure 4.3 STS modeled in PSCAD/EMTDC.

4.4 Control Logic of Static Transfer Switch

STS control system is composed of voltage detection logic and a gating strategy. The detection logic is based on transforming ac voltages into a synchronously rotating frame. The gating system generates suitable gating patterns for the thyristor switches before, during and after a load transfer based on the direction of line current. Two different transfer schemes can be employed; zero current strategy and commutation strategy [19].

Figure 4.4 shows a simplified block-diagram of the voltage-detection logic. Based on abc-to-dq0 transformation, system line voltages are transformed into a synchronously rotating frame. This change of variables is through Park's transformation matrix:

$$V_{dq0p} = K_s V_{abcp} \tag{4.1}$$

Where

$$\left(V_{dq0p}\right)^T = \begin{bmatrix} V_{dp} & V_{qp} & V_{0p} \end{bmatrix} \tag{4.2}$$

$$\left(V_{abcp}\right)^T = \begin{bmatrix} V_{abp} & V_{bcp} & V_{cap} \end{bmatrix} \tag{4.3}$$

$$K_s = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta-120) & \cos(\theta+120) \\ \sin(\theta) & \sin(\theta-120) & \sin(\theta+120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{4.4}$$

$$\theta(t) = \int_0^t w(\zeta)d\zeta + \theta(0) \tag{4.5}$$

Where

V_{abp} V_{bcp} V_{cap} ; are the preferred source line voltages,

V_{dp} V_{qp} V_{Op} ; are dq0 components of the preferred source voltage in the rotating frame, ω is the rotating frame angular frequency, $\theta(0)$ is the initial value of θ.

The rms value of V_{dp} and V_{qp} will then be calculated as:

$$V_p = \sqrt{V_{dp}^2 + V_{qp}^2} \tag{4.6}$$

The Figure 4.4 shows that the output of the abc-to-dq0 transformation block, i.e. , V_P is compared to a dc reference, i.e. V_{ref} .The error e_r is passed through a low-pass filter which attenuates impacts of voltage transients. The filter introduces a certain amount of delay to the error signal which is determined by the filter cut-off frequency (f_c). The filter output is then compared to a tolerance limit E_{tot}. Output of the comparator is the transfer-signal which initiates a transfer process if the preferred source fails. Two identical logics have been used for both sources [20,38]. How we can find transfer signals in PSCAD program are showed in Figure 4.5 and Figure 4.6.

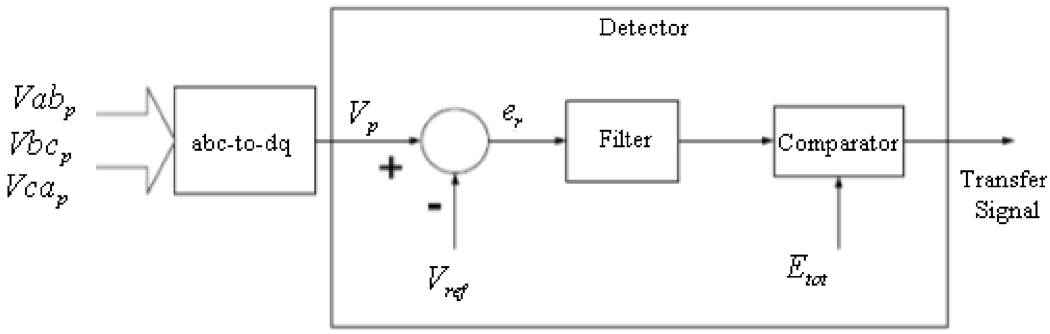

Figure 4.4 Block-diagram of the voltage-detection circuit.

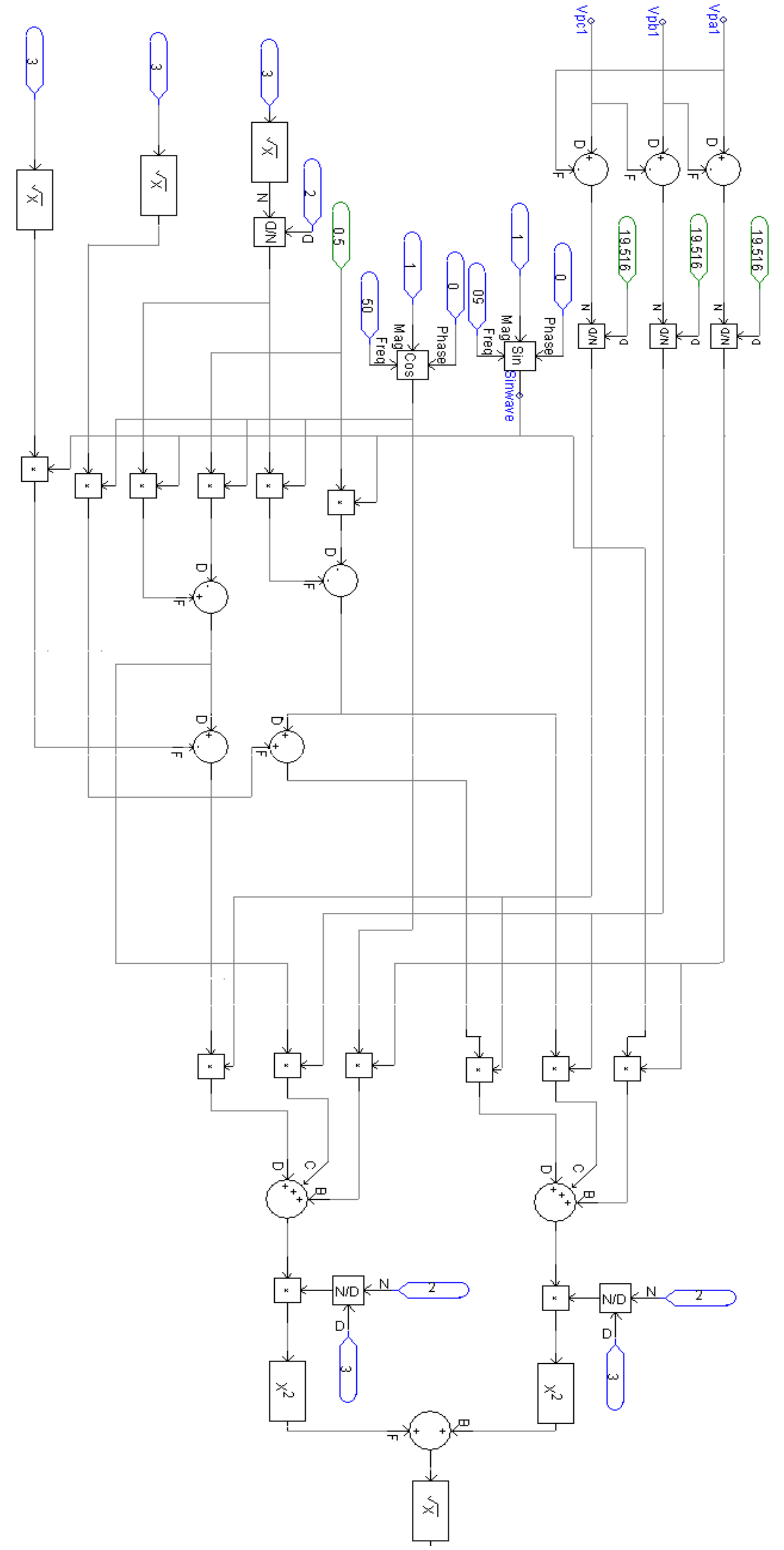

Figure 4.5 abc-to-dq0 transformation block of STS in PSCAD/EMTDC.

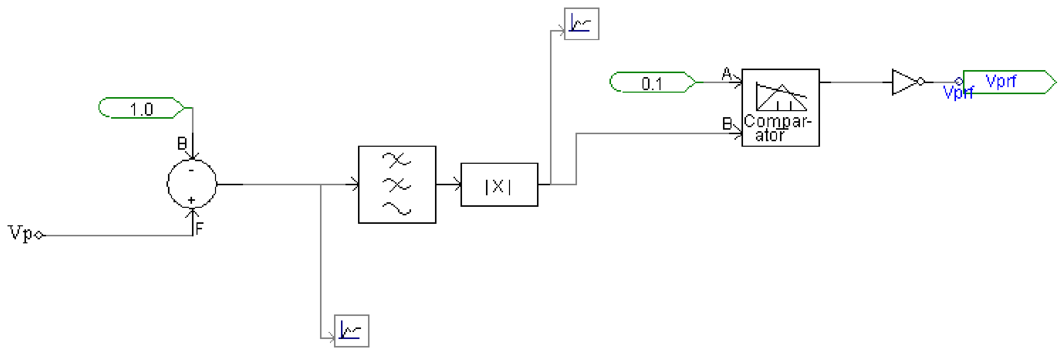

Figure 4.6 V_{prf} signal in PSCAD/EMTDC.

If the utility system operates in normal condition, or if any symmetrical fault occurs, then V_{dp} and V_{qp} are DC quantities. If any unsymmetrical fault occurs, the resulting voltage sag is unbalanced and contains both positive sequence and negative sequence component. The synchronous frame voltages V_{dp} and V_{qp} then have DC components and ripples. Voltage sags will certainly lead to the reduction of the positive sequence voltage component, which is used by the proposed STS controller to identify voltage sags [21, 39]. The detection time is shorter for a more severe fault. The response of the voltage detection logic is mainly determined by the filter cut-off frequency f_c. The higher the f_c is the faster the detection circuit and the shorter the detection time.

4.5 Transfer and Gating Strategy of STS

Flowchart which is given in Figure 4.7 is the block diagram of the STS current-based thyristor-gating strategy [19]. To achieve a fast load transfer, the control system of the STS employs a fast commutation gating strategy. This method of gating is obviously depicted in flowchart. In this gating method, the control system does not wait for the current zero-crossings and starts the transfer as soon as the disturbance is detected. However, to minimize the probability of source paralleling and cross current, the transfer process begins according to the direction of line currents.

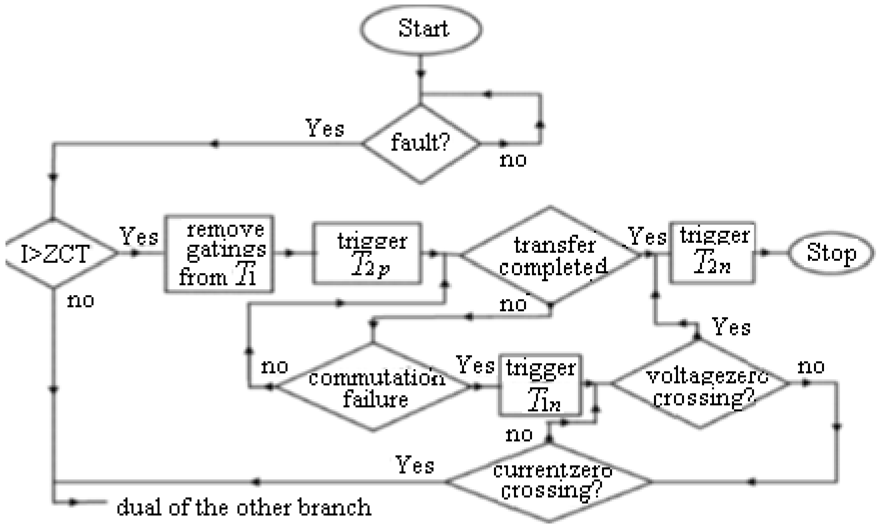

Figure 4.7 Flowchart of thyristor-gating strategy

Current direction and zero crossing detection logic is to detect status of each thyristor switch, i.e., on/off state. This is to avoid paralleling the sources during the transfer process.

Gating-pattern generation logic is to generate selective gating patterns for both T_1 and T_2 thyristor switches. During transfer operation, two scenarios, commutation between the incoming and the outgoing thyristors, e.g., T_{1p} and T_{2p}, begins when a disturbance is detected. In this case, T_{2n} is triggered when the preferred source current drops below, and the alternate source current exceeds, the zero-current threshold limit i_{zth}. The second scenario occurs when commutation between the incoming and outgoing thyristors fails. The outgoing thyristor continues conducting until a zero crossing is reached and commutation begins. Maximum transfer time is determined by the phase in which commutation fails. A turn off time is also considered before gating the incoming thyristor T_{2n} to make sure that the outgoing thyristor has regained its blocking capability.

Line-voltage to phase-voltage conversion and zero-voltage back-up transfer logic is to transfer the load at the zero crossing of phase voltage if the change of current direction/zero-crossing can not be detected. This may occur for low values of line current, e.g., no-load conditions, due to inaccuracies of current measurement devices [38].

Transfer signals for phase A which are composed in PSCAD programs is seen in Figure 4.8. The proposed transfer strategy is based on a selective gating scheme during the transfer. The scheme is to transfer the load within the shortest possible time and prevent the sources from being paralleled during the transfer process. The transfer time is determined by the gating strategy, load type, fault type, fault instant and system configuration [22].

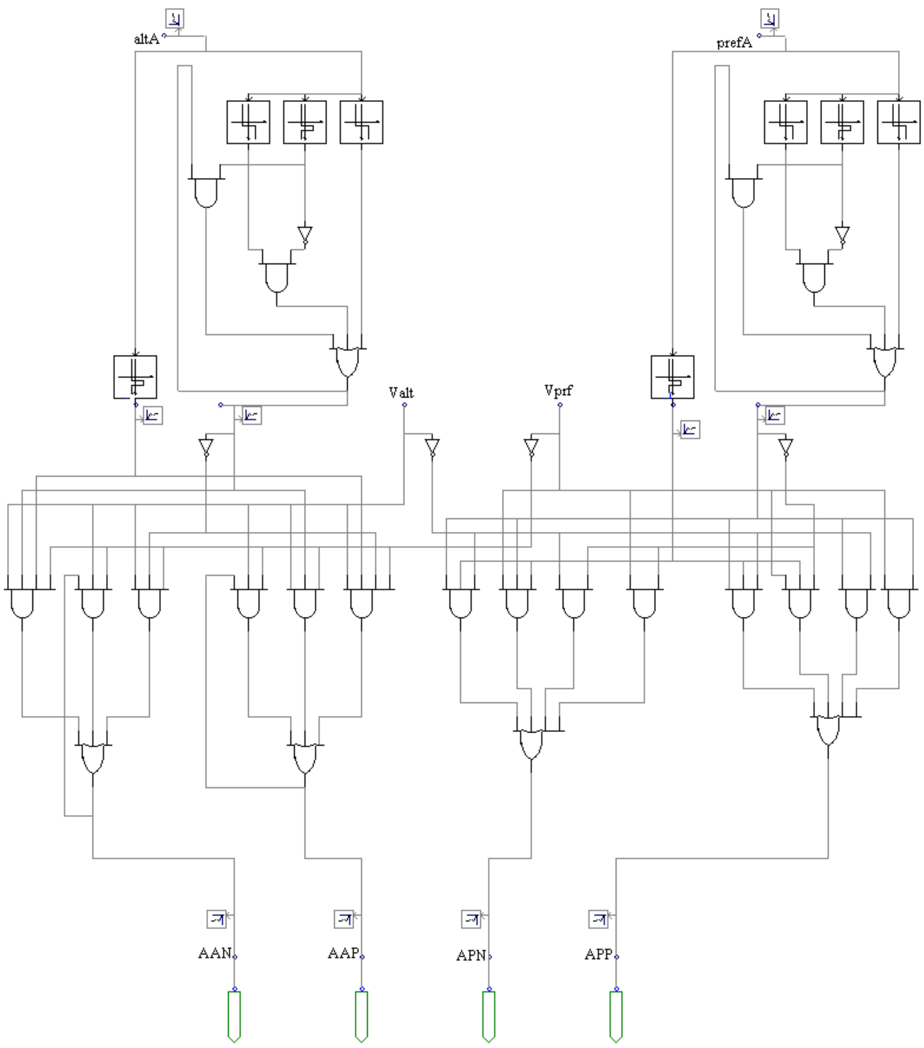

Figure 4.8 Gating signals for one phase in PSCAD/EMTDC.

The gating signals are obtained for all phases. Thyristor gating generation system is a selective gating strategy which generates gating signal for all phases during normal, transfer and post-transfer periods.

5 MODELLING OF THE PROPOSED SYSTEM

5.1 PSCAD model of the Proposed System

The wind energy generating system (WEGS) is connected with grid having the sensitive load. We designed and simulated the WEGS which was generated combining to STS and WTS to maintain PQ for sensitive loads. The proposed system which is designed in PSCAD/EMTDC program is shown in Figure 5.1. There are two feeders first one is wind turbine feeder the other one is alternate feeder. WT feeder is connected to Transformer P and alternate feeder is connected to Transformer A, respectively. Then these transformers are connected to thyristors. The outputs of the thyristors are connected to step down transformer and then the output of the transformer connected to the sensitive load. Fault unit is connected to WTS to observe the response of proposed system at fault duration. The all obtained simulating results are evaluated, comprehensively.

The main purpose of the system is uninterrupted energy for sensitive loads. The transfer signals of thyristors are obtained for all phase from three different units which is shown Figure 5.1. We used breaker operation sequencers to improve starting conditions. To evaluate the performance of the proposed system, many electrical disturbances are implemented to the system. The system is modeled for different fault cases, interruption, voltage sag and voltage swell conditions.

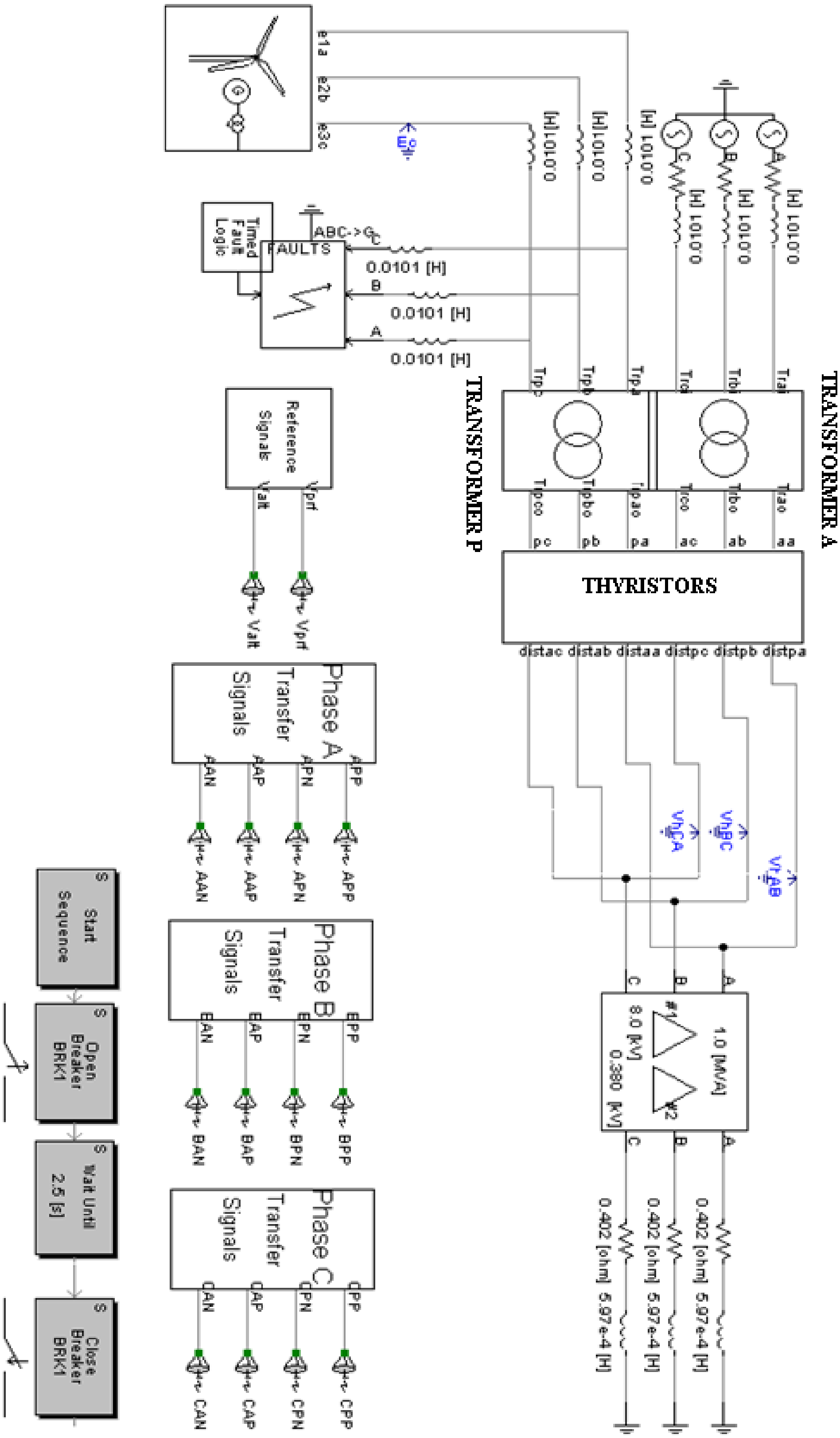

Figure 5.1 STS and WTS implemented in PSCAD/EMTDC.

5.2 Dynamic Response of the Proposed System

The modern wind turbines are equipped with the capability to stay connected and to support the grid during faults. The ability to support the grid during deep voltage transients caused by network disturbances depends on both the technical features and load of the connected generator, and the dynamic characteristics of the grid [40]. Main motivation of this study is to develop new control strategies for wind turbines' fault response that can enable increased wind power penetration in existing power systems without degrading the stability. As discussed above and in literature, risks for security of a stable power system arise with high penetration of wind power, mainly due to distinct characteristics of wind power installations. In this study the purpose of making the WPPs behave similar to CPPs is targeted, focusing on the response of WPPs during different grid faults. And also during interruption, voltage sag and swell condition the PQ of the sensitive load is maintained by STS.

The parameters of the proposed system are as follows:

WTS and alternate source systems:

13.8 kV (Line to line), 50 Hz

$R_{WTS} = R_a = 0.015\ \Omega$, $X_{WTS} = X_a = 0.0101$ H

Transmission line:

8 kV/100kV, 250MVA, 50 Hz Y/Δ step up transformer

100 kV/8kV, 250MVA, 50 Hz Δ/Y step down transformer

Three-phase Δ/Δ load transformer

8 kV/380 V, 1 MVA, 50 Hz

Each pair of thyristor valves has a snubber circuit composed of R = 1 MΩ and C= 0.001 μF

Load system is composed of a three-phase RL load. The series RL load has the following parameters:

$R_L = 0.402\ \Omega$, $X_L = 0.597$ mH

Control circuit parameters:

Voltage-change tolerance limit $E_{tot} = 10\%\ V_{ref}$

6 SIMULATING RESULTS

6.1 Case Studies of Fault Conditions

Figures 6.1-6.104 show simulated performance of proposed system. The simulations are performed by PSCAD/EMTDC simulating program. The all mentioned electrical disturbances are implemented to the proposed system, then currents and voltages of all system are investigated during normal, transfer and post-transfer periods and also these simulating results are evaluated.

Different types of faults are implemented to the WT feeder and the response of the proposed system is observed for all cases. Then, the simulating results are evaluated, respectively.

6.1.1 Case 1: Under 3 Phase Balanced Fault

Figure 6.1 shows the fault circuit of three phases under three phase fault case. The fault occurs at $t_1 = 5$ s and detected at $t_2 = 5.2$ s. Figures 6.2-6.4 show the WTS source voltage at fault duration.

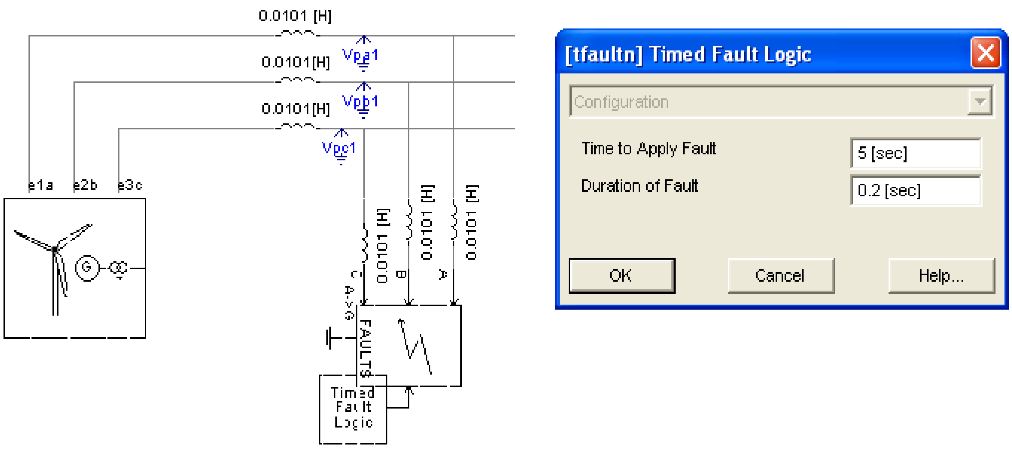

Figure 6.1 Three phase balanced fault block.

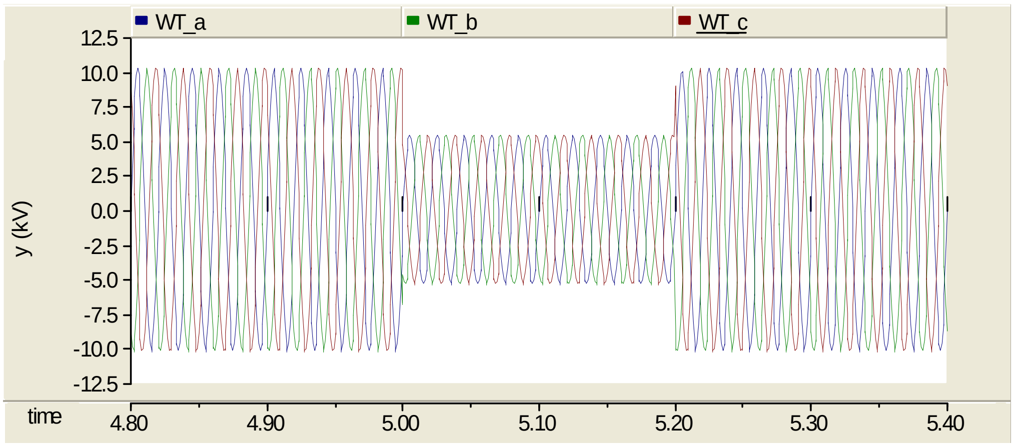

Figure 6.2 WTS source voltages at three phase balanced fault.

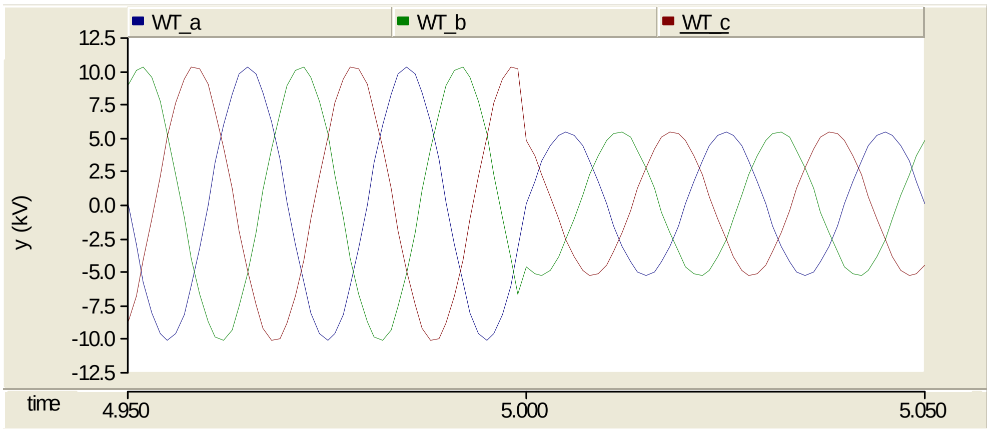

Figure 6.3 Starting region of WTS voltages at three phase balanced fault.

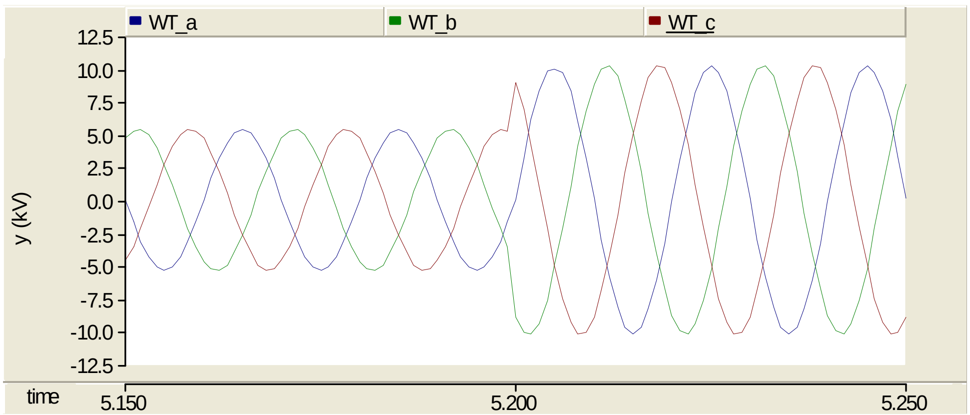

Figure 6.4 Ending region of WTS voltages at three phase balanced fault.

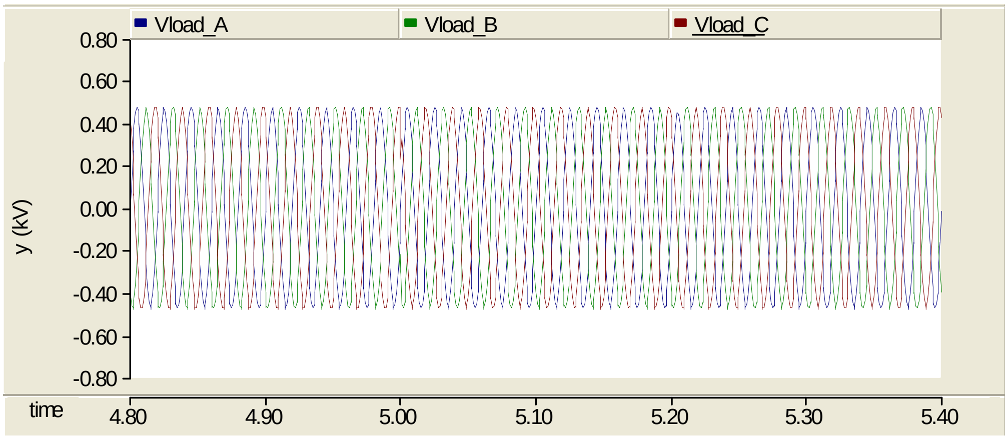

Figure 6.5 Load voltages at three phase balanced fault.

Figure 6.5 shows the load voltages in all process. The simulation has duration of 0.6 s. The transitions can be observed at the Figure 6.6 which shows the transition of WTS to alternate source at 5 s. The fault is detected at 5.2 s and the transition of back to WTS source from alternate source is shown in Figure 6.7.

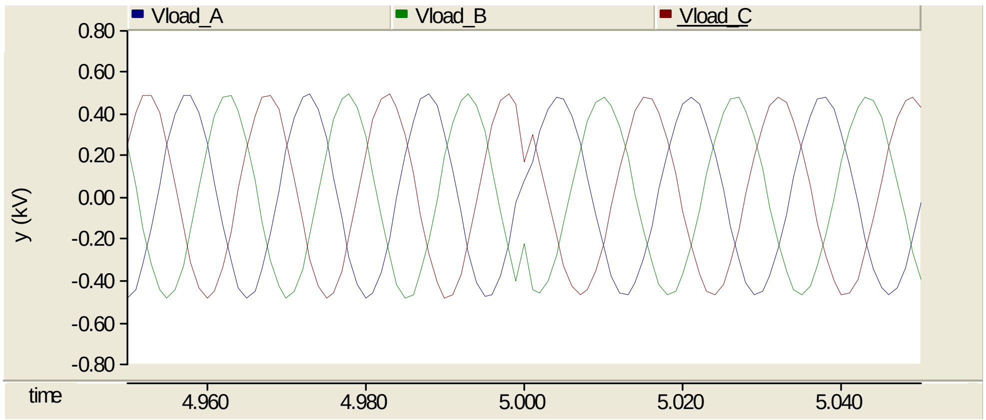

Figure 6.6 WTS to AS transition during three phase balanced fault.

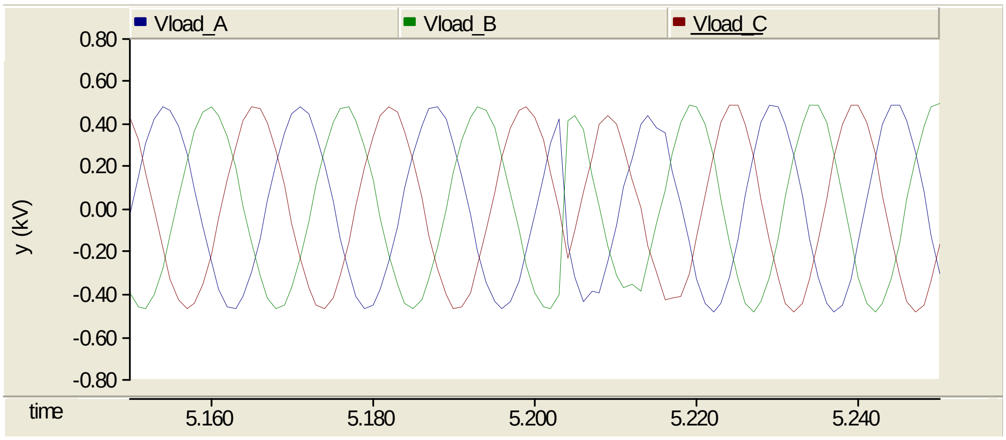

Figure 6.7 AS to WTS transition after three phase balanced fault.

Figure 6.8 shows the magnitude of the error signal. Without fault conditions the value of the error signal is about zero. Since symmetrical fault occurs, V_p is calculated which is a DC value. This signal which is passed through a low pass filter has a cut off frequency 50 Hz. The filter attenuates impacts of voltage transients and introduces a certain amount of delay to the error signal which is determined by the filter cut-off frequency. If the error signal is bigger than 0.1 (10 % sag) system start transfer.

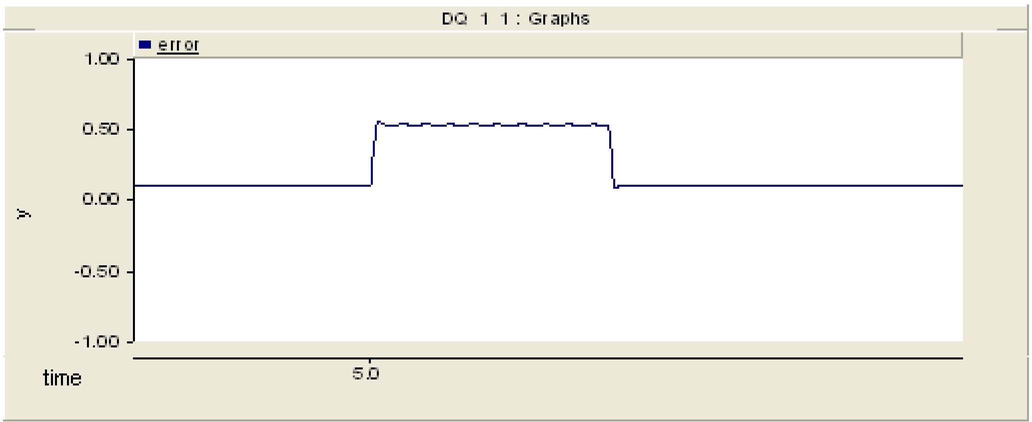

Figure 6.8 Error signal at three phase balanced fault.

Figure 6.9 and Figure 6.10 show the gates positions for two feeder at time between 4.8 s and 5.4 s Wind Tr Signal is on and Valt Tr Signal is off at fault duration after fault Wind Tr Signal is on and Valt Tr Signal is off.

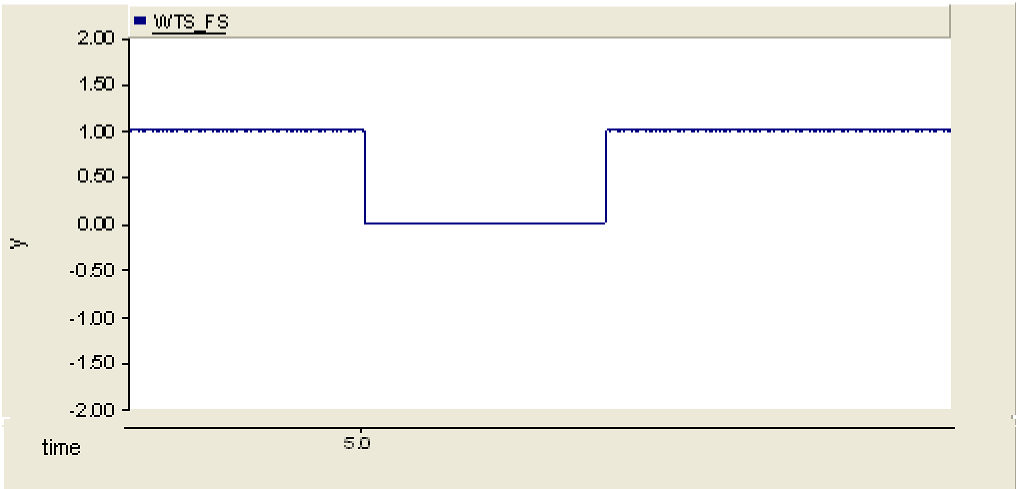

Figure 6.9 WTS feeder firing signal at three phase balanced fault.

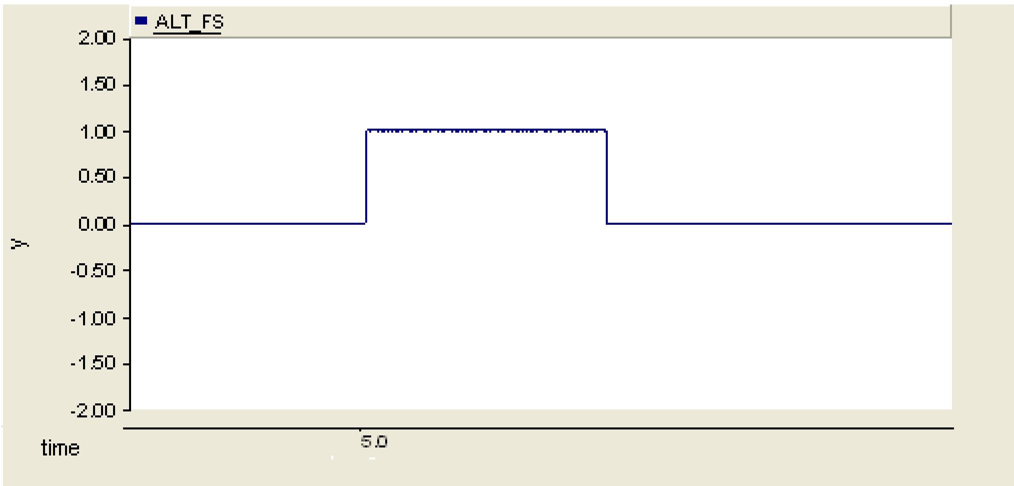

Figure 6.10 Alternate feeder firing signal at three phase balanced fault.

Figures 6.11-6.13 show the addition of line currents of WTS and alternate source which were measured from the high voltage side of the transformer. In the Figures the blue colored graphs represents WTS currents and green colored currents represents alternate source currents. It is seen that load is feed from only one of the sources, there isn't any source paralleling and there isn't any cross currents.

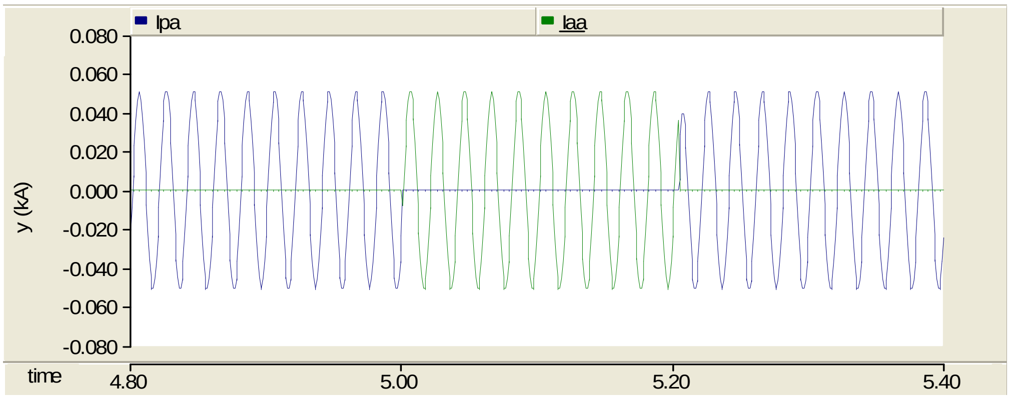

Figure 6.11 Current phase A at three phase balanced fault.

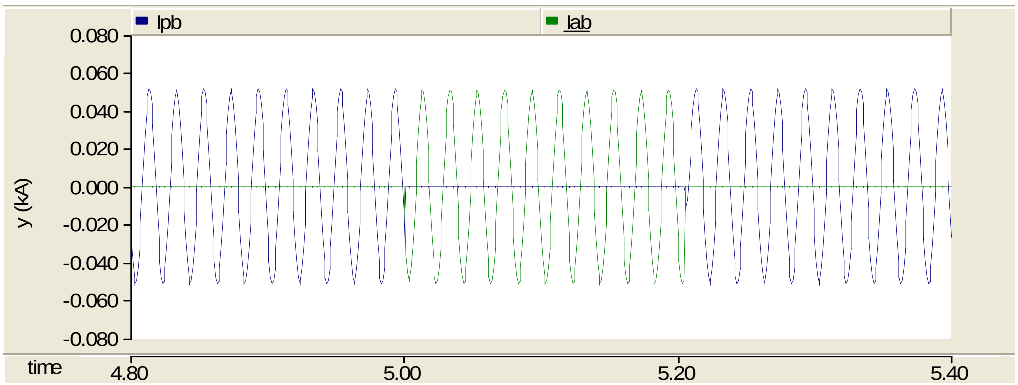

Figure 6.12 Current phase B at three phase balanced fault.

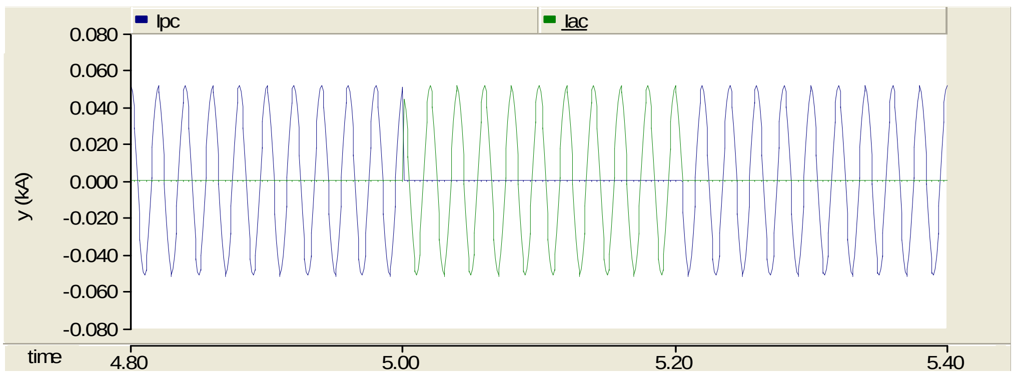

Figure 6.13 Current phase C at three phase balanced fault.

Figures 6.14-6.16 show the load currents which were measured the low voltage side of load transformer.

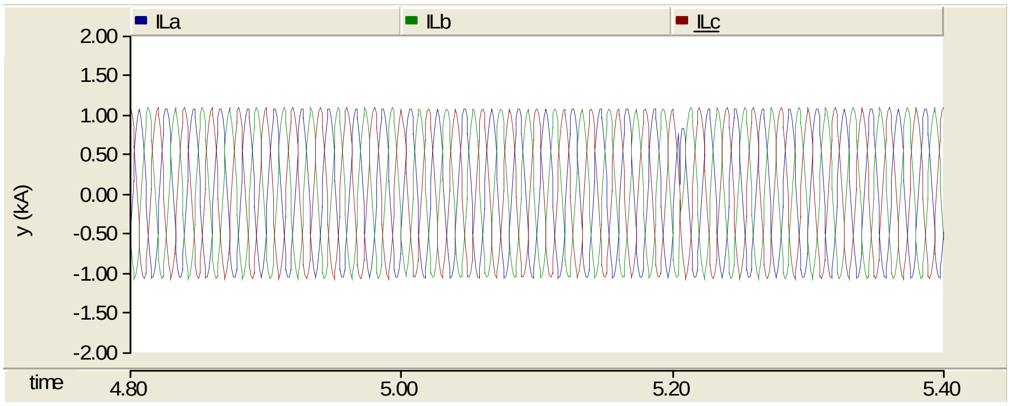

Figure 6.14 Load currents at three phase balanced fault.

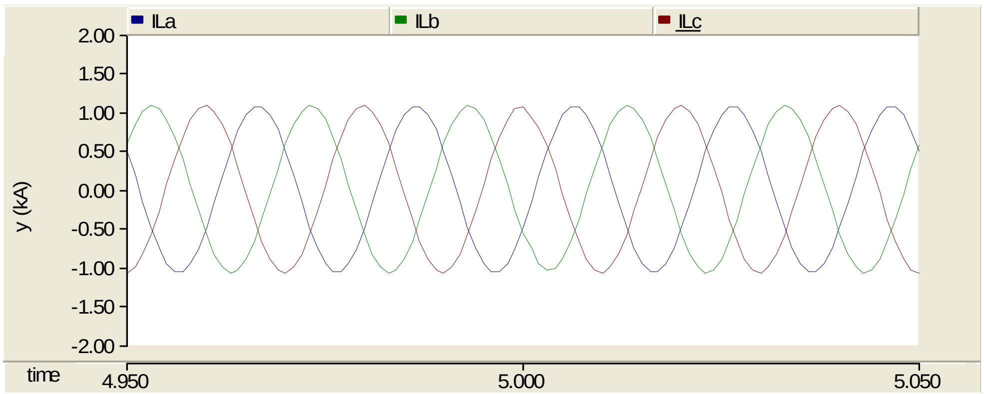

Figure 6.15 Starting region of load currents at three phase balanced fault.

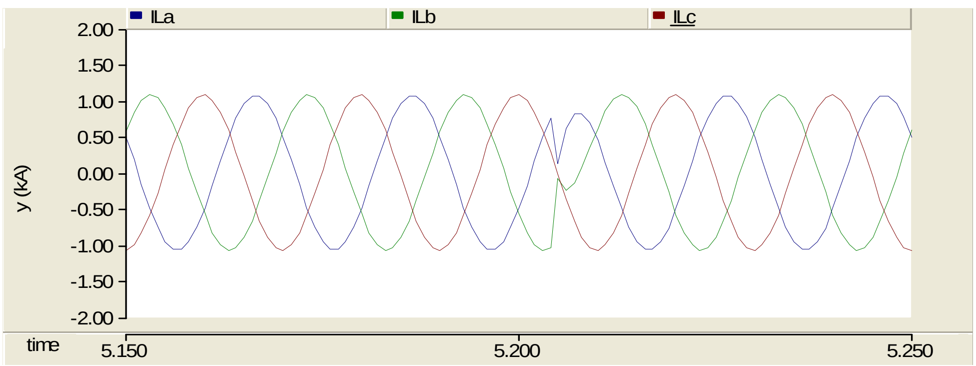

Figure 6.16 Ending region of load currents at three phase balanced fault.

Figures 6.17-6.19 show the WTS currents which were measured from high side of the source transformer.

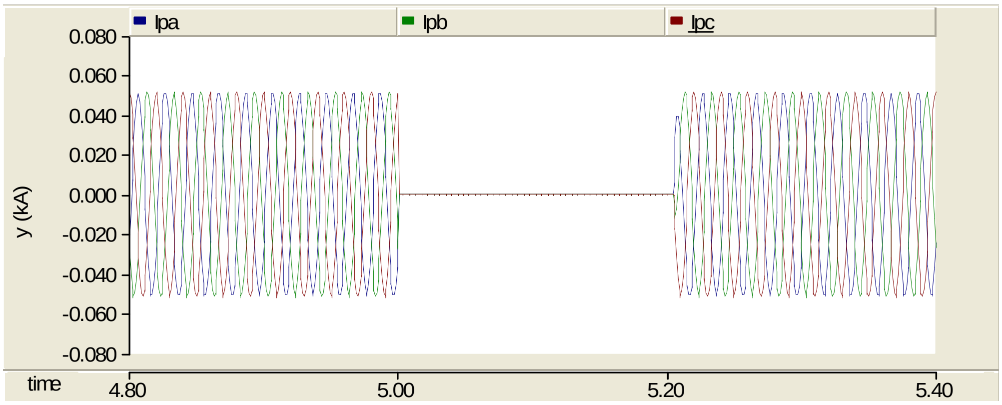

Figure 6.17 WTS currents at three phase balanced fault.

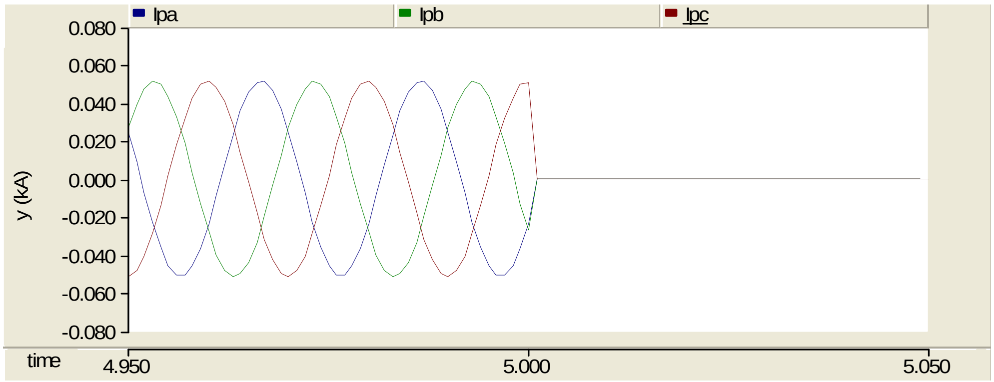

Figure 6.18 Starting region of WTS currents at three phase balanced fault.

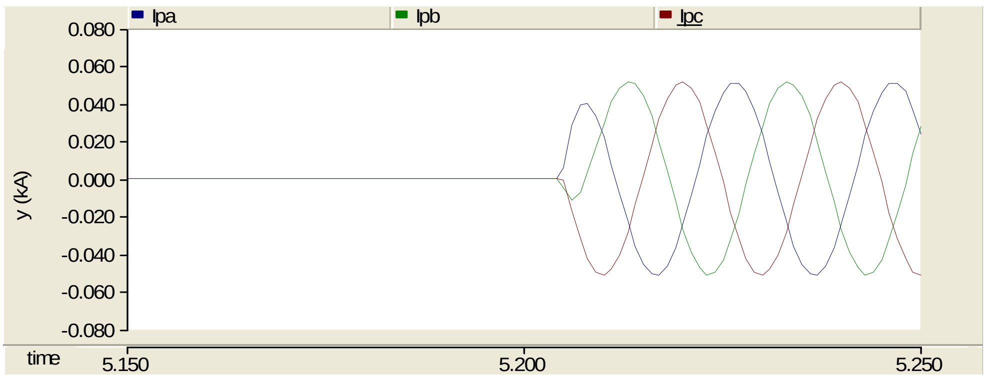

Figure 6.19 Ending region of WTS currents at three phase balanced fault.

Figures 6.20-6.22 show the alternate source currents which were measured from high side of the source transformer.

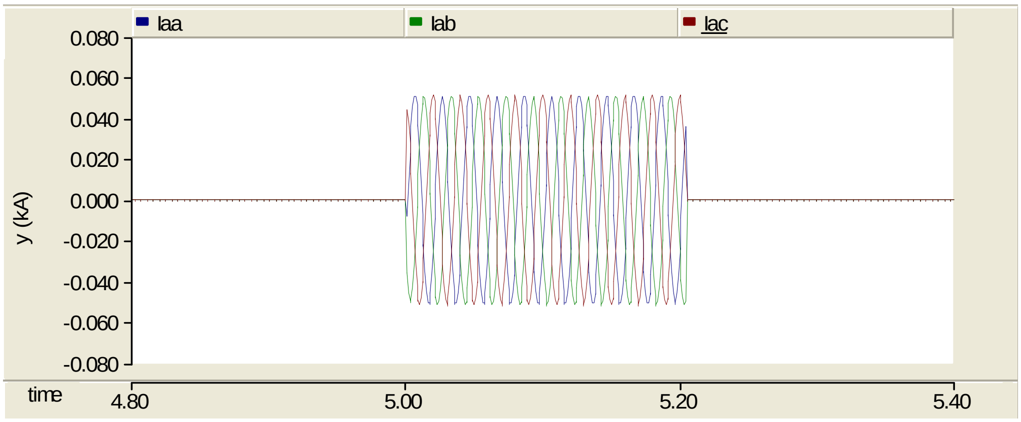

Figure 6.20 AS currents at three phase balanced fault.

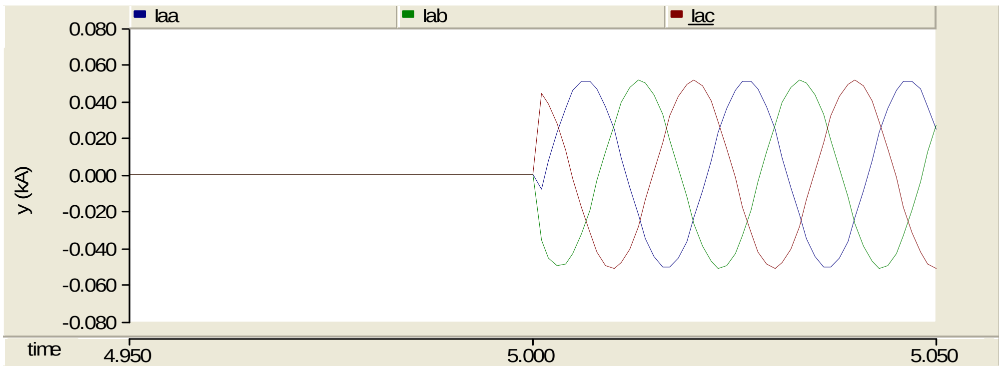

Figure 6.21 Starting region of AS currents at three phase balanced fault.

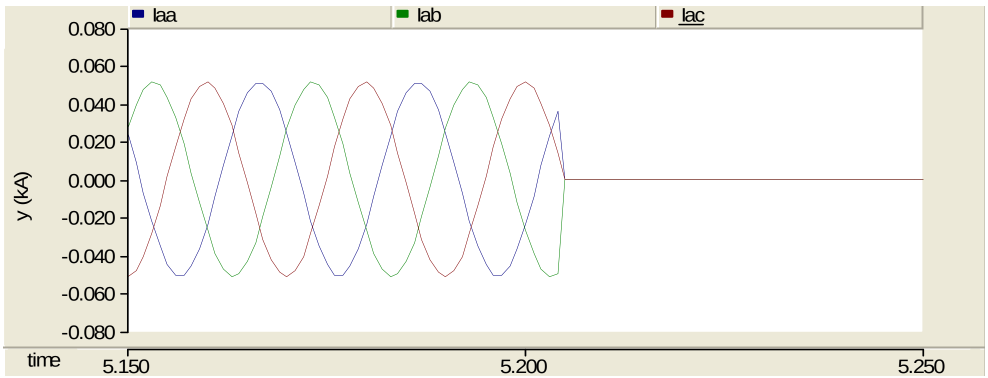

Figure 6.22 Ending region of AS currents at three phase balanced fault.

6.1.2 Case 2: Under Single Phase to Ground Fault

Figure 6.23 shows the fault circuit of phase to ground fault case. This single phase fault is implemented to phase A. The fault occurs at t_1= 5.4 s and detected at t_2=5.6 s. Figures 6.24-6.26 show the preferred source voltage at fault duration.

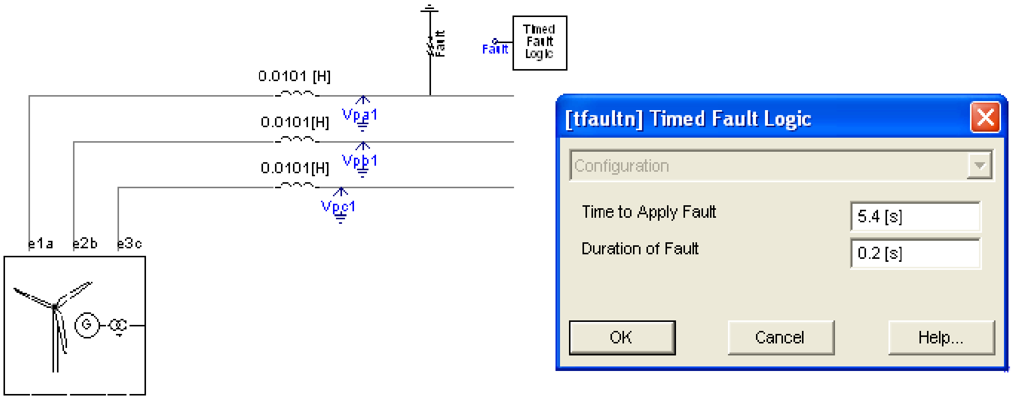

Figure 6.23 Fault block at single phase to ground fault.

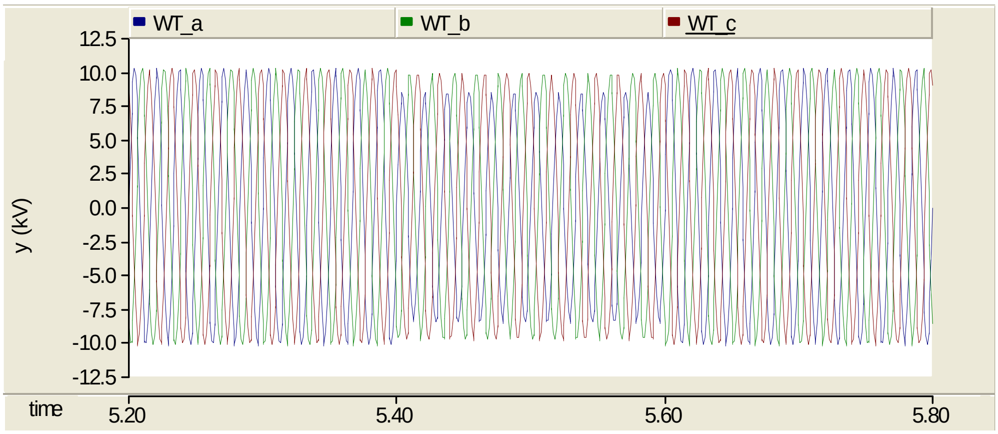

Figure 6.24 WTS voltages at single phase to ground fault.

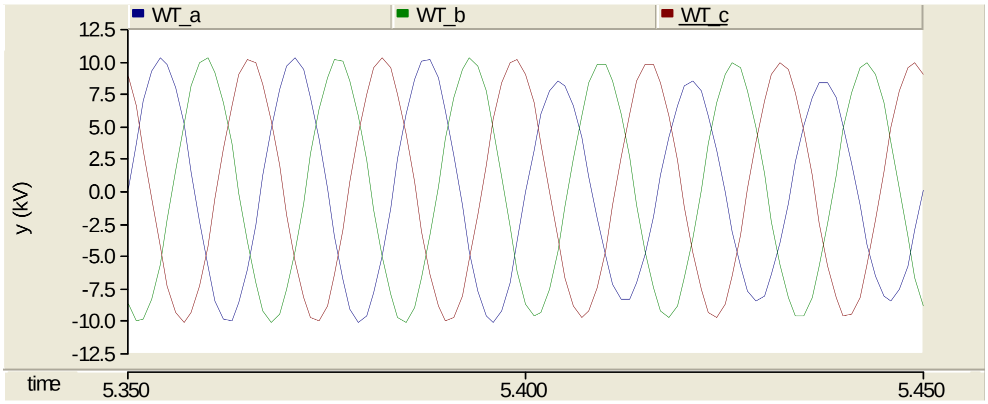

Figure 6.25 Starting region of WTS voltages at single phase to ground fault.

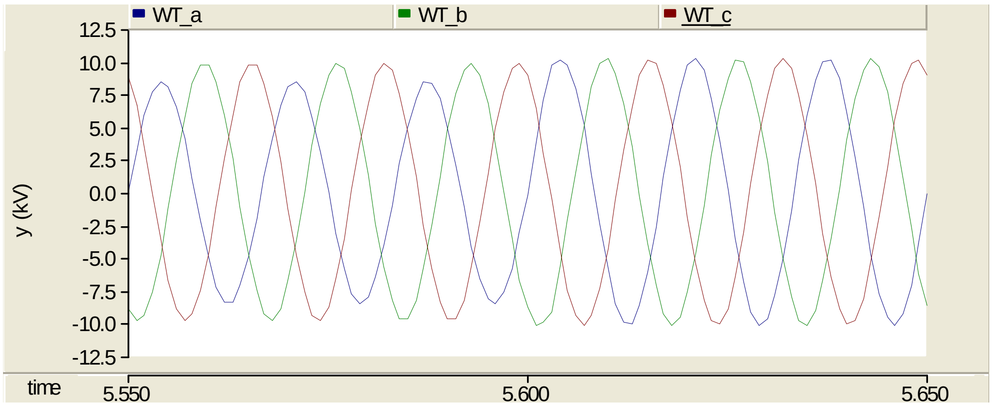

Figure 6.26 Ending region of WTS voltages at single phase to ground fault.

Figure 6.27 shows the load voltages in all process. The simulation has duration of 0.6s. Figure 6.28 shows the transition of WTS to alternate source. Figure 6.29 shows that the transition of back to WTS at 5.6 s.

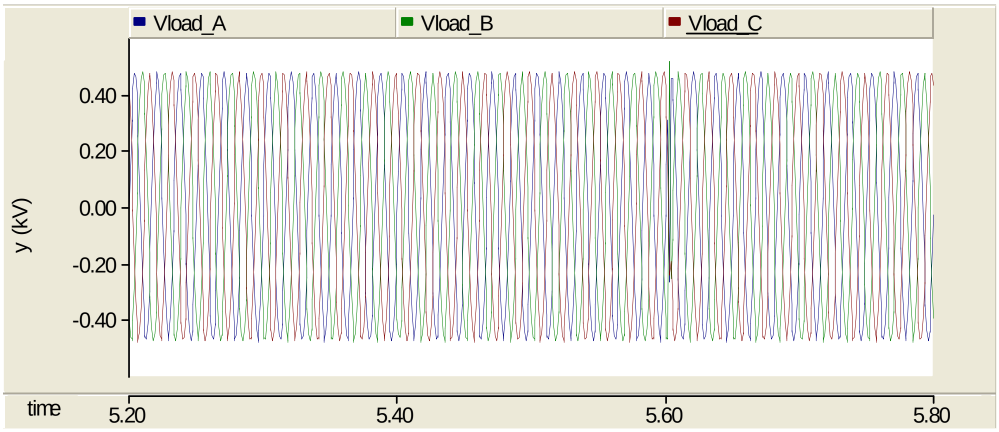

Figure 6.27 Load voltages at single phase to ground fault.

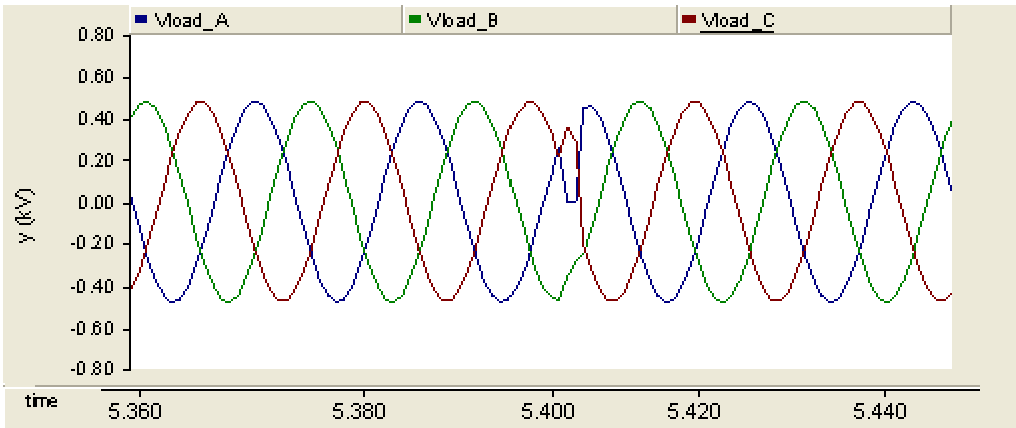

Figure 6.28 WTS to AS transition during single phase fault.

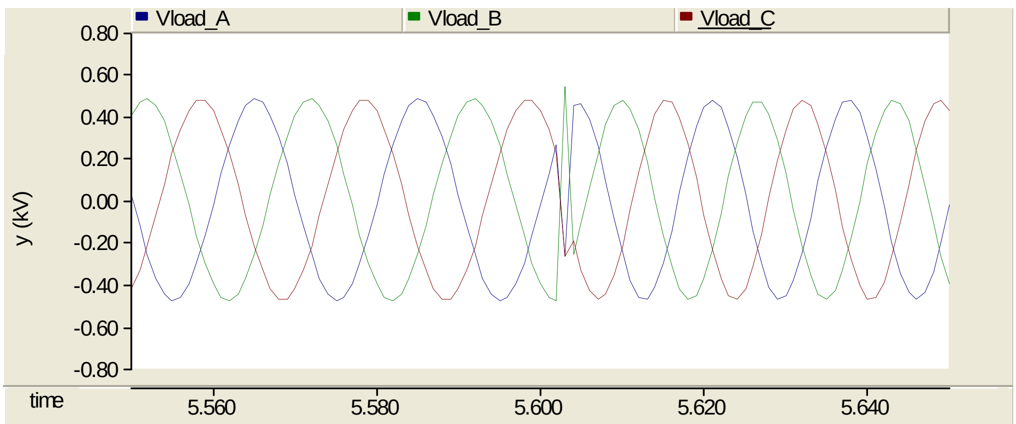

Figure 6.29 Alternate source to WTS transitions after single phase fault.

Figure 6.30 shows the magnitude of the error signal. Without fault conditions the value of the error signal is about zero. Since single phase to ground fault occurs, error signal is calculated. If the error signal is bigger than 0.1 (10 % sag) system starts transfer.

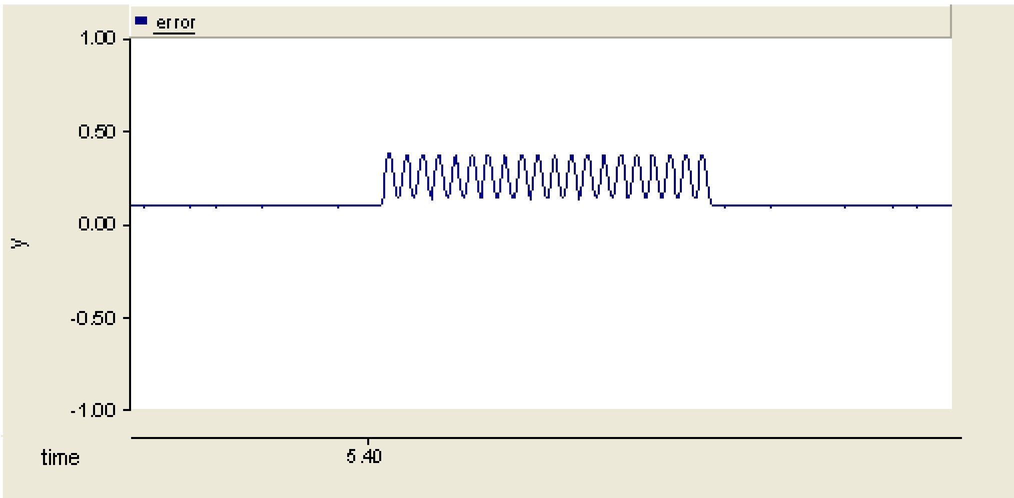

Figure 6.30 Error signal at single phase to ground fault.

Figure 6.31 and Figure 6.32 show the gates positions at time between 5.2 s and 5.8 s Wind Tr Signal is on and Valt Tr Signal is off at fault duration after fault Wind Tr Signal is on and Valt Tr Signal is off.

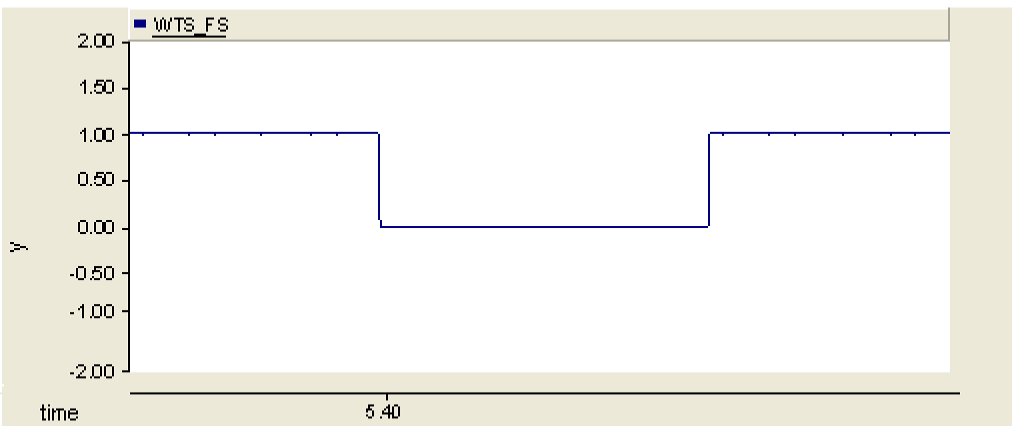

Figure 6.31 WTS feeder firing signal at single phase to ground fault.

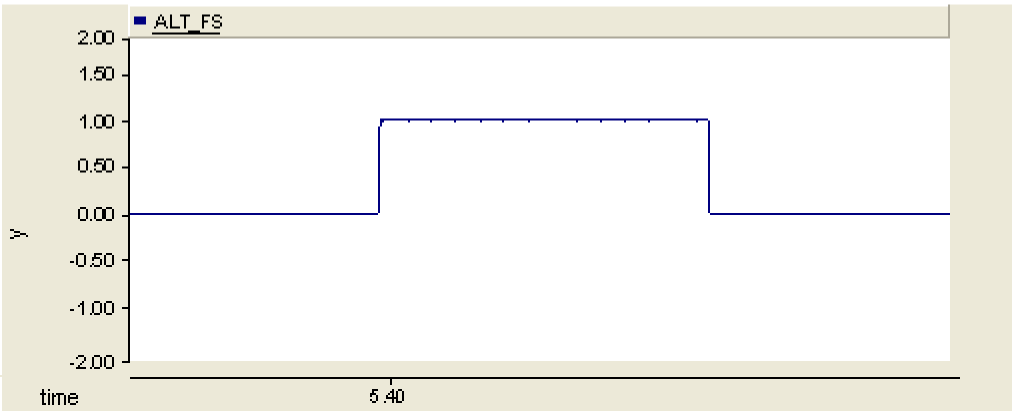

Figure 6.32 Alternate feeder firing signal at single phase to ground fault.

Figures 6.33– 6.35 show the addition of line currents of WTS and alternate source which were measured from the high voltage side of the transformer.

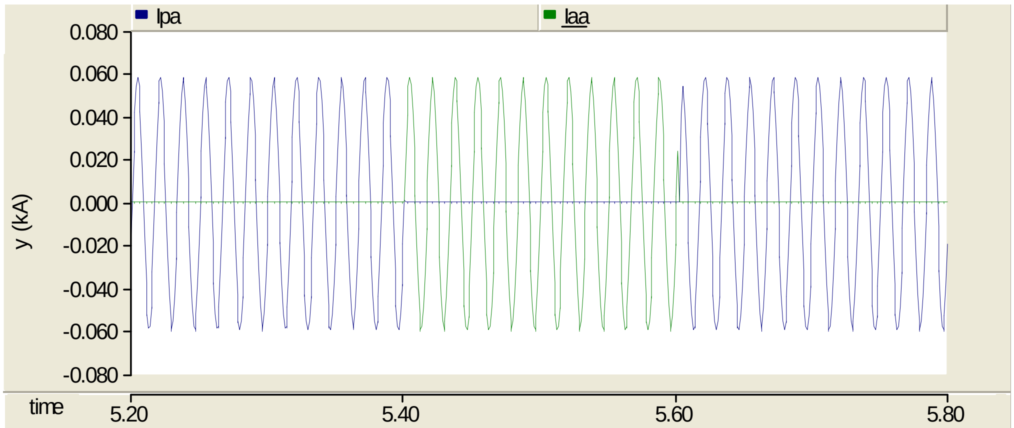

Figure 6.33 Current phase A at single phase to ground fault.

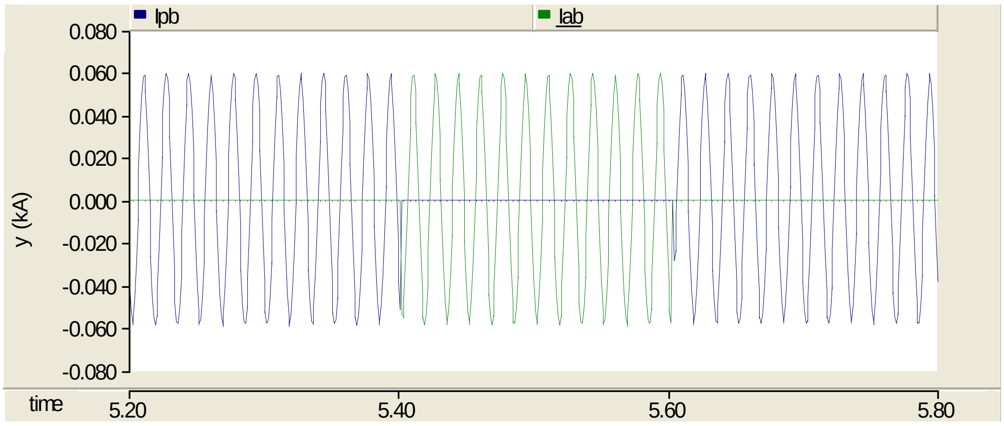

Figure 6.34 Current phase B at single phase to ground fault.

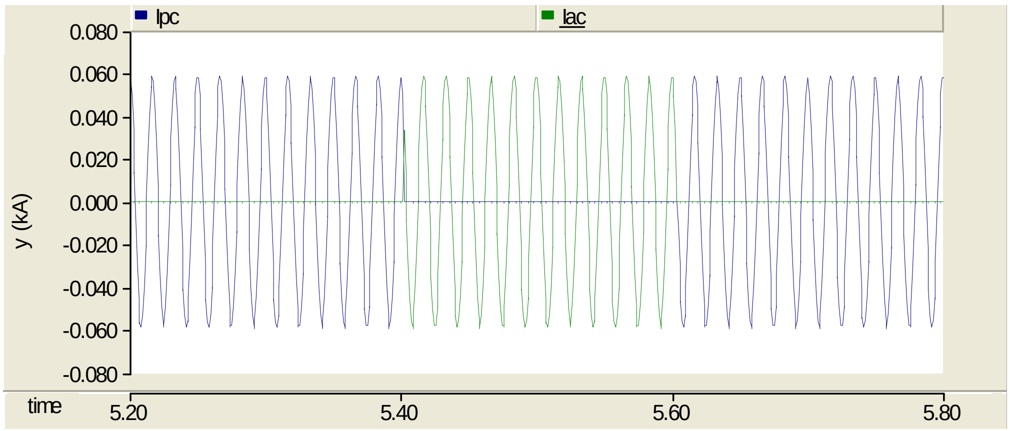

Figure 6.35 Current phase C at single phase to ground fault.

Figures 6.36-6.38 show the load currents which were measured the low voltage side of load transformer.

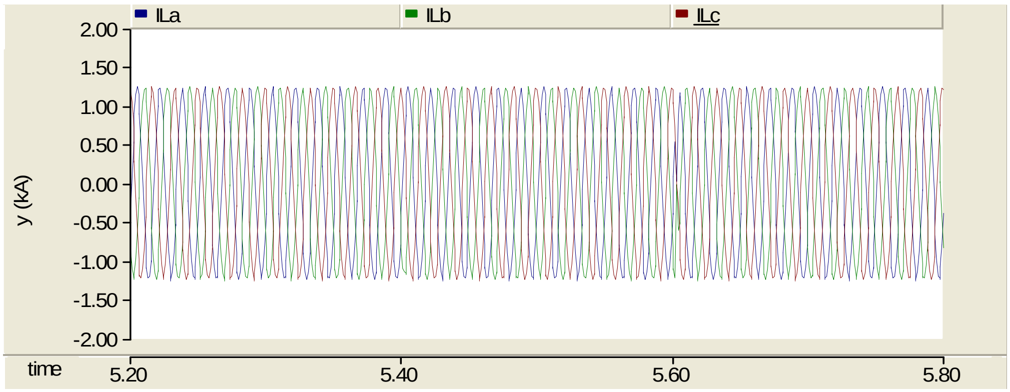

Figure 6.36 Load currents at single phase to ground fault.

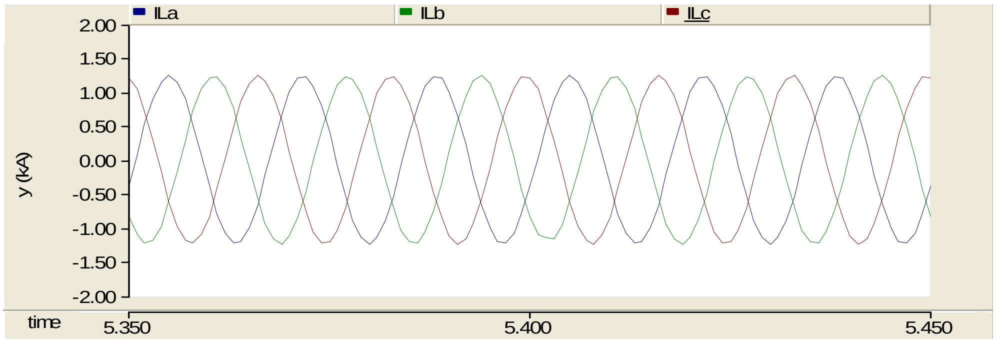

Figure 6.37 Starting region of load currents at single phase to ground fault.

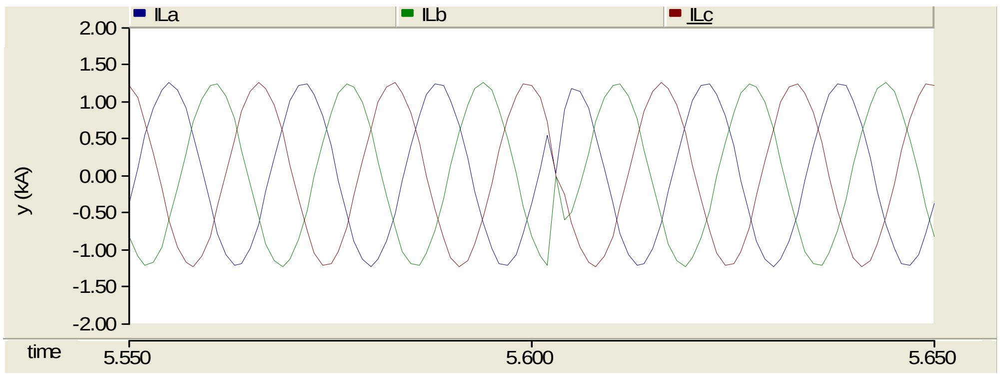

Figure 6.38 Ending region of load currents at single phase to ground fault.

Figures 6.39-6.41 show the preferred source currents which were measured from high side of the source transformer.

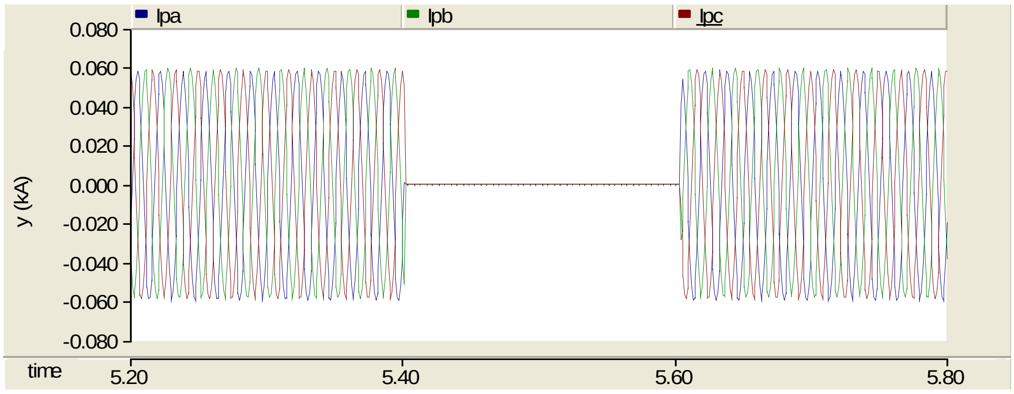

Figure 6.39 WTS currents at single phase to ground fault.

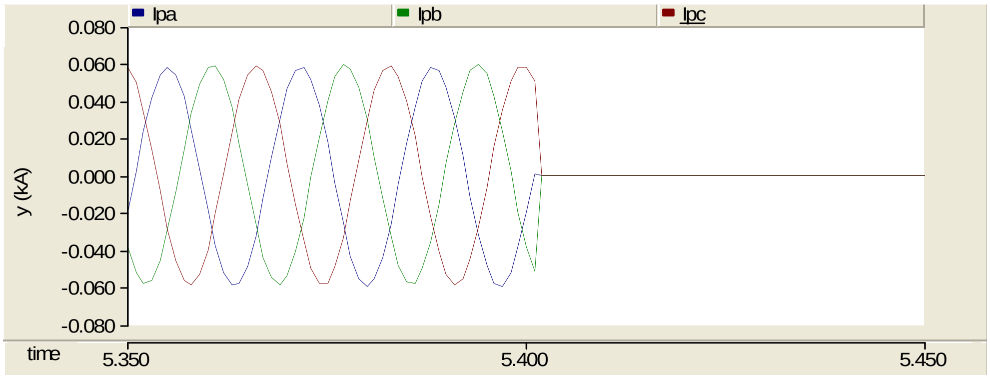

Figure 6.40 Starting region of WTS currents at single phase to ground fault.

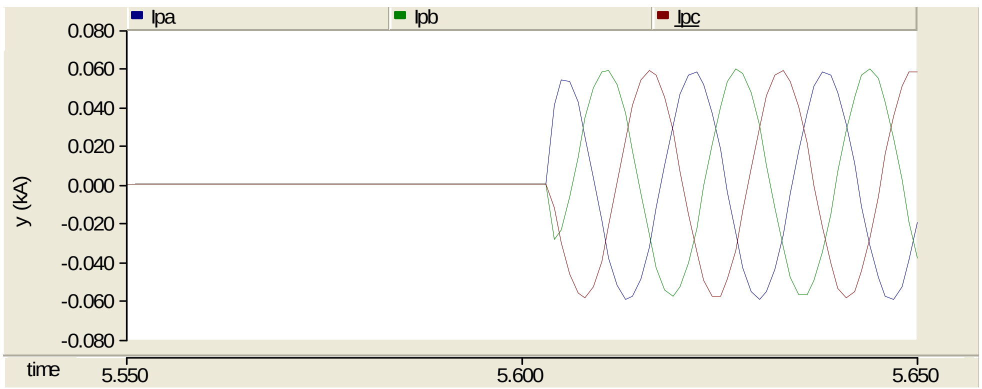

Figure 6.41 Ending region of WTS currents at single phase to ground fault.

Figures 6.42-6.44 show the alternate source currents which were measured from high side of the source transformer.

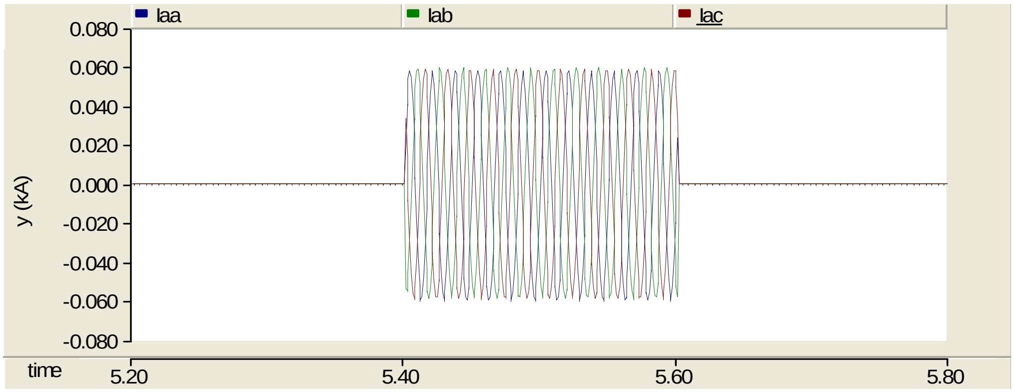

Figure 6.42 AS currents at single phase to ground fault.

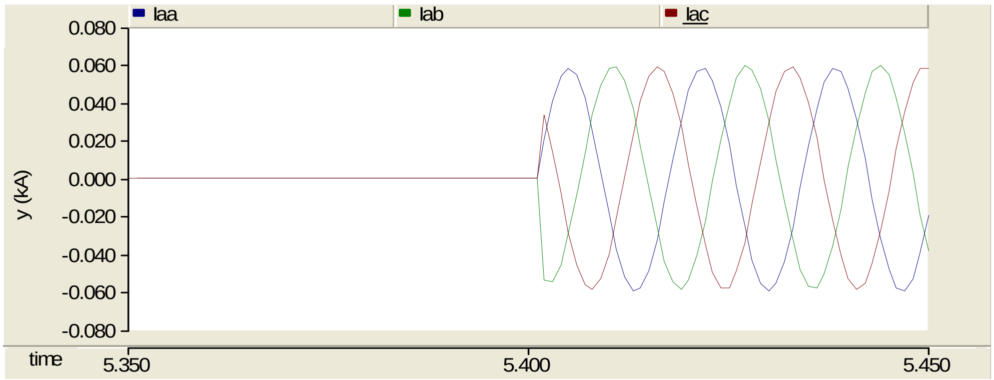

Figure 6.43 Starting region of AS currents at single phase to ground fault.

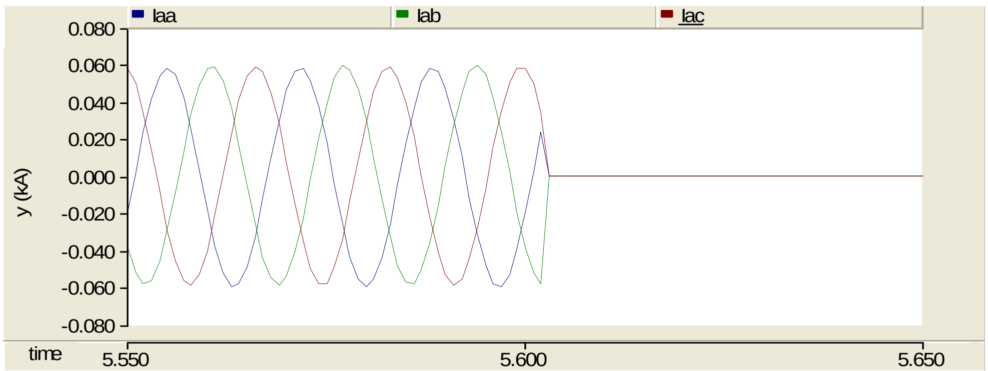

Figure 6.44 Ending region of AS currents at single phase to ground fault.

6.1.3 Case 3: Under Phase to Phase Fault

Figure 6.45 shows the fault circuit of phase to phase under voltage disturbance. The fault which is implemented between phase B and phase C occurs at t_1 = 6.2 s and detected at t_2 =6.4 s. Figures 6.46-6.48 show the WTS voltage at fault duration.

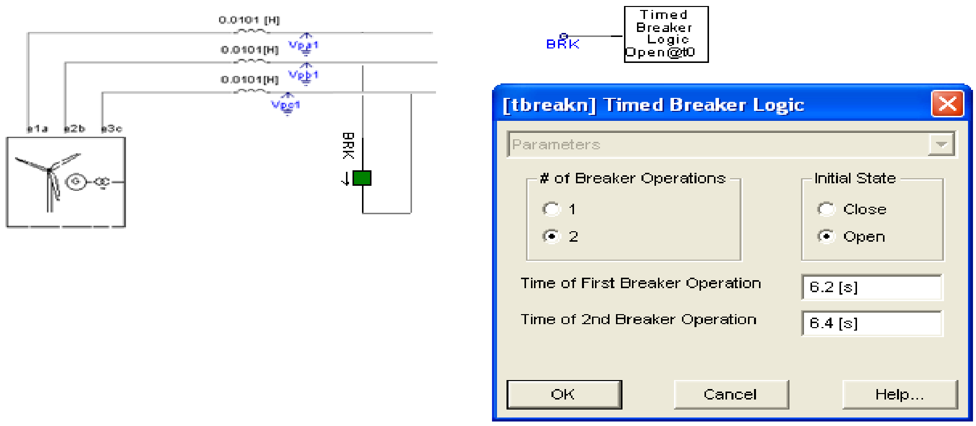

Figure 6.45 Fault block at phase to phase fault.

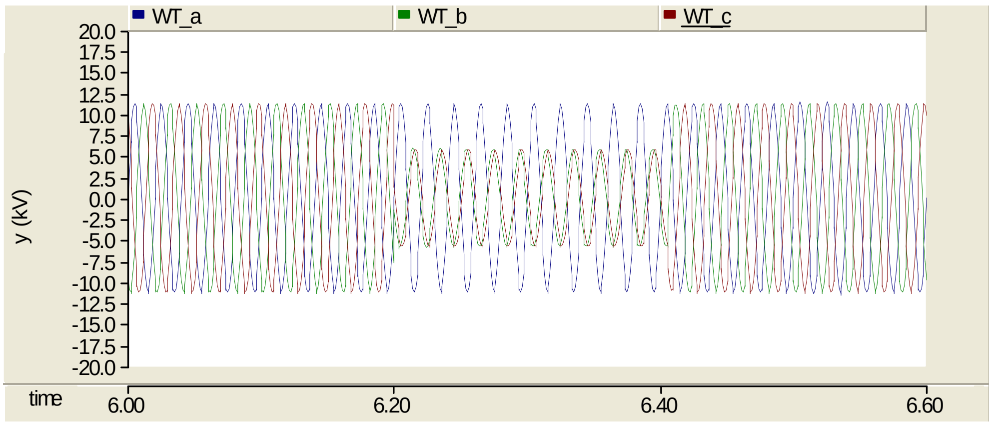

Figure 6.46 WTS voltages at phase to phase fault.

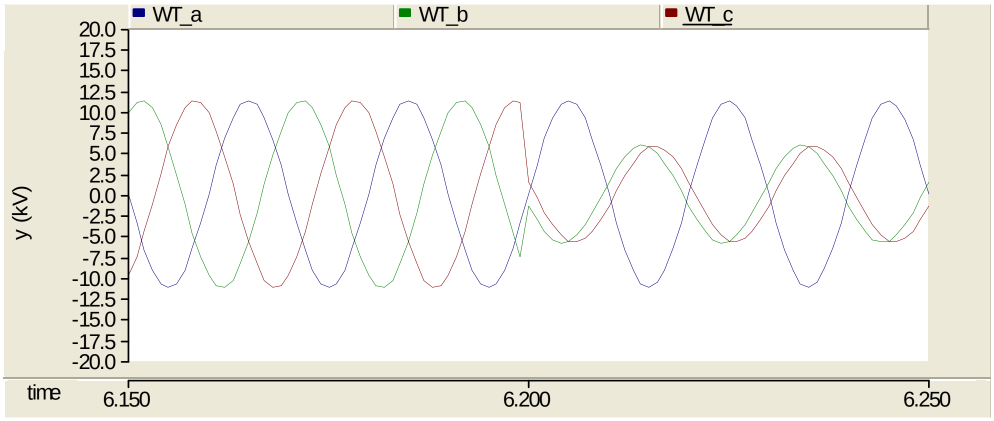

Figure 6.47 Starting region of WTS voltages at phase to phase fault.

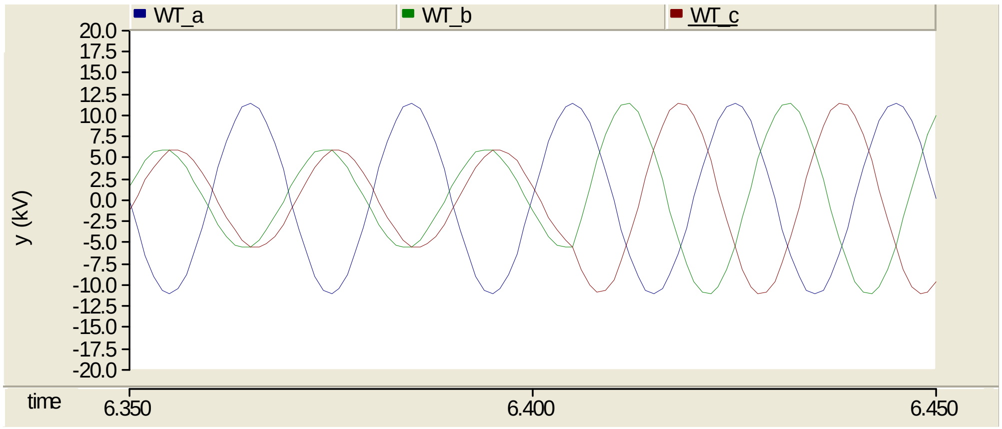

Figure 6.48 Ending region of WTS voltages at phase to phase fault.

Figure 6.49 shows the load voltages. The simulation has duration of 0.6 s. Figure 6.50 shows the transition of WTS to alternate source. Figure 6.51 shows the transition of back to WTS from alternate source.

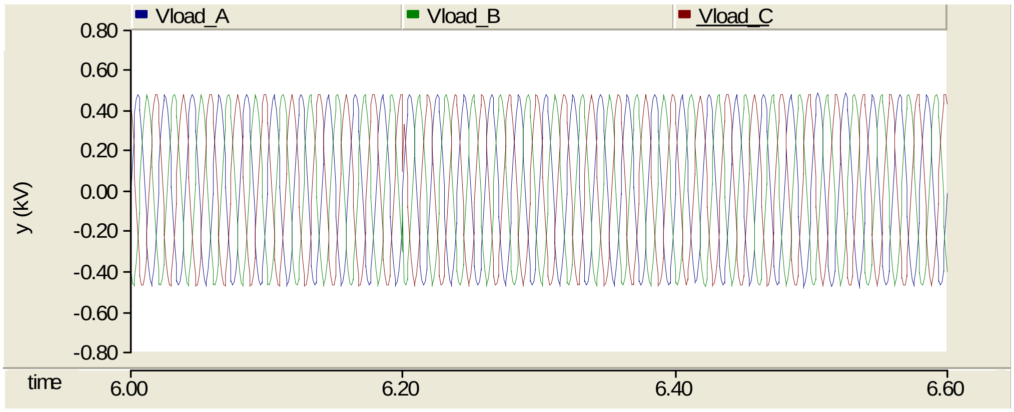

Figure 6.49 Load voltages at phase to phase fault.

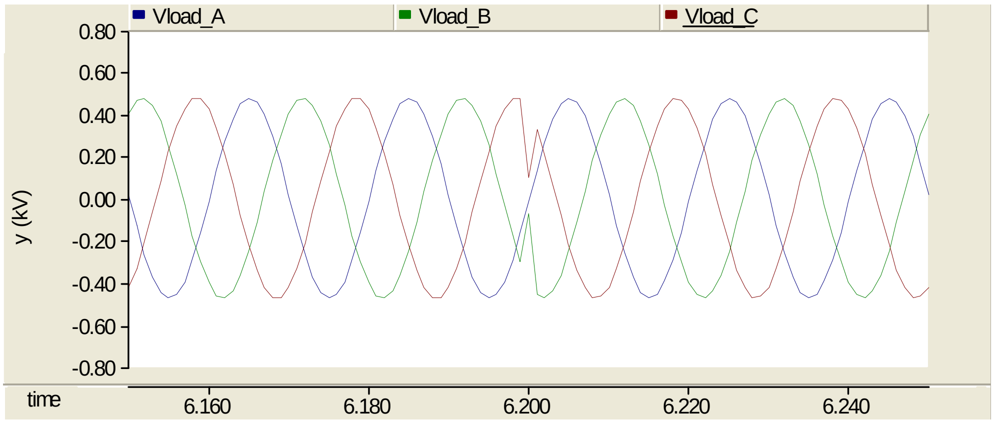

Figure 6.50 WTS to AS transition during phase to phase fault.

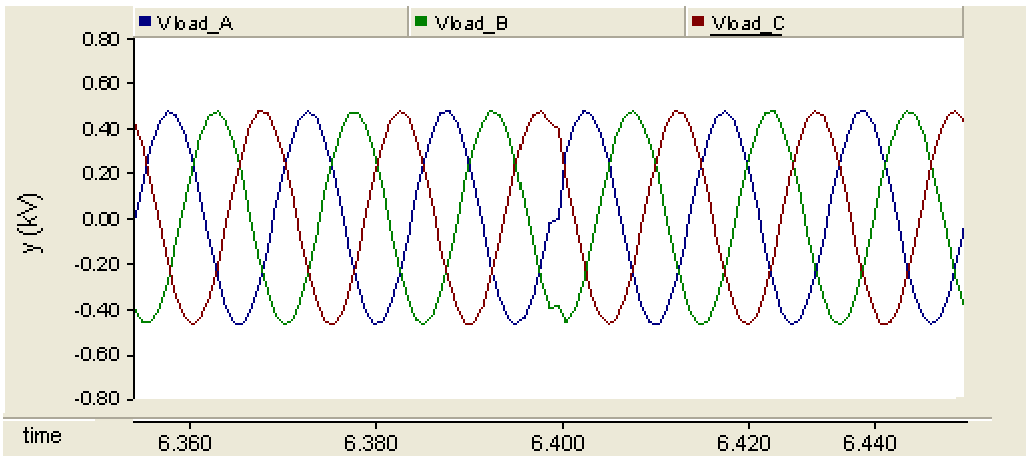

Figure 6.51 AS to WTS transition after phase to phase fault.

Figure 6.52 shows the magnitude of the error signal which is passed through a low pass filter. The voltage sag is unbalanced and contains both positive sequence and negative sequence component.

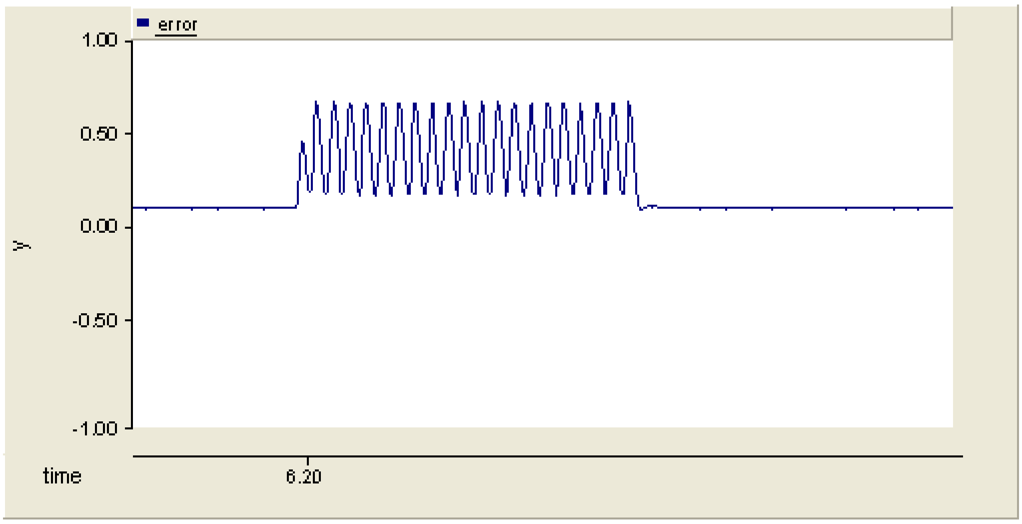

Figure 6.52 Error signal at phase to phase fault.

Figure 6.53 and Figure 6.54 show that gates positions at time between 6 s and 6.6 s Wind Tr Signal is on and Valt Tr Signal is off at fault duration after fault Wind Tr Signal is on and Valt Tr Signal is off.

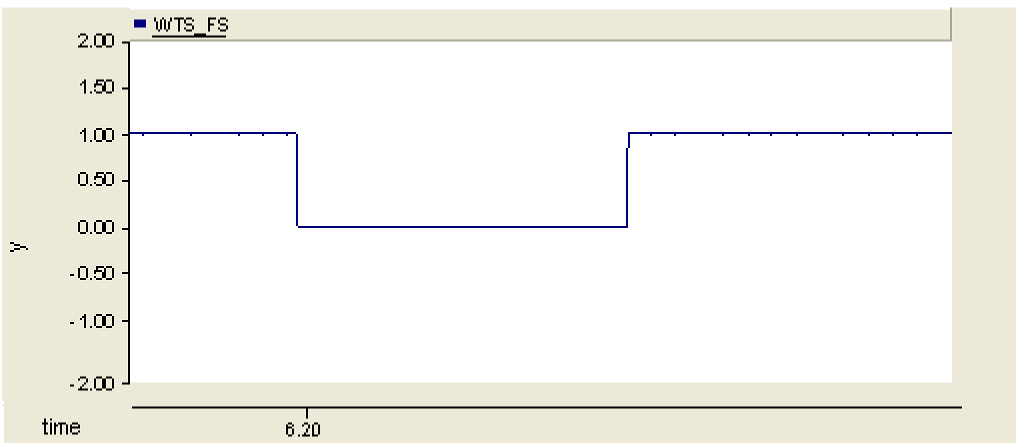

Figure 6.53 WTS feeder firing signal at phase to phase fault.

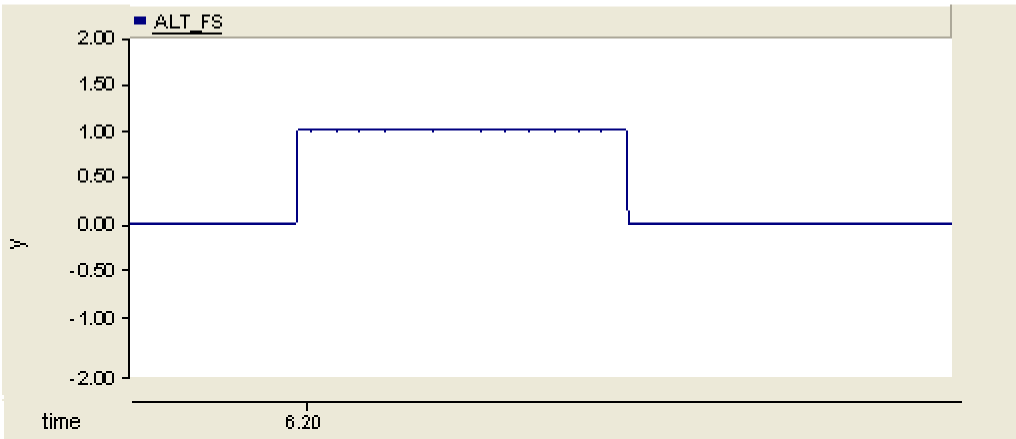

Figure 6.54 Alternate feeder firing signal at phase to phase fault.

The WTS phase currents and alternate source phase currents which were measured from the high voltage side of the transformer are shown in Figures 6.55-6.57, respectively.

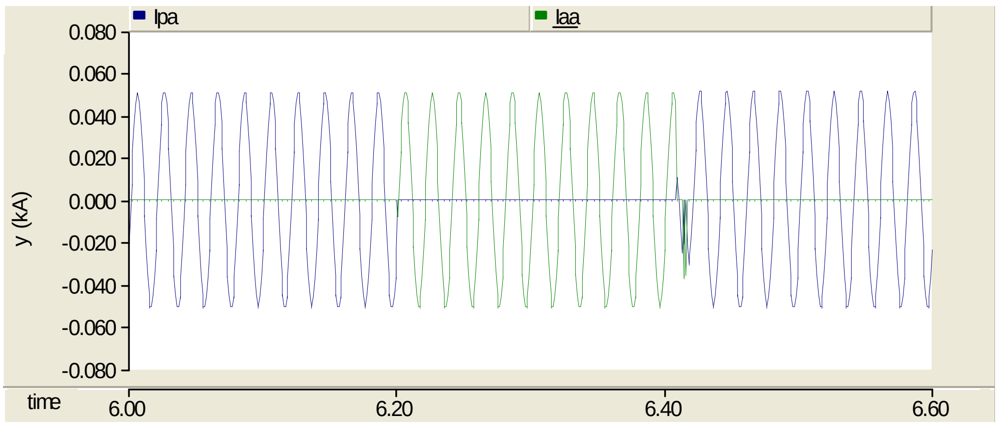

Figure 6.55 Current phase A at phase to phase fault.

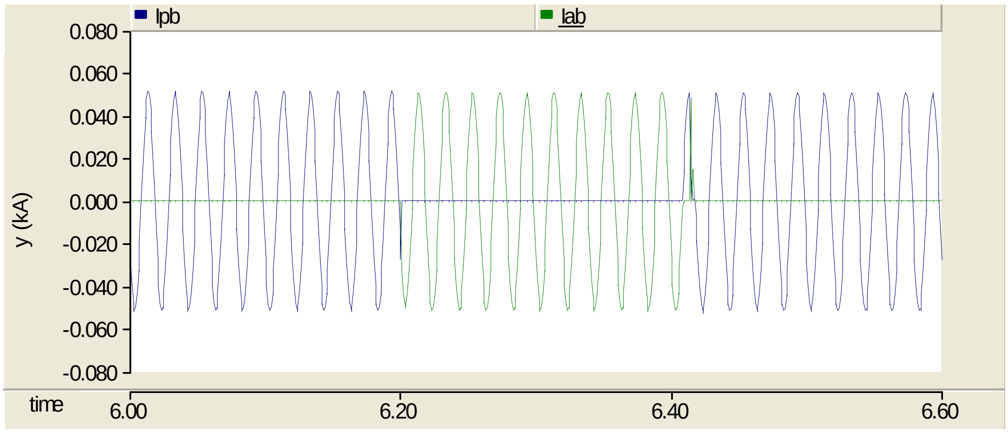

Figure 6.56 Current phase B at phase to phase fault.

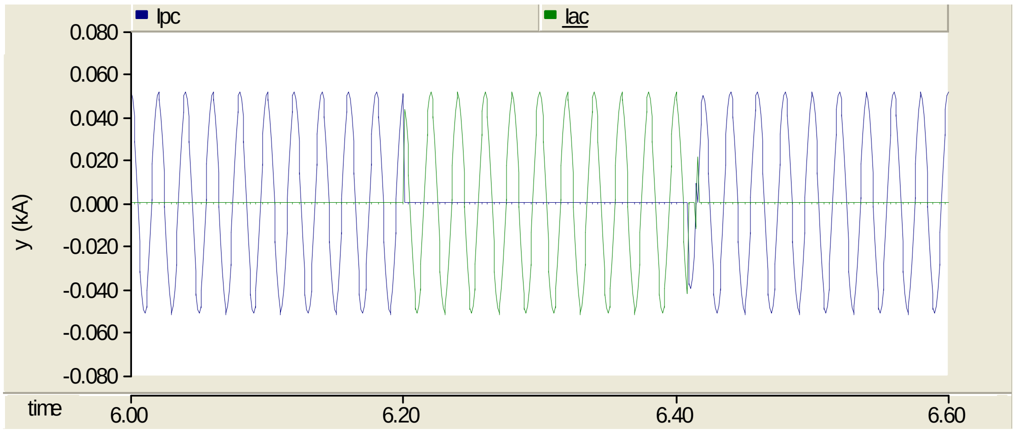

Figure 6.57 Current phase C at phase to phase fault.

Figures 6.58-6.60 show the load currents which were measured the low voltage side of load transformer.

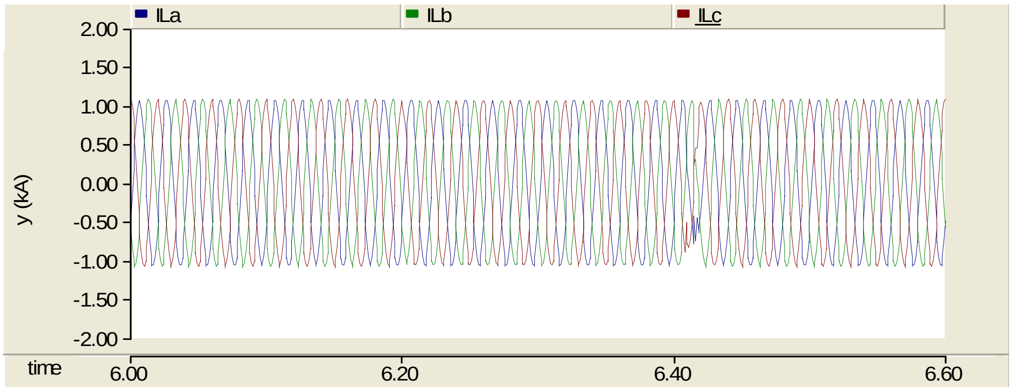

Figure 6.58 Load currents at phase to phase fault.

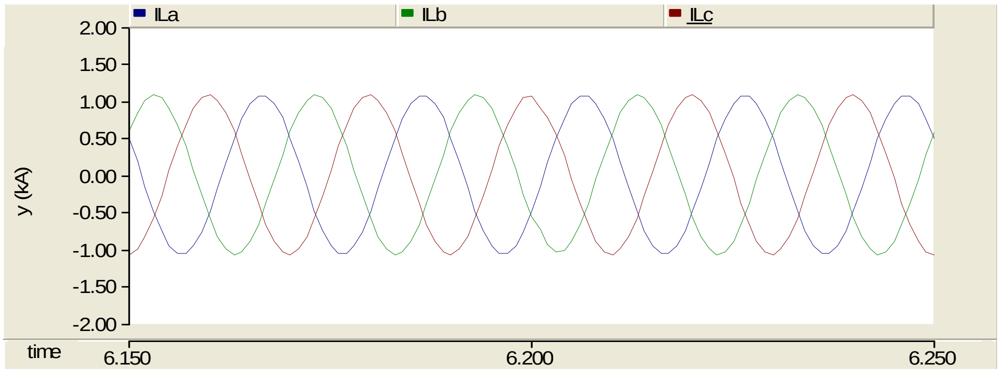

Figure 6.59 Starting region of load currents at phase to phase fault.

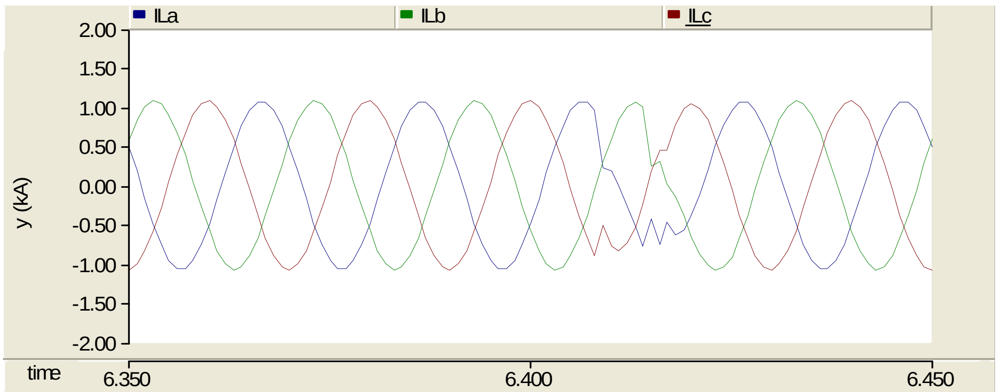

Figure 6.60 Ending region of load currents at phase to phase fault.

Figures 6.61-6.63 show the WTS phase currents which were measured from high side of the source transformer.

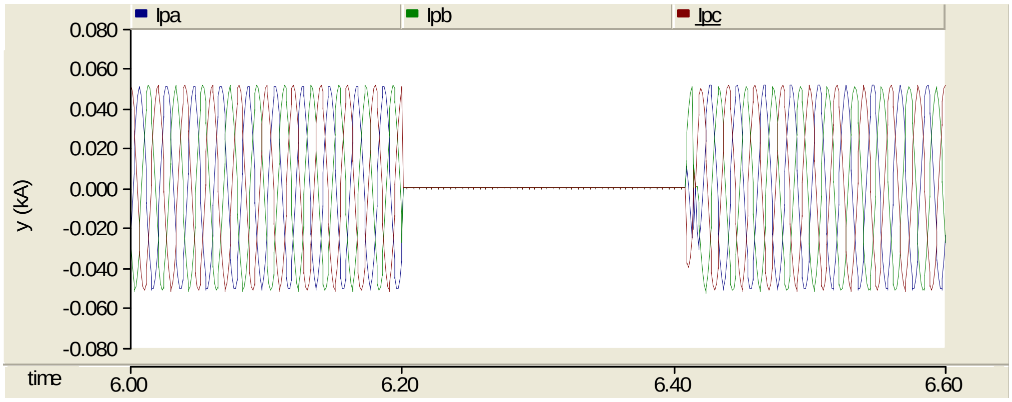

Figure 6.61 WTS currents at phase to phase fault.

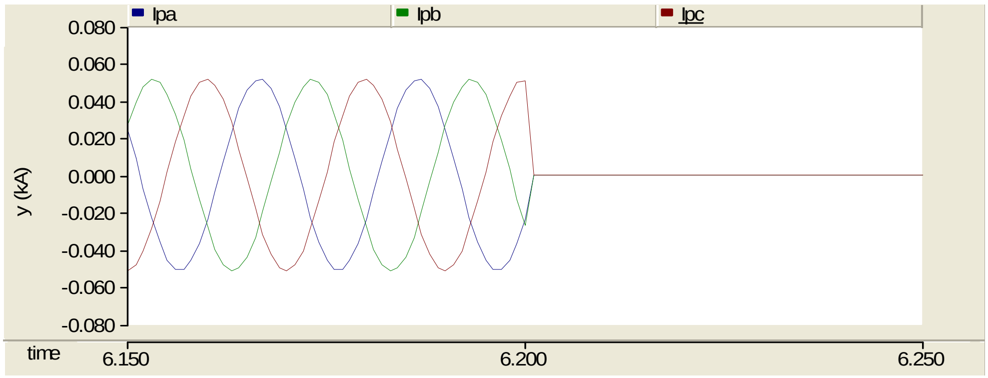

Figure 6.62 Starting region of WTS currents at phase to phase fault.

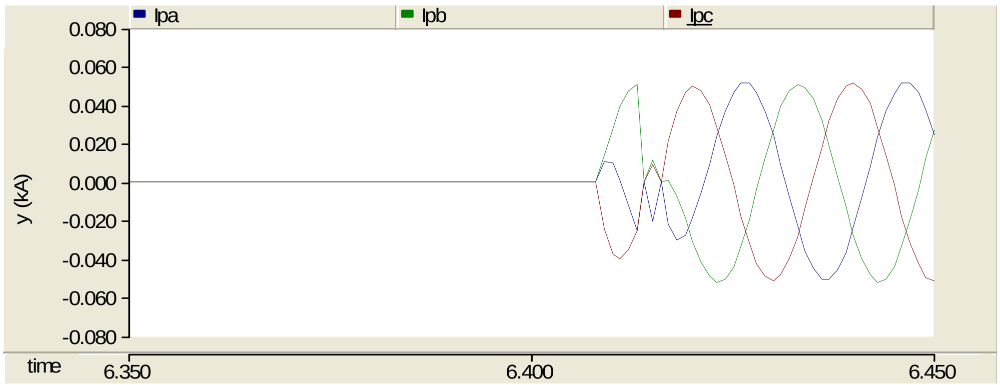

Figure 6.63 Ending region of WTS currents at phase to phase fault.

Figures 6.64-6.66 show the alternate source currents which were measured.

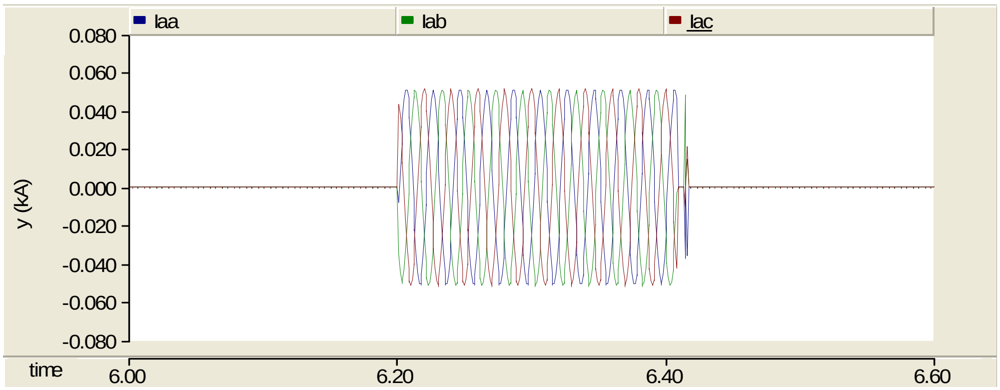

Figure 6.64 AS currents at phase to phase fault.

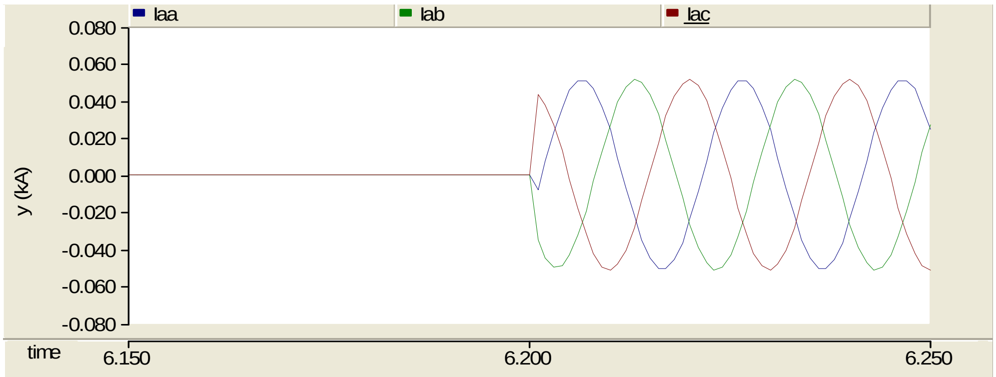

Figure 6.65 Starting region of AS currents at phase to phase fault.

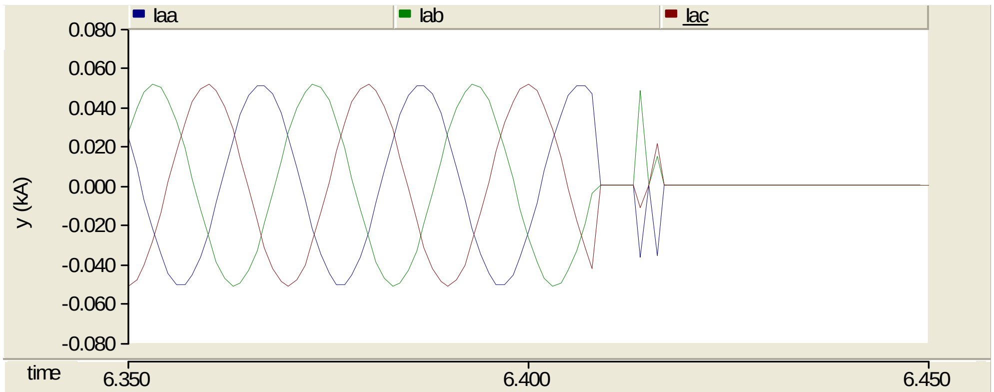

Figure 6.66 Ending region of AS currents at phase to phase fault.

6.2 Short Supply Interruptions

Figure 6.67 shows the interruption of the WTS. The fault occurs at $t_1 = 4.5$ s and detected at $t_2 = 4.8$ s. The simulation duration is 0.7 s.

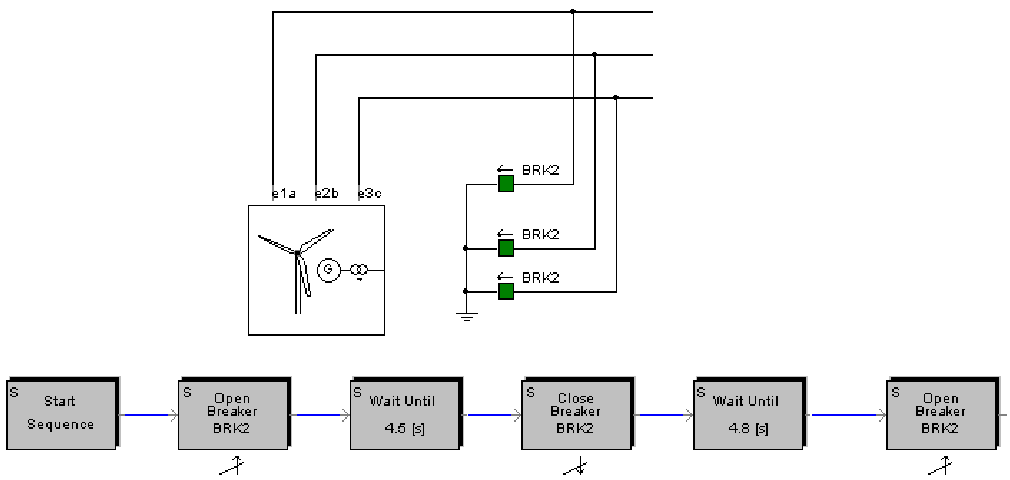

Figure 6.67 Interruption circuit of the WTS.

WTS phase voltages are shown in Figures 6.68-6.70 for all duration of the interruption.

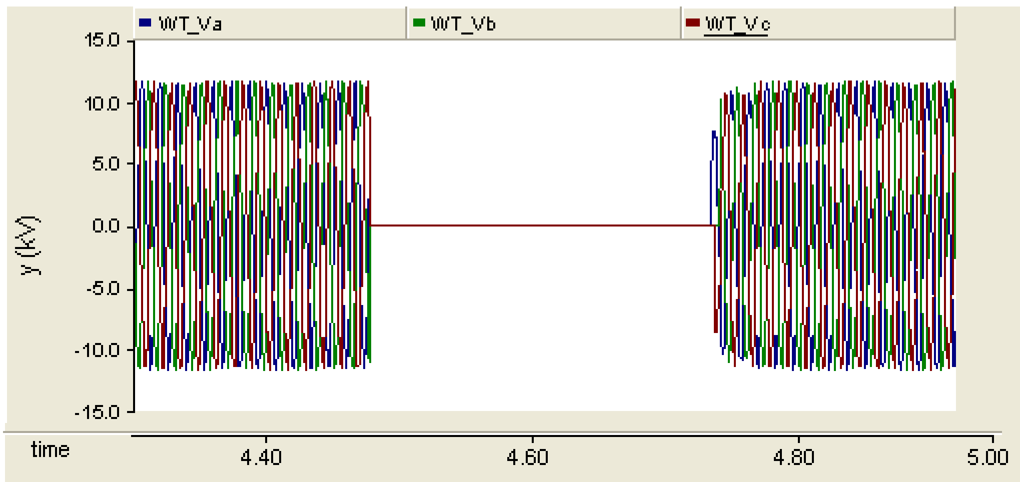

Figure 6.68 WTS voltages during interruption.

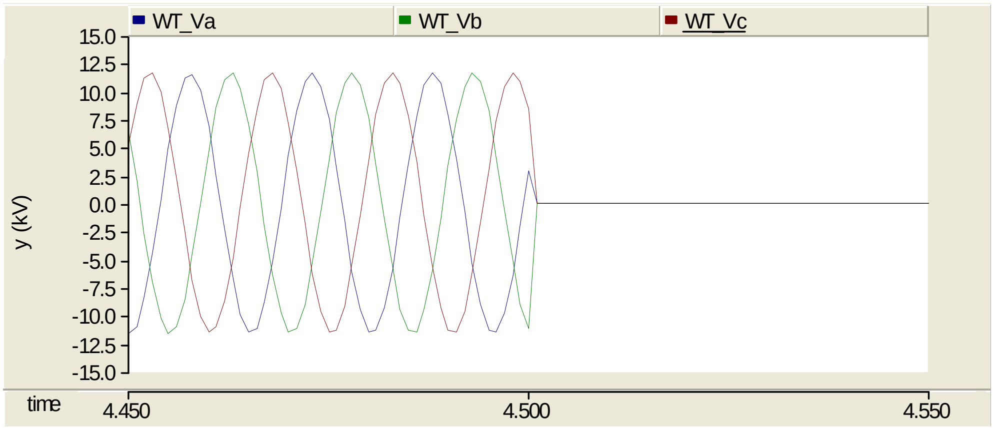

Figure 6.69 Starting region of WTS voltages during interruption.

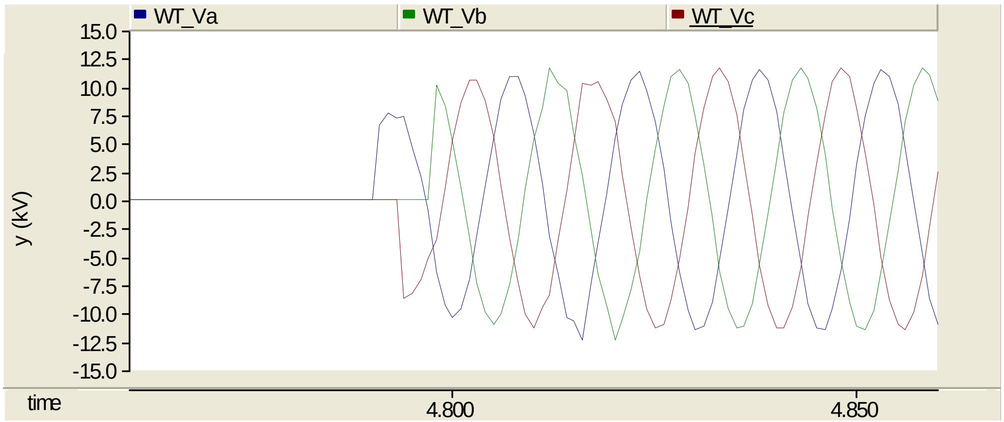

Figure 6.70 Ending region of WTS voltages during interruption.

Load phase voltages are shown in Figures 6.71-6.73 at interruption duration, respectively.

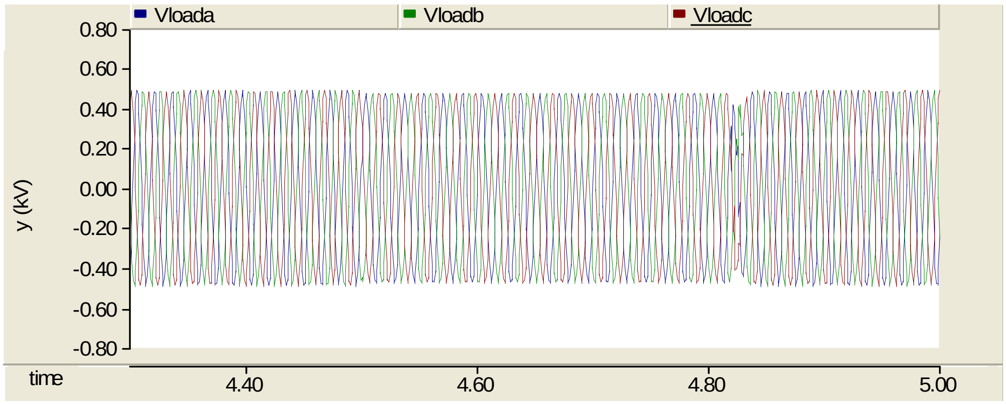

Figure 6.71 Load voltages during interruption.

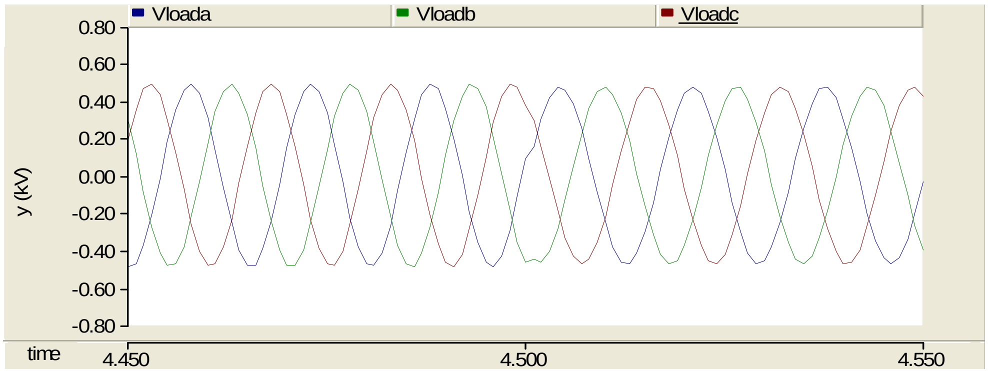

Figure 6.72 Starting region of load voltages during interruption.

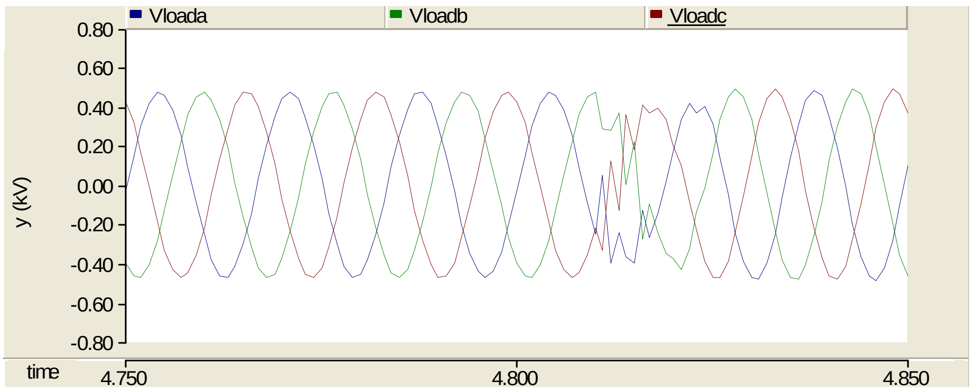

Figure 6.73 Ending region of load voltages during interruption.

The currents of WTS which were measured from the high voltage side of the transformer are shown in Figures 6.74-6.76.

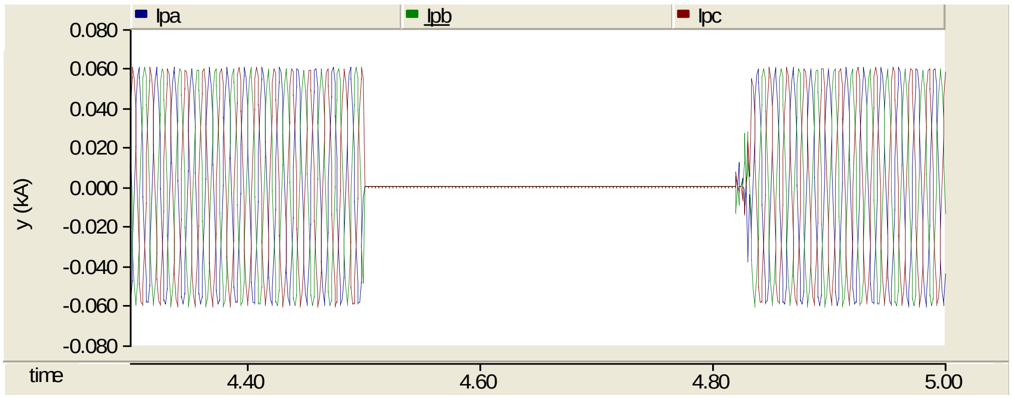

Figure 6.74 Line currents of WTS during interruption.

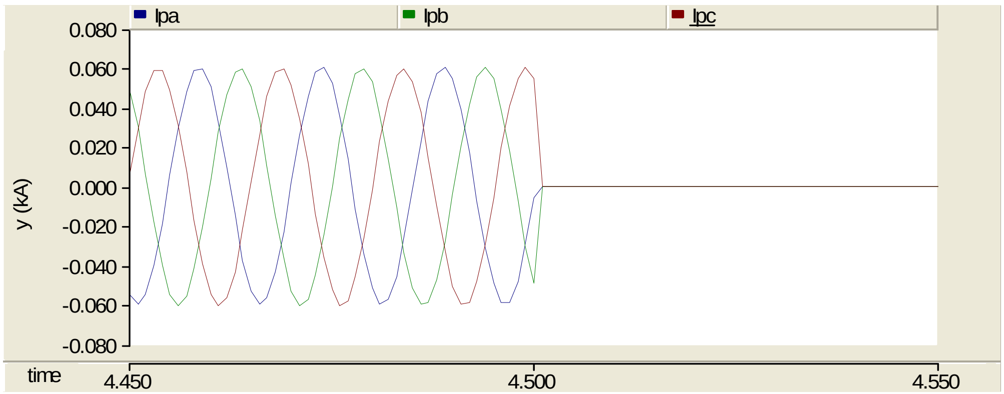

Figure 6.75 Starting region of line currents of WTS during interruption.

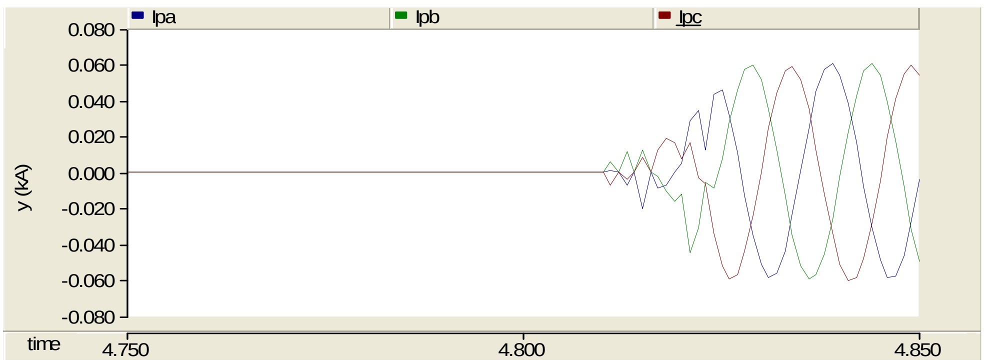

Figure 6.76 Ending region of line currents of WTS during interruption.

Alternate source which were measured from the high voltage side of the transformer are shown in Figures 6.77-6.79 at interruption duration, respectively.

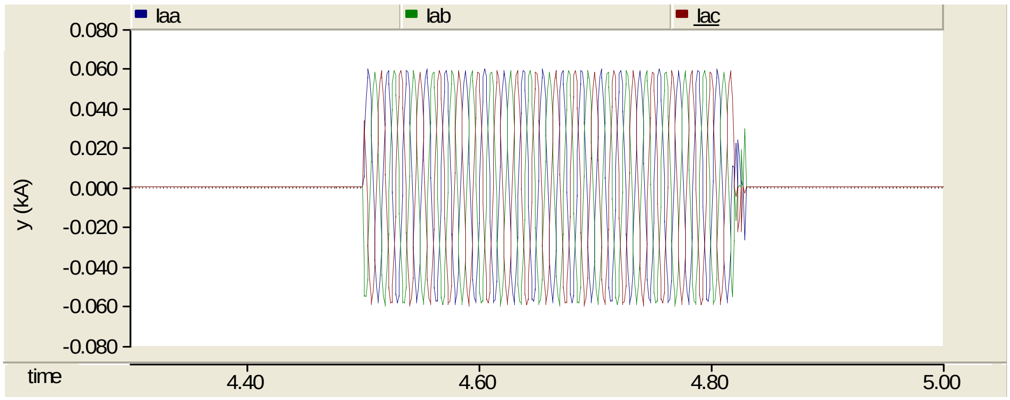

Figure 6.77 Line currents of AS during interruption.

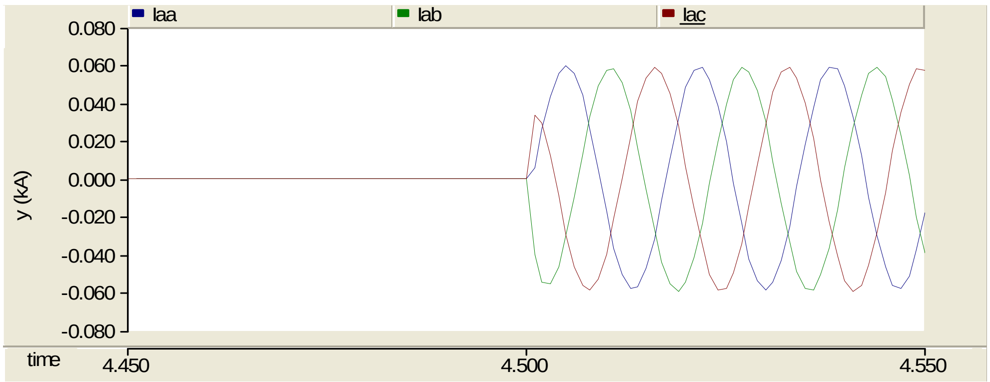

Figure 6.78 Starting region of line currents of AS during interruption.

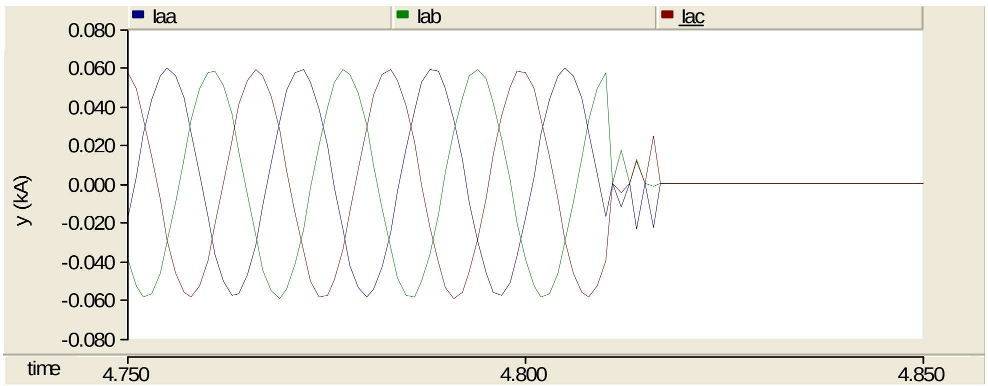

Figure 6.79 Ending region of line currents of AS during interruption.

6.3 Voltage Sag-Swell Condition

Figure 6.80 shows the Sag-Swell condition of the WTS. The voltage sag-swell occurs at t_1= 6.8 s and which is ended at t_2 =7 s. The simulation duration is 0.7 s. There are two WTS source to show sag or swell condition for the system. This source 2 gives the sag or swell added signal to the system. We can observe the system response of this duration. Firstly BRK 1 is off position so the WTS 1 connected to system at time 6.8 s BRK 1 is open position and BRK 2 is on position so the WTS 2 connected to system until time 7.0 s.

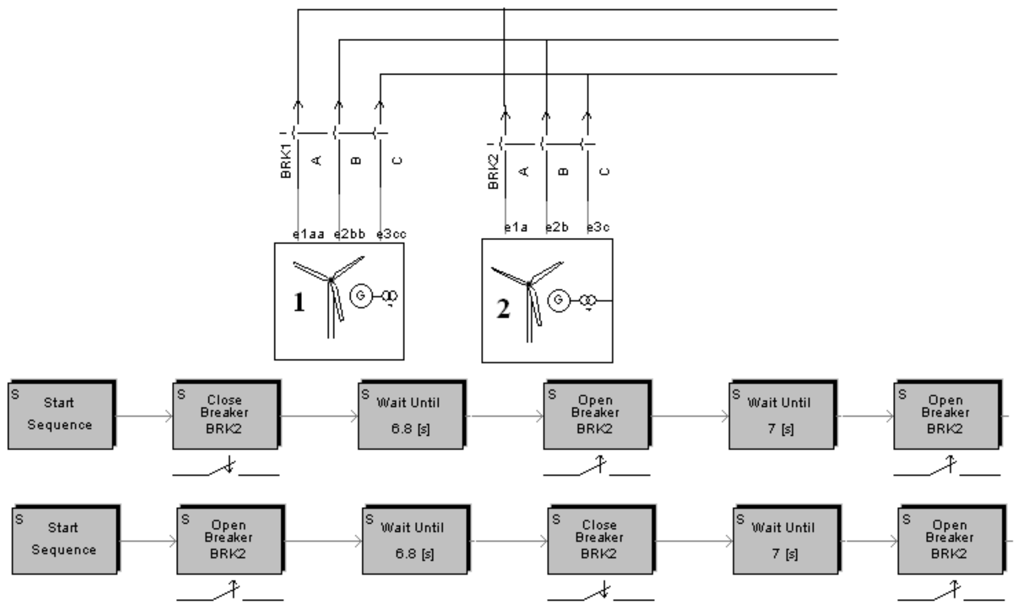

Figure 6.80 The circuit of the WTS to show sag-swell condition.

6.3.1 Voltage Sag Condition

WTS phase voltages are shown in Figures 6.81-6.83 at sag duration, respectively.

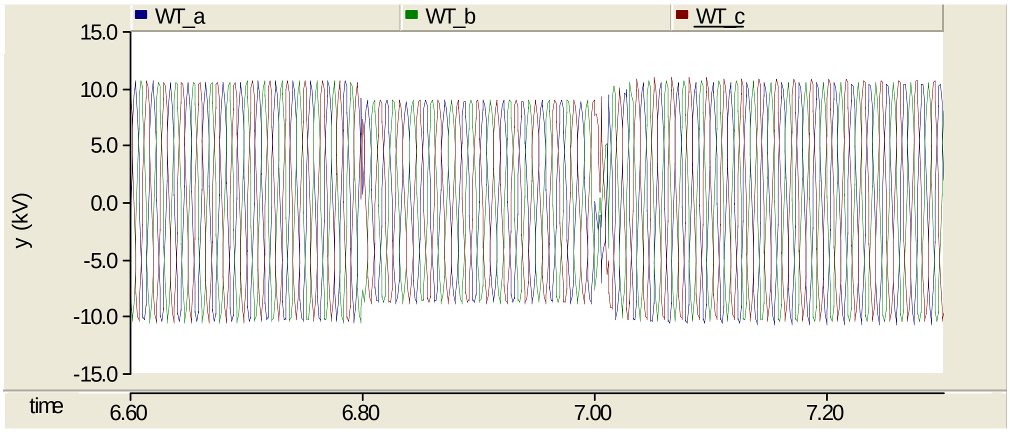

Figure 6.81 WTS voltages during sag condition.

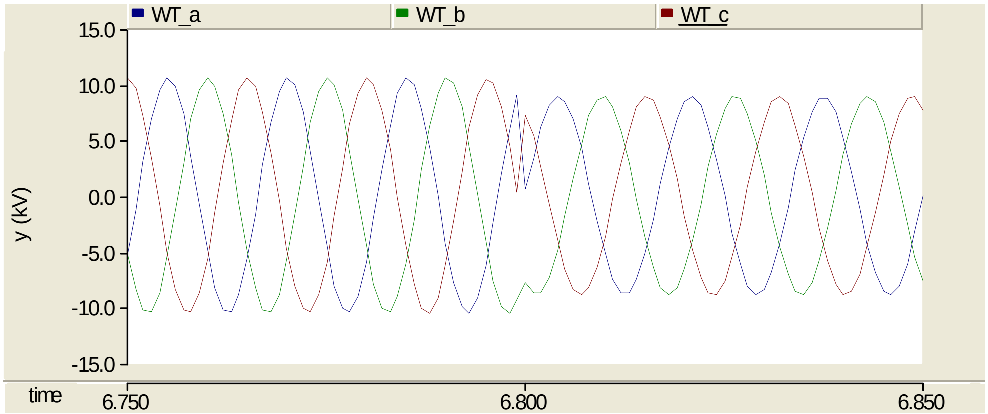

Figure 6.82 Starting region of WTS voltages during sag condition.

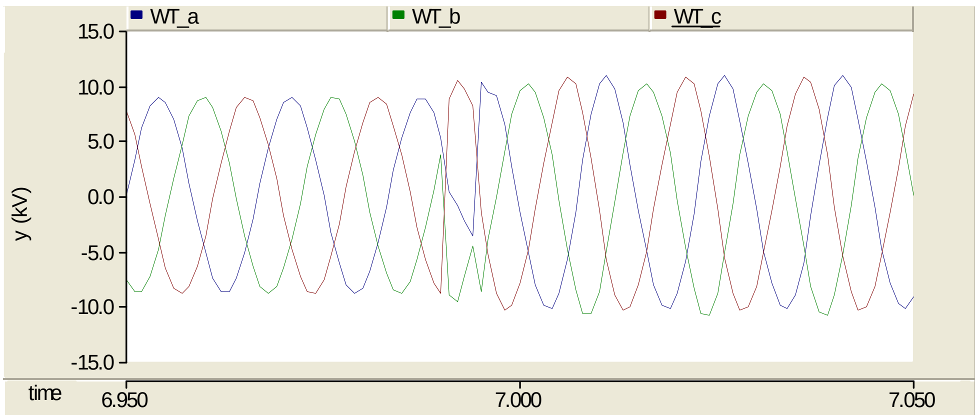

Figure 6.83 Ending region of WTS voltages during sag condition.

Load phase voltages are shown in Figures 6.84-6.86 at sag duration, respectively.

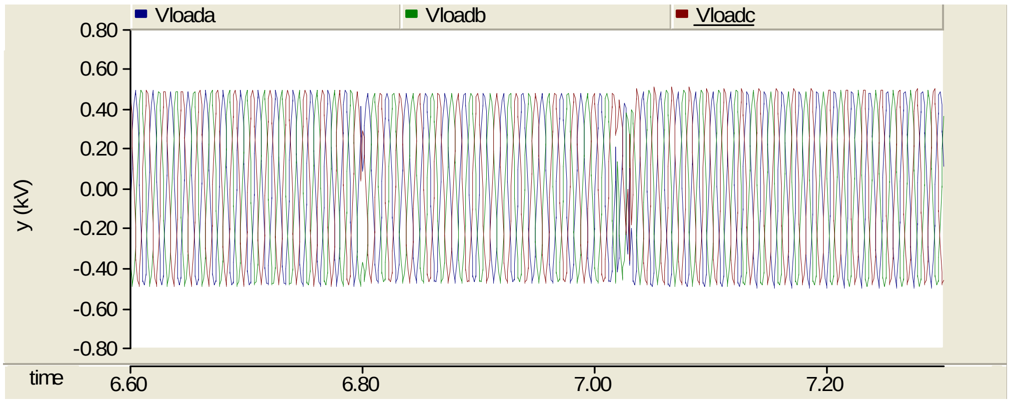

Figure 6.84 Load voltages during sag condition.

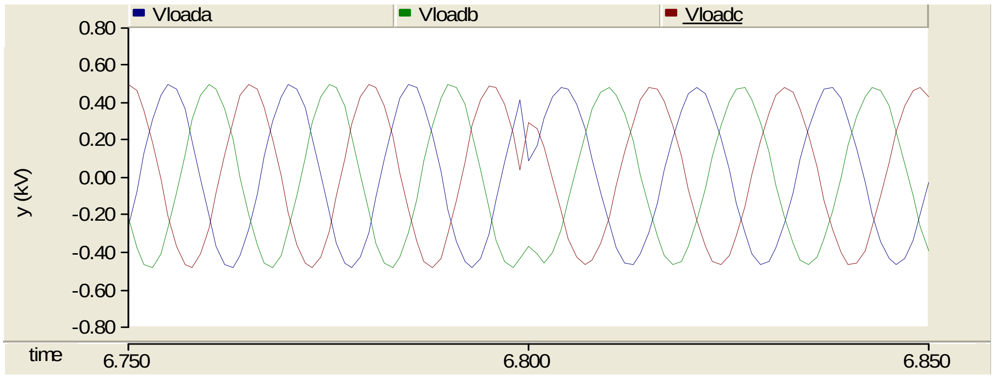

Figure 6.85 Starting region of load voltages during sag condition.

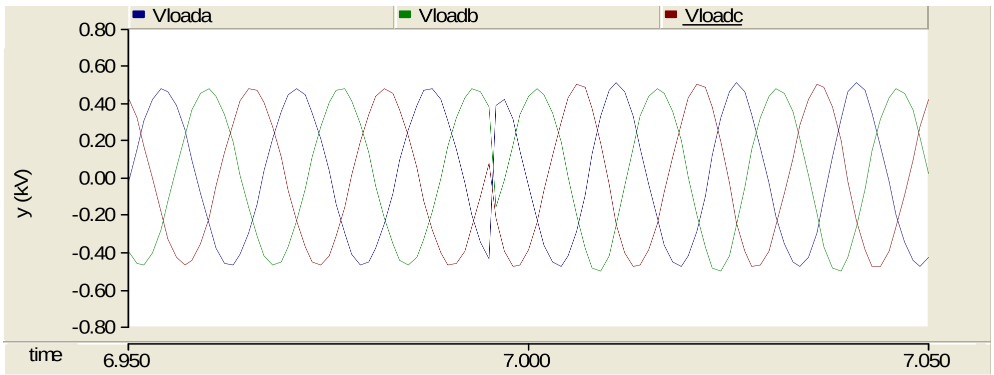

Figure 6.86 Ending region of load voltages during sag condition.

The currents of WTS which were measured from the high voltage side of the transformer are shown in Figures 6.87-6.89 at sag duration, respectively.

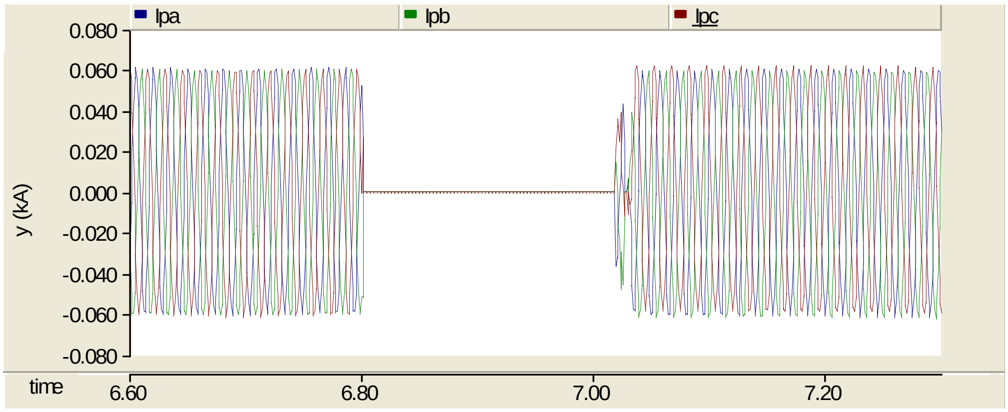

Figure 6.87 Line currents of WTS during sag condition.

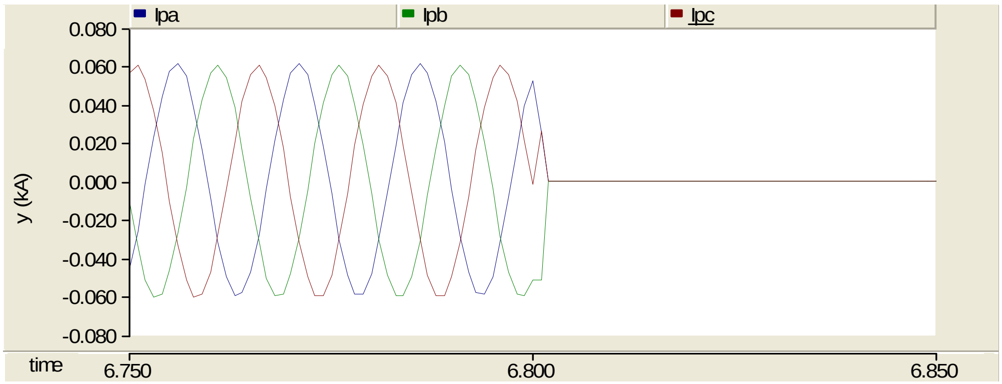

Figure 6.88 Starting region of line currents of WTS during sag condition.

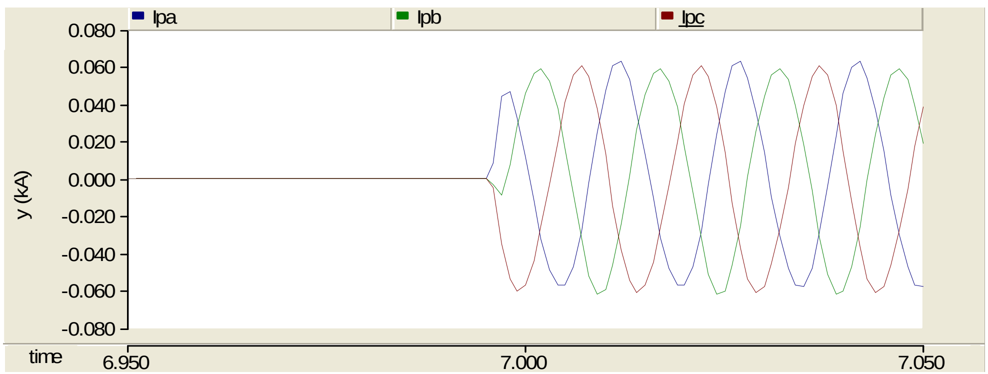

Figure 6.89 Ending region of line currents of WTS during sag condition.

The currents of Alternate source which were measured from the high voltage side of the transformer are shown in Figures 6.87-6.89 at sag duration.

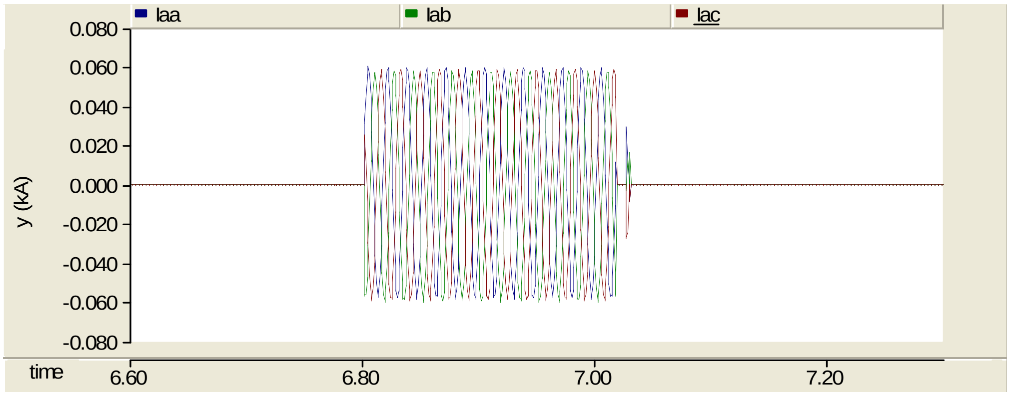

Figure 6.90 Line currents of AS during sag condition.

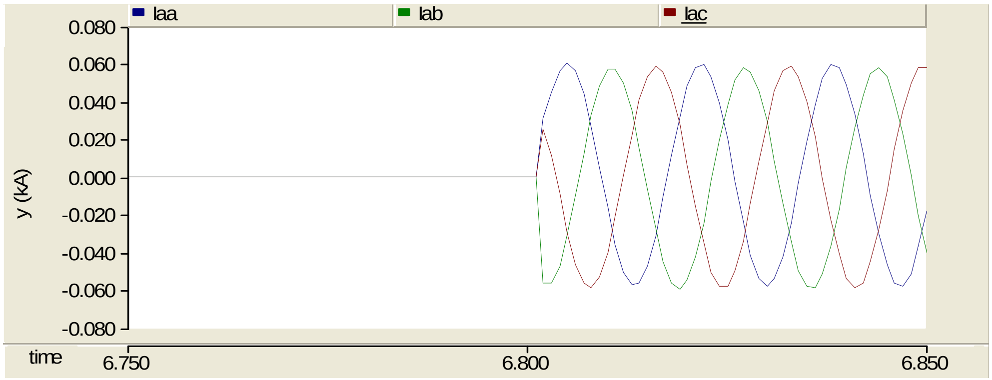

Figure 6.91 Starting region of line currents of AS during sag condition.

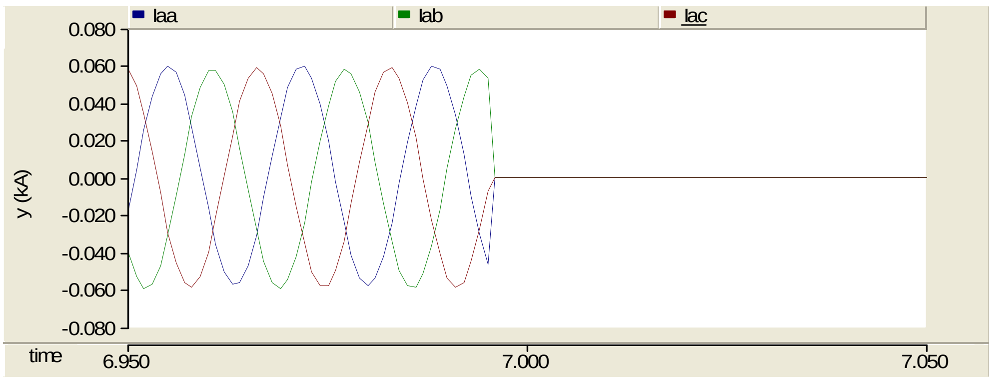

Figure 6.92 Ending region of line currents of AS during sag condition.

6.3.2 Voltage Swell Condition

WTS phase voltages are shown in Figures 6.93-6.95 at swell duration.

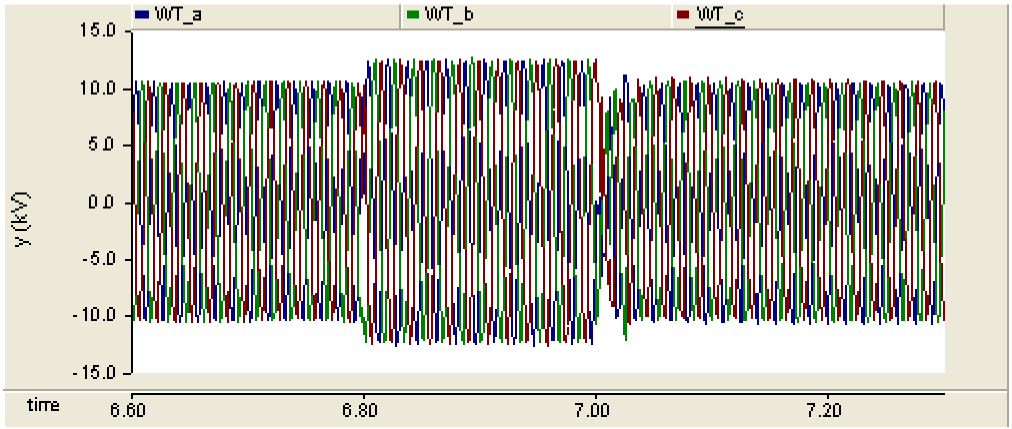

Figure 6.93 WTS voltages during swell condition.

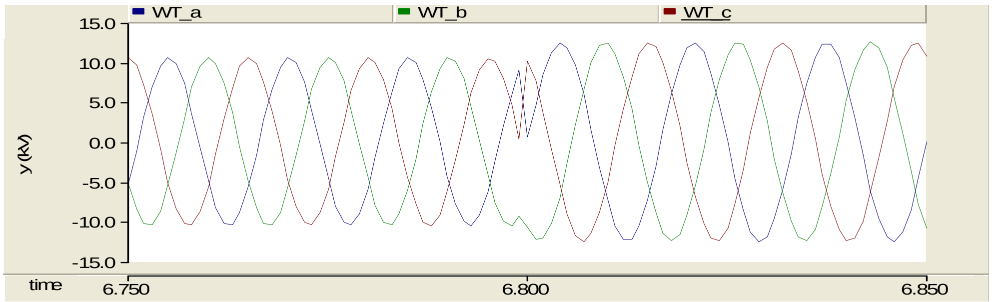

Figure 6.94 Starting region of WTS voltages during swell condition.

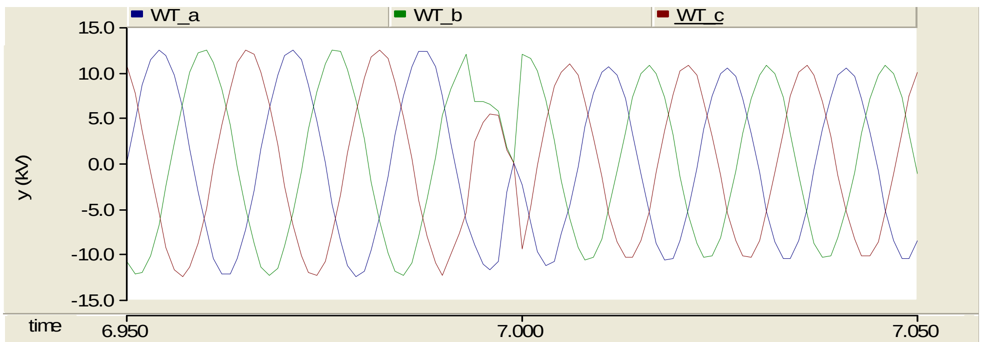

Figure 6.95 Ending region of WTS voltages during swell condition.

Load phase voltages are shown in Figures 6.96-6.98 at swell duration, respectively.

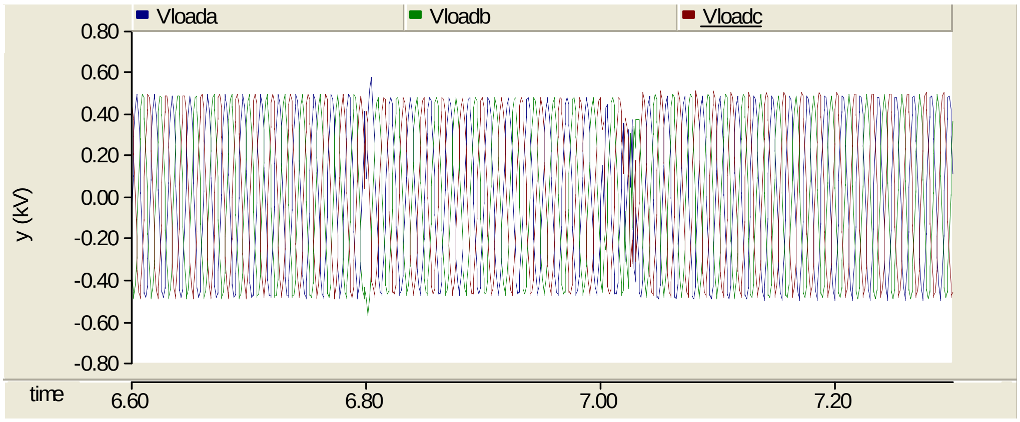

Figure 6.96 Load voltages during swell condition.

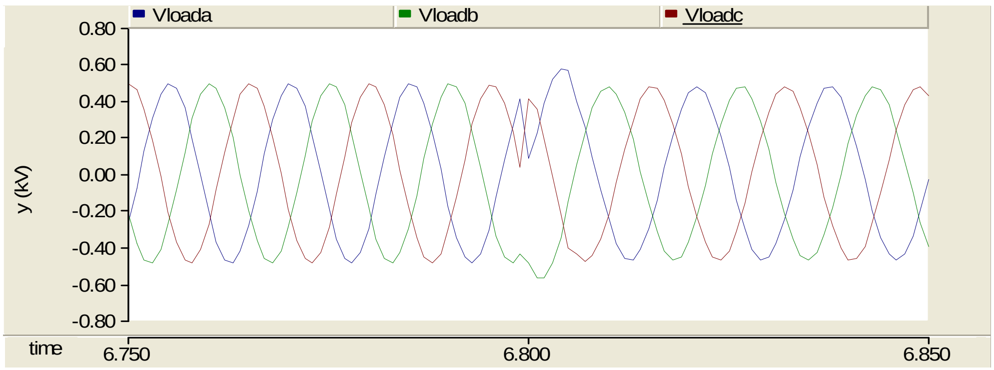

Figure 6.97 Starting region of load voltages during swell condition.

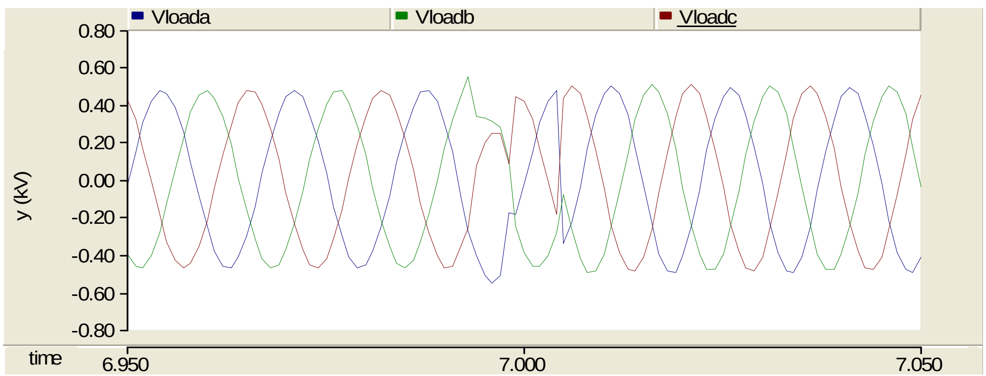

Figure 6.98 Ending region of load voltages during swell condition.

The currents of WTS which were measured from the high voltage side of the transformer are shown in Figures 6.99-6.101 at swell duration, respectively.

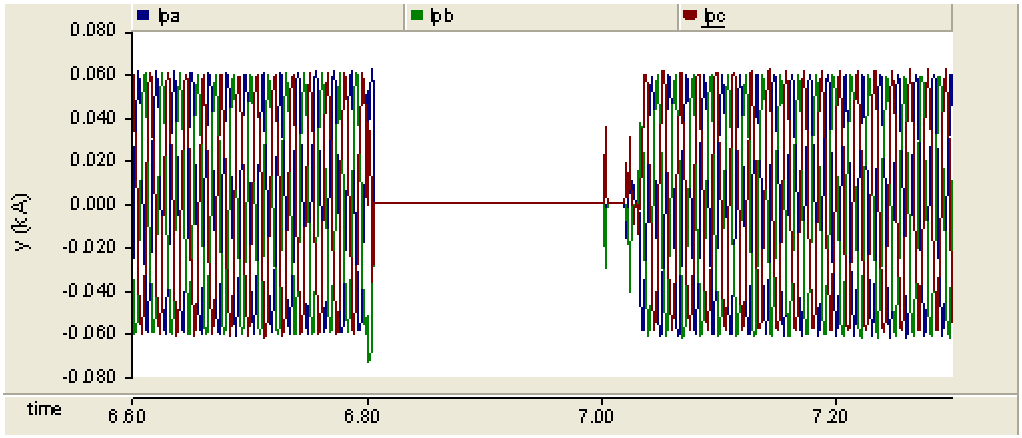

Figure 6.99 Line currents of WTS during swell condition.

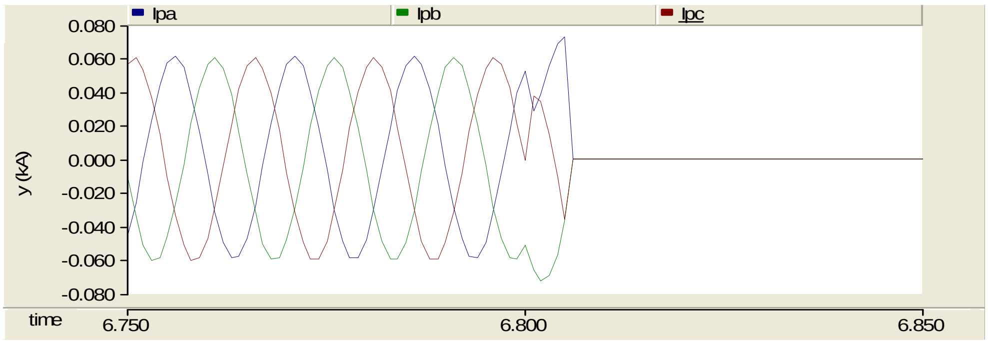

Figure 6.100 Starting region of line currents of WTS during swell condition.

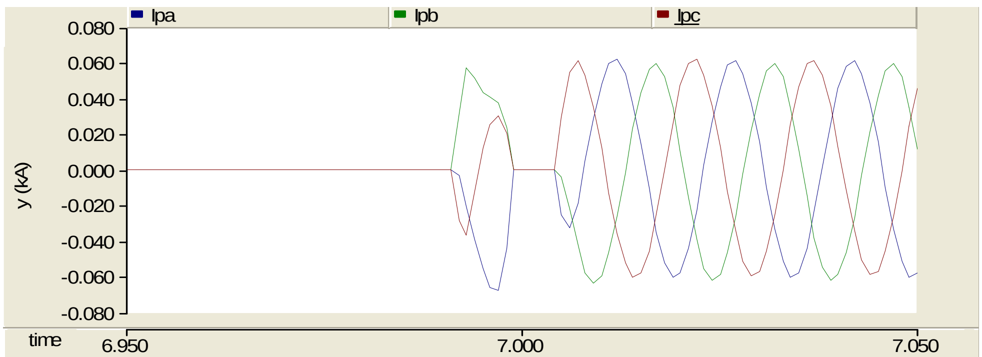

Figure 6.101 Ending region of line currents of WTS during swell condition.

The currents of Alternate source which were measured from the high voltage side of the transformer are shown in Figures 6.102-6.104 at swell duration, respectively.

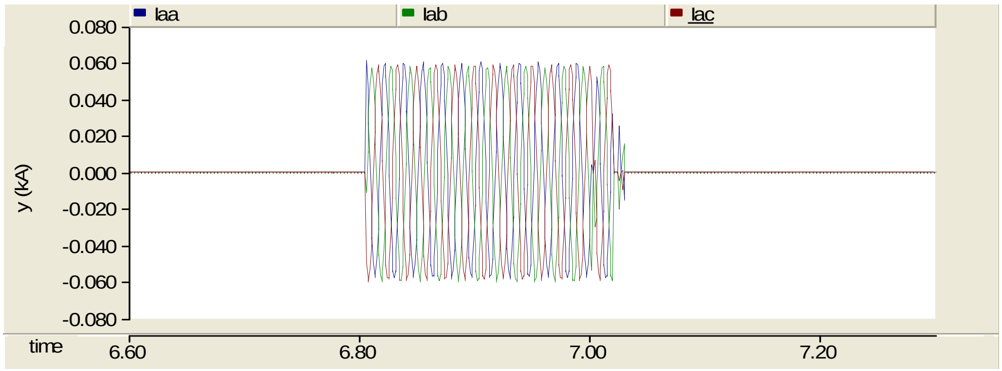

Figure 6.102 Line currents of AS during swell condition.

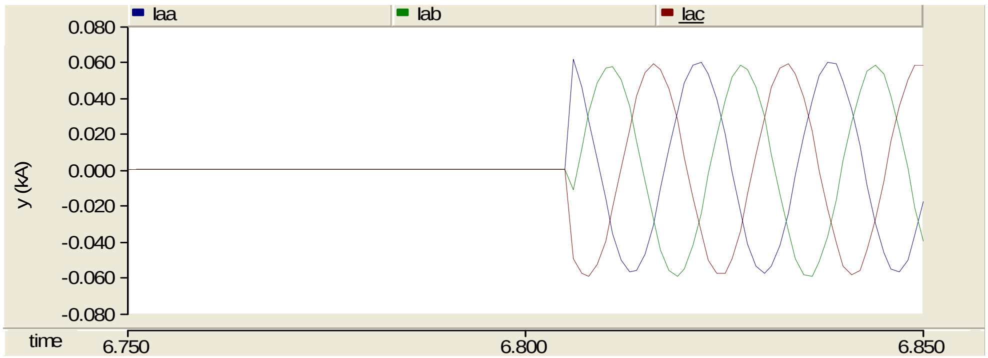

Figure 6.103 Starting region of line currents of AS during swell condition.

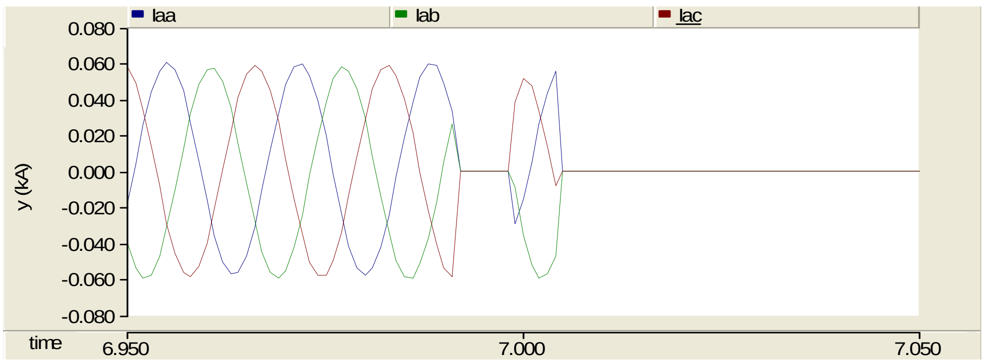

Figure 6.104 Ending region of line currents of AS during swell condition.

7 CONCLUSIONS

In this thesis the important of sustainable, reliable and good quality power which is provided by utilities are emphasized. Mainly, sensitive loads are fed by WTS feeder, but in case of voltage sag/interruption or fault conditions, the control logic of STS transfers the sensitive loads to alternate feeder network. Hence, the reliability and quality of electric power can be significantly improved for critical loads. This study presents the WTS control scheme for power quality improvement in grid connected wind generating system and with sensitive load. The power quality issues and its consequences on the consumer and electric utility are presented. The operation of the control system developed for the WTS in PSCAD/EMTDC program for maintaining the power quality is simulated. It maintains the source voltage and current in-phase and support the reactive power demand for the wind generator. Voltage interruption of power system can be solved using STS. In this thesis, the current status of STS and WTS are summarized firstly, and the characteristic of PMSG based variable speed wind turbine with STS is investigated. Control system requirements for performing fast transfer between two power supplies without affecting the operation of the healthy source are explained. The performance of static transfer switch for WTS reconfiguration has been assessed and evaluated in PSCAD/EMTDC program. It is clearly seen that faults have no effect on the load current and voltage at the fault time. The response of WPPs during faults is investigated and control solutions are developed within this thesis. The different cases are investigated and control solutions are developed for problems occurring during these cases. For all of the cases only the faulted period (from the instant of the fault occurrence till the clearance) of the fault is considered, excluding the recovery period. Any disturbance caused by disconnection of any (faulted) line in conjunction with the fault clearance is kept out of scope. As soon as fault occurs at WTS, STS transfers the sensitive loads on the alternate feeder. When fault is removed, control circuit of STS transfers the sensitive loads back on WTS feeder. The simulation results of various case studies show that the quality of power has been improved using STS. The simulation results show that using STS, voltage disturbances can be eliminated and power quality improvement can be maintained effectively and efficiently.

7.1 Contributions of Thesis

The main differences and important of contributions of this thesis can be summarized as follows: Nowadays, to supply an uninterrupted and quality power is a very important issue for using wind energy in the electrical grid. In this work; a wind turbine has been designed which is connected to network with STS. Thus the electrical network has been made safer and reliable to increase the use of wind turbines for generating electrical power. The new method is presented for the power generation of wind turbines. In the literature; theoretically, there has been reported not much work on the proposed system, design procedure and experimental analysis. This thesis will also contribute to the concept finding solutions to the electric power quality problems of WTS. The wide literature survey for STS and WT's has been accomplished and proposed system has been modeled. Similar methods for improving power quality are studied in different simulating programs.

STS in the proposed system, transfers the load from a WTS to an alternate feeder. In this thesis, a fast thyristor based STS system that employs fast voltage-detection and thyristor-gating strategies are presented. The voltage-detection logic is able to detect faults/disturbances in the power system with a short time and can be used for any three-phase system. The proposed controller uses the magnitude of the positive sequence component of the line voltages to detect if any voltages sag occurs. The positive sequence voltages are transformed into DC quantities under the synchronous reference frame. Then the magnitude of the positive sequence voltage is calculated. If the magnitude reduces below a certain threshold level 90% of the normal value, then the controller recognizes the occurrence of a voltage sag event and issues the transfer command to the STS. The proposed control method can identify voltage sags very rapidly, typically less than 5ms. The use of a low-pass filter makes the detection logic insensitive to capacitor-switching voltage transients. Also, the designed selective thyristor-gating scheme performs a fast load-transfer and prevents paralleling the two sources.

The performance of the proposed system is simulated for different faults/disturbance scenarios using the PSCAD program. It can be seen from the simulating results of the proposed system that the system has fast dynamic response and good steady state performance. All obtained simulating results of the proposed system are compared to the STS model which is modeled in MATLAB program. As a result, it is confirmed that the obtained simulating results of the proposed system are the same as simulating results of the STS which is modeled in MATLAB program. The running time of STS model in PSCAD program is less than 10 seconds but it is more than one minute in MATLAB program. We can say that the proposed system which is modeled in PSCAD program gives faster response than MATLAB simulating program. This study mainly demonstrated that the proposed system can improve the power quality and reliability of the power system.

7.2 Future Research

This thesis focused on performance evaluation of STS operating individually and with WTS. As a future work a Custom Power Park model should be implemented and performance of the Park and device interactions and coordination should be studied during different fault scenarios. Number of installations of Custom Power Devices is increasing in the world.

Increasing competitiveness and new utility regulations force the industrial consumers towards installation of Custom Power Devices. The installations of power devices for improving the power quality of WTS are reported in Turkey and the market and research on Custom Power Devices in WTS are expected to grow in the near future. For example Static Compensator or Dynamic Voltage Restorer can be added to the proposed system. Static Compensator which is a shunt connected custom power device can be used in WTS. Static Compensator specially designed for power factor correction, current harmonics filtering, and load balancing. It can also be used for voltage regulation. Dynamic Voltage Restorer is a series connected custom power device to protect sensitive loads from supply side disturbances (expect outages).

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