MITIGATION OF INRUSH CURRENT IN LOAD TRANSFORMER FOR SERIES VOLTAGE SAG COMPENSATOR

DISSERTATION

Submitted in partial fulfillment of the
Requirement for the award of the
Degree of

MASTER OF TECHNOLOGY
IN
ELECTRICAL ENGINEERING

By

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Under the Esteemed Guidance of

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APRIL 2014

CERTIFICATE

This is to certify that the Thesis titled “ **MITIGATION OF INRUSH CURRENT IN LOAD TRANSFORMER FOR SERIES VOLTAGE SAG COMPENSATOR**” that is being submitted by “**Asif Hameed Wani**” is in partial fulfillment of the requirements for the award of **MASTER OF TECHNOLOGY DEGREE (POWER SYSTEMS)**, is a record of bonafide work done under my /our guidance. The contents of this Thesis, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma and the same is certified.

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Objective of the Thesis is satisfactory / unsatisfactory

Examiner I **Examiner II**

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CERTIFICATE

This is to certify that **Asif Hameed Wani** bearing Registration no. **11202502** has completed objective formulation of thesis titled, **“MITIGATION OF INRUSH CURRENT IN THE LOAD TRANSFORMER FOR SERIES VOLTAGE SAG COMPENSATOR”** under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the thesis has ever been submitted for any other degree at any University.

The thesis is fit for submission and the partial fulfillment of the conditions for the award of **MASTER OF TECHNOLOGY.**

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DECLARATION

I, **Asif Hameed Wani**, student of **MASTER OF TECHNOLOGY (POWER SYSTEMS)** under Department of **ELECTRICAL ENGINEERING** of Lovely Professional University, Punjab, hereby declare that all the information furnished in this dissertation report is based on my own intensive research and is genuine.

This dissertation does, to the best of my knowledge, contain part of my work which has been submitted for the award of my degree either of this university or any other university without proper citation.

Date: **ASIF HAMEED WANI**

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ABSTRACT

In the power system voltage sag become the important issue for industries and many other consumers. According to the survey 92% of the interruptions at industrial installations are voltage sag related. In various companies voltage sag may affect many manufactures and may reduce the efficiency of the system which results sufficient losses in the power system. The voltage sag compensator, based on a transformer coupled with voltage source inverter for serial connection, is among the most cost-effective solution against voltage sags. A transformer inrush may occur at the start of sag compensator. This over current may damage the inrush protection of the series connected inverter and the transformer output voltage is greatly reduced due the magnetic saturation. When the compensator restores the load voltage, the flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. This paper proposes a new technique for mitigating the inrush of the coupling transformer and preserving the output voltage for effective sag compensation.

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CHAPTER 1
INTRODUCTION

The main reason of accepting ac system rather than dc system for the generation, transmission and distribution purposes is that, alternating current and voltages can be increased or decreased very conveniently with the help of transformers. For reasonable causes, the electrical power is to be transmitted at higher voltage level whereas it has to be distributed at low voltage level for the safety point of view. This increase in voltage at generation side and decrease in voltage at distribution side for consumption can only be accomplished by means of transformer.

1.1 TRANSFORMER

A transformer even though is not an energy conversion device, it forms a very important component of the energy conversion system. It is almost an indispensable component in both the electric and electronic systems. A transformer transforms electric energy from a certain voltage and current levels to another voltage and current levels keeping the frequency of the supply the same. It is because of the availability of the transformer that it is possible to generate energy from where it is available in abundance far away from the load centre and the energy so generated at suitable voltage levels can be transmitted at economic voltage levels using transformers and the same energy can be utilised at economic and safe voltage levels as required by the devices using the electric energy. The importance of transformer in electric energy system can be gauged by the fact that a generation of 1 MW requires transformers of 3 to 3.5 MVA capacity from power plant to the consumer points. The transformer is also very widely used in electronic circuits i.e. low power low current electronic and control circuits for performing such functions as matching the impedance of a source and the load for maximum power transfer. A transformer has normally two windings, the primary and the secondary. The primary is one where the source is connected and across the secondary load is connected. If the secondary voltage is higher than the primary voltage it is known as step-up transformer and it is known as step down if the secondary voltage is smaller than the primary voltage.

However, if the two voltages are equal, it is known as an isolation transform. The one to one transformers are used when it is necessary or desirable to insulate the secondary side of the circuit from the primary circuit for though both the circuits will then have the same difference of potential between their terminals, they will not necessarily have the same difference of potential to ground. It is to be noted that either of the two windings can be considered as primary while the other then serves as the secondary. The primary is therefore defined as one which receives energy from the supply and the secondary as the one which delivers energy to the load. In general, however, the windings are designated as low tension (LT) or high tension (HT) windings. In its simplest form the transformer consists of the insulated windings wound on a ferromagnetic core and so disposed with respect to each other as shown in Fig. 1.1 that a current through one of the windings will set up a magnetic flux linking more or less completely with the turns of the other. According to Faraday's laws of electromagnetic induction an emf is induced in the secondary which is proportional to the number of turns of the secondary and the flux linking the secondary. However, the frequency of the secondary voltage is same as that of the source.

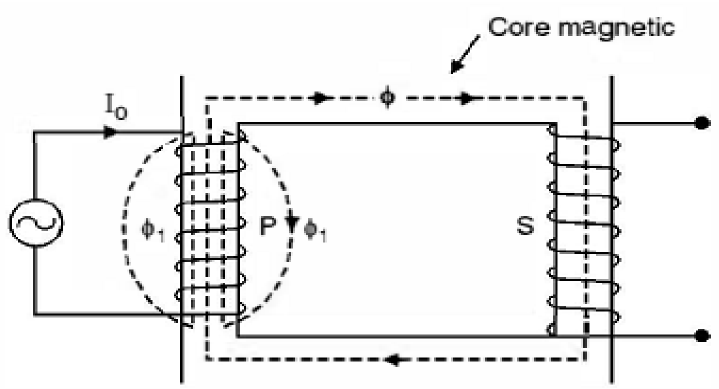


Fig. 1.1. Transformer under load condition

In order to ensure the most effective magnetic linkage of the two windings, the core which serves to support them mechanically as well as to carry their mutual magnetic flux is usually made of a highly permeable iron or steel alloy designed to have a low reluctance. In some specially designed transformers the core may be of non-magnetic materials. Such transformers are known as air cored transformers. These transformers are normally used in radio devices and in certain types of measuring and testing instruments.

1.1.1 TRANSFORMER EQUIVALENT CIRCUIT

In the equivalent circuit as shown in fig. 1.2. V_P, R_P, $X_{l,P}$, and I_P are the terminal voltage, winding resistance, winding leakage reactance and current respectively of the primary side, whereas V_S, R_S, $X_{l,S}$, and I_S are the terminal voltage, winding resistance, winding leakage reactance and current respectively of the secondary side. R_c, X_m and I_e are the eddy currents/ core losses, magnetising reactance and magnetising current.

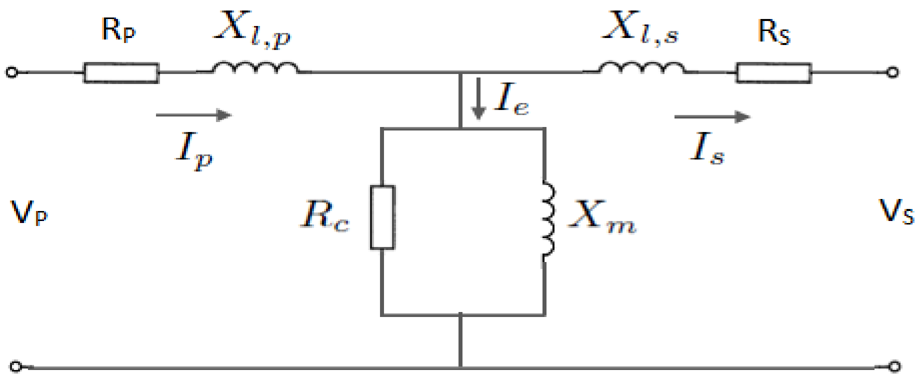


Fig. 1.2. Basic equivalent circuit diagram

1.1.2 LOSSES IN TRANSFORMER

There are mainly two types of losses in a transformer as mentioned earlier (1) Copper loss and (2) Core loss or iron loss. Iron loss is further divided into two (a) hysteresis loss and (b) eddy current loss.

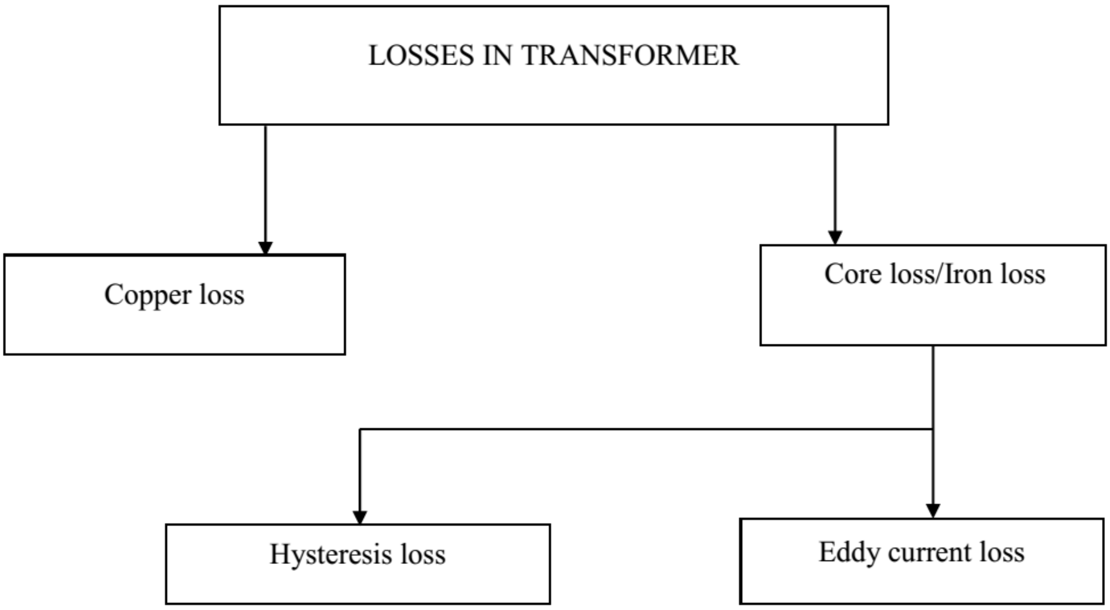


Fig. 1.3. Block diagram of transformer losses

1.1.2.1 Copper loss:-

This is due to the flow of current through the conductors of the winding i.e. it is an ohmic loss $I^2 R$ where R is the resistance of the conductor. In addition to this, there is loss caused by nonuniform distribution of the current density in the conductors. This nonuniformity may be considered due to the flow of eddy currents superimposed upon the theoretically uniform current density (assuming I to be flowing uniformly across the section of the conductor of the winding) which of itself would cause the pure ohmic loss.

1.1.2.2 Hysteresis loss:-

This is caused by similar to molecular friction as the ultimate particles of the core tend to align themselves first in one direction, then in the other, as the magnetic flux alternates periodically as shown in Fig. 1.3 The area of the loop ABCD EA represents loss in one cycle of variation of ac current.

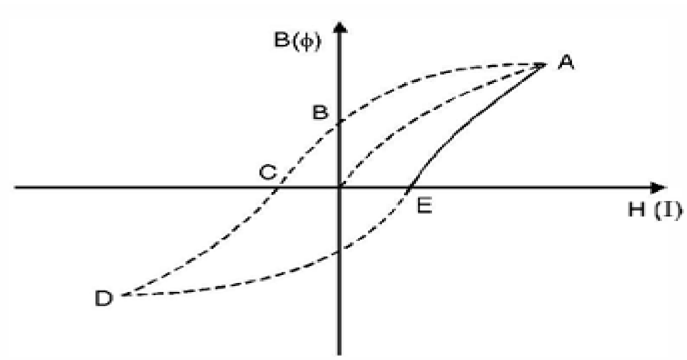


Fig. 1.4. Magnetisation/ B-H curve.

The curve is known as B-H curve. The larger the value of permeability (µ) the smaller is the loop and hence smaller the hysteresis loss in the core. Also hysteresis loss is proportional to fre-quency of supply and proportional to F where x varies between 1.5 and 2. So smaller the B the lower will be the hysteresis loss. However from transformer emf equation, for certain operating voltage if B is low the area of cross section of the core should be large. It is really a design problem and is out of the scope of this book. Normally silicon steel is used for the core material.

1.1.2.3 Eddy current loss:-

The alternating flux due to alternating current flowing through the winding induces voltage in the stampings (laminations) of the core just as it does in the coil of the windings. This voltage circulates current in the stampings in the form of eddies. These currents, therefore, heat the stampings and results in power loss. This is known as eddy current loss. The eddy current loss is proportional to B2ft2 where tis the thickness of the stampings. The smaller the thick-ness, the lower the eddy current losses. This is why the core is laminated so as to reduce the eddy current loss. The thickness is usually 0.5 mm.

1.2 INRUSH CURRENT

When a voltage is subjected to a transformer at a period when normal steady-state flux would be at a different value from that remaining in the transformer, a current transient happens, known as magnetizing inrush current. The saturation of the magnetic core of a transformer is the key source of an inrush current transient. The saturation of the core is owing to an sudden variation in the system voltage which can be produced by switching transients, synchronization of a generator remains out of phase, outdoor faults and faults renovation. The energization of a transformer produce to the simplest situation of inrush current and the flux in the core may extent a maximum theoretical significance of two to three times the evaluated flux peak. Fig. 1.4 demonstrates how flux linkage and current changes**.** There is no straight sign that the energization of a transformer can produce an abrupt failure due to high inrush currents. Though, insulation failures in power transformers which are repeatedly energized under no load situation support the mistrust that inrush currents have a dangerous result.

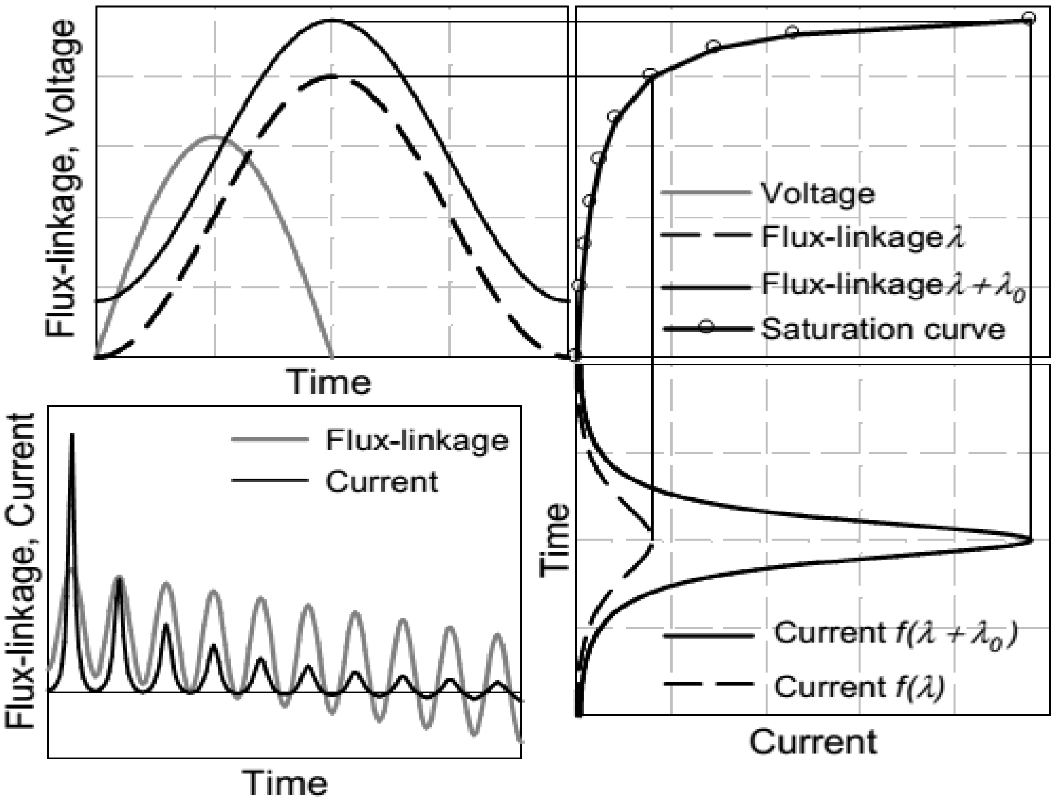


Fig. 1.5. Inrush current occurrence and the result of the residual flux. [6]

Magnetizing inrush can occur under three conditions and are described as:

(1) Initial, (2) Recover, and (3) Sympathetic.

1. The initial-magnetizing inrush can happen when energizing the transformer after an earlier period of de-energization. This was defined previous and has the probability of creating the maximum value.

2. All through a fault or temporary dip in voltage, an inrush may happen when the voltage yields to normal. This is called the retrieval inrush. The poorest case is a solid three phase external fault close the transformer bank. During the fault, the voltage is condensed to nearly zero on the bank then, when the fault is cleared, the voltage abruptly proceeds to a normal value. This may yield a magnetizing inrush, but its maximum will not be as high as the early inrush because the transformer is moderately energized.

3. A magnetizing inrush can happen in an energized transformer once an adjacent transformer is energized. A common event is paralleling a second transformer bank with one previously in operation. The DC component of the inrush current may also saturate the energized transformers, consequential in an apparent inrush current. This transient current, when added to the inrush current of the bank that is energized, delivers an offset symmetrical total current that is very little in harmonics. This would be the current flowing in the supply circuit to both transformer banks.

The inrush current in the transformer consume very high magnitudes and always hold harmonics and these high magnitudes of current and harmonics could cause harms and may decrease the life of the transformer. The overvoltage due to switching may also cause damages in the system, because the overvoltage also causes inrush current. This inrush current may happen due to the unexpected change in the system voltage. The inrush current in the transformer can happen when the energizing unloaded transformer, when fault happens, and the voltage restoring when external fault gets cleared and the synchronizing of generators with altered frequencies. The magnitude of the inrush current may remain high as a current due to short circuit, it becomes important to investigation the thing so that it may not disturb the protective system of the transformers such as transformer security. Taking all the in respects some important approaches such as numerical and analytical methods have been through.

In power systems, differential protection is applied for transformer ratings above 10MVA, whereas over-current protection is used for transformer ratings below 10MVA for main protection that contains simple theory and greatest protection results. But, the transformer will generate huge inrush currents while the transformer operates on no-load. This inrush currents contains a huge and extensive dc component, which is rich in harmonics, assumes huge peak values initially about 6 to 30 times of the rated value. This state roots unbalance of current loop of differential relay that will happen by false trip. In order to avoid false tripping owing to an inrush current, a method using the content of the second harmonic component in the current waveform is usually used. However, this technique cannot deliver total solution for inrush current. Therefore, we present digital simulation technique to examine and to test to distinguish the best transformer protection arrangements.

1.3 VOLTAGE SAG

In the electrical system, voltage sags are most responsible for power quality problems, because voltages sags may affect various kinds of loads connected to the system. The sag occurrence is a short duration in rms voltage which may happen due to system faults, variation of load and by induction loads. The hazardous causes of this problem is the flow of fault current through the power system impedance to the location of fault. Therefore faults in transmission or distribution system can interrupt separately a small or large number of consumers. The faults may cause various harms in the connecting equipments upto hundreds of km away from the fault location. Voltage sag due to faults either in distribution or transmission may produce abnormal operation of the industrial consumer equipments or reduce the equipment efficiency.

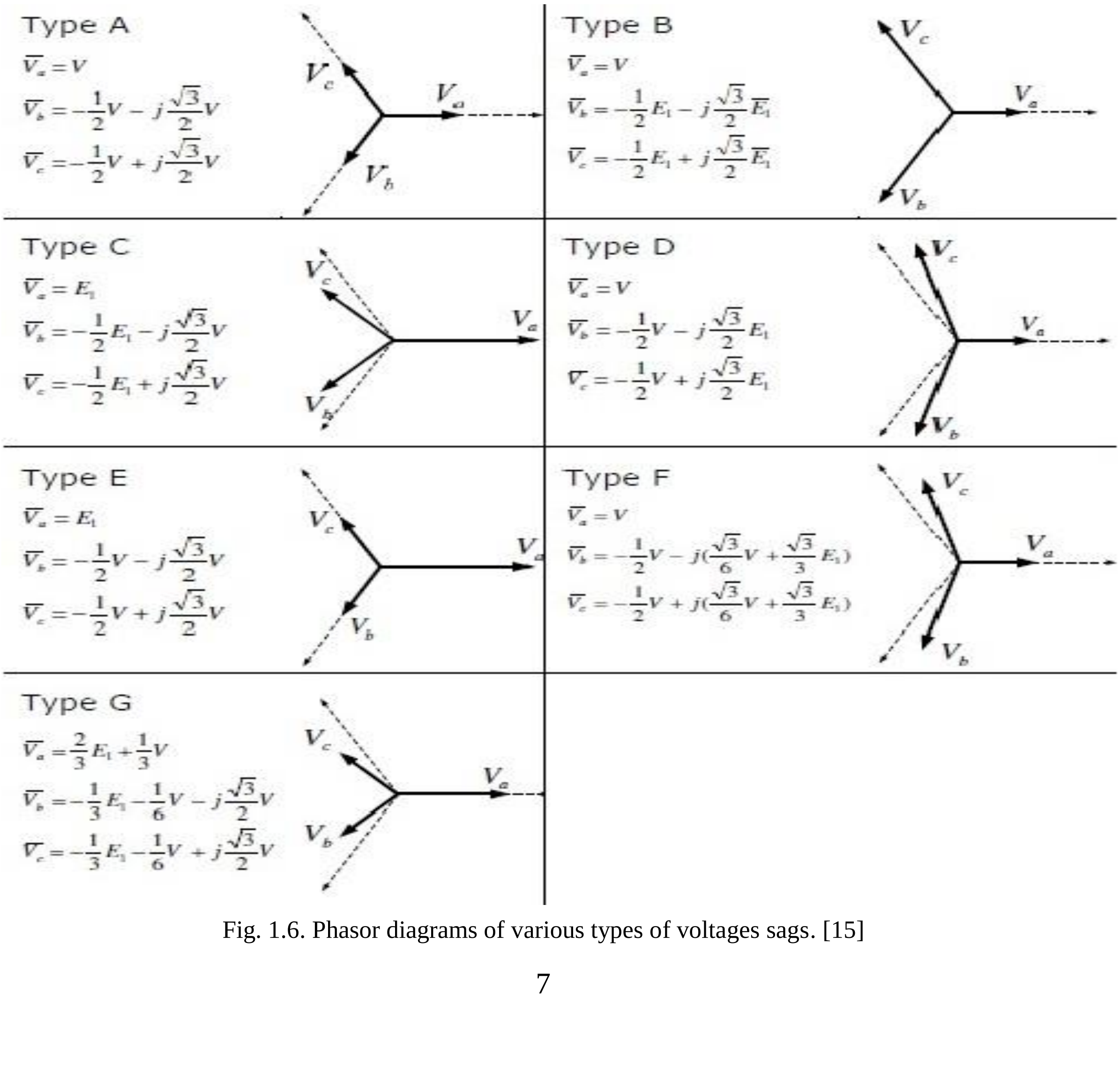


Fig. 1.6. Phasor diagrams of various types of voltages sags. [15]

Voltage sags, which are also recognised as voltage dips or rms voltage variations. In the power equipment's, even the least sags can produce huge complications, from loss of data to interruption of the production line. Because voltage sags can be produced by multiple factors, both by internal actions such as the start-up of a huge load or by a fault on the power system themself, they have been difficult to address. Key to determining the problem is recognizing the source of the problem and whether that difficult is inside the capability or in the supply network of the provider. Within the capability, the Sag Directivity Answer Module can control where the sag happened in relation to the monitoring location.

From the recent study expression about 92% of the trouble happen in the power system is due to the voltage sags. In three phase system, voltage sags can be classified into seven different types as exposed in fig. 5.1. Protective devices in the power system may trip immediately and shut down the delicate loads when the voltage sag happens. Now it becomes very important to study about these voltage sags and how the delicate load behaves when the voltage sag happens. These are the cause for building voltage sag generators that can inject the compensation voltage when the voltage sag happens. The purpose of building these kind of generators are the protection of sensitive equipments due to voltage sag.

1.4 VOLTAGE SAG COMPANSATOR

The voltage sag compensator of two main parts that is voltage source inverter which is coupled with the transformer serial connected with the system. Voltage sag compensator always remain bypassed by the thyristors when the system is normal. The voltage sag compensator comes into the picture when the sag occurs and injects compensating voltage through series coupled transformer which is required for the stability of the critical load as shown in below figure 1.6.

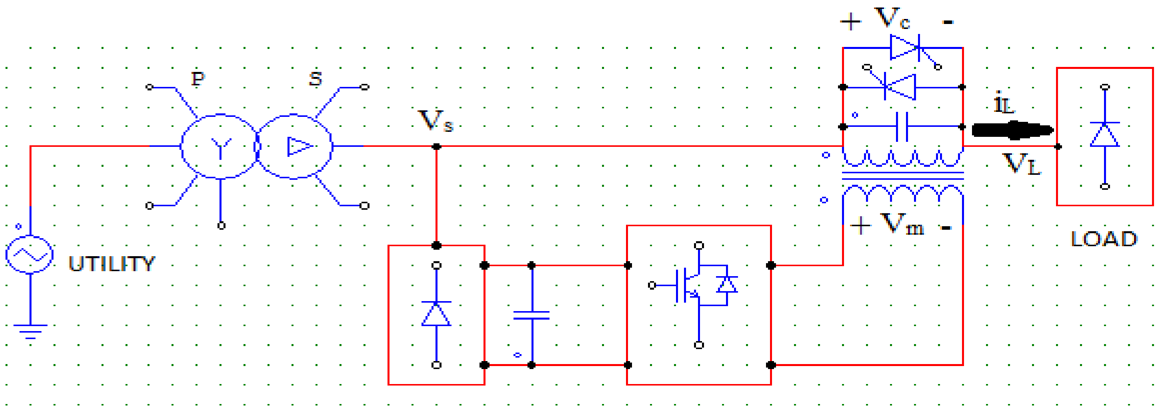


Fig. 1.7. The transformer coupled series compensator

There are several techniques which may reduce the inrush current and have been presented like, controlling phase angle and the voltage magnitude, or controlling of current in the transformer. These all techniques may use to alter the output wave shape of the convertor. These alterations are not good for the voltage sag compensators.

In this thesis, the issue of the inrush current in load transformers when the voltage sag compensator comes into the picture. A technique is introduced and implemented in synchronous frame voltage sag compensator controller. The inrush reduction technique can be implemented with the conventional closed loop control on load voltage. The technique used for control can successfully mitigate the load transformer inrush current and also make improvement in the disturbance rejection capability and voltage sag compensator robustness.

The main issue of this thesis is inrush current in the load transformer at a start of voltage sag compensator. This very high peak value of current may cause lot of damages in the protective devices and the protection of the voltage sag compensator, inverter, and it may also effect the transformer output waveform which may reduce due to saturation of the core. The system may fail to provide the compensation of voltage dip. Oversizing the transformer at more than the rated flux may become a proper and common techniques to reduce the inrush current. But the using of this technique may increase the weight and size of the compensator which becomes a limitations for many manufactures. In this thesis a technique which is newly developed for reduction of the inrush current in the transformer. The method is to control the injection voltage of voltage sag compensator. The transformer inrush can be reduced while stabilizing the output voltage for sag compensation.

CHAPTER 2
LITERATURE SURVEY

Subhransu Sekhar Dash (2013) et al. Switching of loads, capacitors, along with the proliferation of power electronics equipment, non-linear loads in industrial, commercial and domestic applications have led to power quality issues in the distribution system. Power quality issues such as voltage sag, voltage swell and harmonics, which are certainly major concerning issues in the present era. These issues can lead to failure or malfunction of the many sensitive loads connected to the distribution system, thus incurring a high cost for end users. Power quality problems are solved by advanced custom power devices. This study presents how the custom power device Distribution Static Compensator (D-STATCOM) is used to mitigate voltage sag and voltage harmonics in distribution system. Artificial Neural Network (ANN) controller based D-STATCOM is simulated in MATLAB-SIMULINK environment. Prototype model for single phase D-STATCOM is developed to verify the results. The simulation and hardware results show clearly the performance of the D-STATCOM in mitigating voltage sag and voltage harmonics in distribution system.

Joaquín Eduardo Caicedo Navarro (2013) et al. This paper describes a methodology for voltage sag characterization using Matlab/Simulink. It includes single-phase and three-phase fault simulations in different power systems for voltage sag magnitude calculation using Simulink, based on the Sim Power Systems toolbox, and also considering electrical protection-systems modeling for sag duration calculation. Other sag characteristics, such as phase-angle jump and shape, are described and simulated.

Jamali Arand (2013) et al. The inrush current is a transient current that results from a sudden change in the exciting voltage across a transformer’s windings. It may cause inadvertent operation of the protective relay system and necessitate strengthening of the transformer’s mechanical structure. Many methods were reported in the literatures for reduction and mitigation of transformer inrush currents. This paper represents a study of techniques that have been proposed for transformer inrush current mitigation. A new, simple and low cost technique to reduce inrush currents caused by transformer energization is presented here. In this method, a controlled switching approach with a grounding resistor connected to transformer neutral point and a magnetic flux shunt is used. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series- inserted resistor and thereby significantly reduces the inrush currents. The dimensions of the magnetic flux shunts are chosen such that the inrush current amplitude is further reduced. The proposed method has been tested by computer simulation using 2-D FEM (two-dimensional finite element method) by Maxwell software.

Venkatesh Dugyala (2013) et al. Inrush currents generated by unloaded power transformer often reduce power quality on the system. To improve this situation, this paper proposes an active inrush current compensator that is capable of reducing the inrush current effectively during start-up mode. The proposed compensator is based on an inverter-based series compensator which is comprised of a single-phase inverter and series transformer. Voltage sags are very frequent events with energization of transformer or starting of large motors although their duration is very short. Hence, during voltage stabilizer mode, the existing series compensator is controlled by a voltage stabilizer controller and superimposes a compensating voltage on the inverter output whenever the load voltage deviate from the nominal value. This strategy is easier to implement because it requires no information of the transformer parameters, power on angle of circuit breaker and measurement of residual flux. Some simulations results show satisfactory performance of the proposed technique on both inrush current reduction and correcting voltage sags.

Dr. M. Padma Lalitha (2013) et al. In many countries, high-tech manufacturers concentrate in industry parks. Survey results suggest that 92% of interruption at industrial facilities is voltage sag related. An inrush mitigation technique is proposed and implemented in a synchronous reference frame sag compensator controller. The voltage sag compensator consists of a three phase voltage source inverter and a coupling transformer for serial connection. It is the most cost effective solution against voltage sags. When voltage sag happen, the transformers, which are often installed in front of critical loads for electrical isolation, are exposed to the disfigured voltages and a DC offset will occur in its flux linkage. When the compensator restores the load voltage, the flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. The compensator is likely to be interrupted because of its own over current protection. This paper proposes an inrush current mitigation technique together with a state-feedback controller for the Voltage sag compensator.

H. Lakshmi (2013) et al. The dynamic voltage restorer (DVR) is used to regulate the voltage at the load terminals from various power quality problems like sag, swell, harmonics, unbalance etc., in supply voltage. This paper presents modelling aspects of several types of Dynamic Voltage Restorer (DVR) working against various voltage sags by simulation in PSCAD/EMTDC. The reference signal for the series connected DVR is obtained indirectly from the extracted load terminal reference voltage. It then provides analyses of working performance of the device, including capability and quality of compensation. Significant simulation results show that these several types of the modelled device can work very well against balanced and/or unbalanced voltages caused by faults in a distribution system. In addition, appropriate ways to obtain a good quality output voltage by a DVR during voltage sag is also presented.

Shan Gao (2012) et al. The dynamic voltage restorer (DVR) is among the most cost-effective solution against voltage sags. By using the transformer coupled topology, DVR could take the advantage of electrical isolation and voltage boost. However, at the start of compensation, the injection transformer may experience a flux linkage that is up to twice its steady-state value. The flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. Over sizing the transformer is a common approach to avoid the inrush current, but this would dramatically increase the cost, size and weight. This paper proposes a new technique for mitigating the inrush current. By taking use of the relationship between injection voltage and flux linkage, this method is characterized by interrupt compensation around the peak or trough of injection voltage to make the interruption time shortest. Detailed explanations of this technique are presented, and the effectiveness of this scheme is verified by laboratory test results.

Salman Kahrobaee (2012) et al. The energizing of large power transformers has long been considered a critical event in the operation of an electric power system. When a transformer is energized by the utility, a typical inrush current could be as high as ten times its rated current. This could cause many problems from mechanical stress on transformer windings to harmonics injection, and system protection malfunction. There have been numerous researches focusing on calculation and mitigation of the transformer inrush current. With the development of smart grid, distributed generation from independent power producers (IPPs) is growing rapidly. This paper investigates the inrush current due to black start of an IPP system with several parallel transformers, through a simulation model in Dig SILENT Power Factory software. The study demonstrates that a single genet is capable of energizing a group of transformers since the overall inrush current is slightly above the inrush of the transformer directly connected to the generator.

Abbas Ketabi (2011) et al. Transformer inrush currents have always been a concern in a power industry. Inrush currents generated by unloaded power transformer often reduce power quality on the system. Over the last decades, methods have been proposed to remove transformer inrush currents. To improve this situation, this paper proposes an active inrush current compensator that is capable of reducing the inrush current effectively during start-up mode. The method uses a voltage source PWM converter is connected in series to the transformer that produce a dynamic resistor in series with transformer and remove inrush current. This method was tested by PSCAD/EMTDC simulation. Simulate shows that proposed method removes inrush current completely. This strategy is easier to implement because it has simple control method and requires no information of the transformer parameters, power on angle circuit breaker and measurement of residual flux and so on.

Baris Kovan (2011) et al. A methodology for the reduction of the residual flux in network transformers is proposed in this paper. The purpose is the mitigation of large inrush currents taken by numerous transformers when a long feeder is energized. Time-domain simulations are used to prove that a small-power device can substantially reduce the residual flux of all transformers simultaneously. The device consists of a low-voltage dc source, a suitable power-electronic switching unit, and a simple controller. Before a feeder is re-energized, the residual flux is reduced to a minimum and, as a consequence, the large inrush currents are reduced to an acceptable level. This greatly enhances the probability for the feeder to be successfully energized when otherwise a false trip would have occurred. Inrush current reductions of more than 60% are obtained at the head of the feeder.

Yu Hsing Chen (2010) et al. Survey results suggest that 92% of interruption at industrial facilities is voltage sag related. The voltage sag compensator, based on a transformer-coupled series-connected voltage source inverter, is among the most cost-effective solution against voltage sags. When voltage sags happen, the transformers, which are often installed in front of critical loads for electrical isolation, are exposed to the disfigured voltages and a dc offset will occur in its flux linkage. When the compensator restores the load voltage, the flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. The compensator is likely to be interrupted because of its own over current protection, and eventually, the compensation fails, and the critical loads are interrupted by the voltage sag. This paper proposes an inrush current mitigation technique together with a state-feedback controller for the voltage sag compensator. The operation principles of the proposed method are specifically presented, and experiments are provided to validate the proposed approach.

Yu Hsing Chen (2010) et al. Unexpected voltage sags or outages often interrupt the operation of manufacturing processes or even lead to equipment damage. Numerous critical loads rely on the uninterruptible power supply system to uphold the power during these events and maintain the normal operation. As disturbances occur in the utility, the uninterruptible power supply (UPS) should take over the load within 1–5 ms to prevent any interruptions. However, the startup process of the UPS can cause the significant inrush current phenomenon on the load transformer due to magnetic saturation. The inrush current could result in reduced line voltages and even trigger the UPS's overcurrent protection. To prevent the inrush current, this paper proposes a flux offset compensation technique based on the synchronous reference frame (SRF) to regulate the flux of the load transformer. The proposed technique can be integrated with the existing voltage control and the pulse-width modulation (PWM) of the UPS inverter without any additional sensors. The proposed technique can provide a very smooth and timely transition without the risk of inrush current for critical loads under power outages and voltage sags.

Adel Z. El Dein (2010) et al. The paper presents an efficient way to mitigate the magnetic field resulting from the three-phase 500kV single circuit high voltage transmission line existing in Egypt, by using a passive loop conductor. The aim of this paper is to reduce the amount of land required as rights-of-way (ROW). The paper used an accurate method for the evaluation of 50Hz magnetic field produced by overhead transmission lines. This method is based on the matrix formalism of multiconductor transmission lines (MTL). This method obtained a correct evaluation of all the currents flowing in the MTL structure, including the currents in the subconductors of each phase bundle, the currents in the ground wires, the currents in the mitigation loop, and also the earth return currents. Furthermore, the analysis also incorporates the effect of the conductor's sag between towers, and the effect of sag variation with the temperature on the calculated magnetic field. Good results have been obtained and passive loop conductor design parameters have been recommended for this system at ambient temperature (35^{o} C).

Yu Hsing Chen (2009) et al. The transformer inrush current contains a large amount of harmonic components and high current magnitude which could result in reduced line voltages, and even trigger the UPS's overcurrent protection. To mitigate the inrush current fast and also satisfy the load voltage requirement, the estimation of transformer flux is required in the UPS control design. However, in most of the flux estimation technique, the transformer flux is calculated by integrating the measured line voltages directly. Therefore, a major problem with the pure integrator is that it lacks a virtual damper for convergence and a large error on estimated transformer flux. The estimation error of transformer flux could lower quality of UPS's output voltage and affect the performance of inrush current reduction. To improve the accuracy of flux estimation, this paper develops a flux observer-based inrush current reduction technique based on the synchronous reference frame (SRF). The flux observer-based inrush current reduction technique can make the UPS system to track the variation of transformer flux fast and precisely. Therefore, it can benefits the voltage quality and reduces the required voltage for inrush current reduction.

H. S. Bronzeado (2009)et al. Transformers are normally energized by closing arbitrarily the circuit breaker contacts, with the system voltage being applied on the transformer windings at random instants. In general, this switching introduces an asymmetrical magnetic flux in the windings, driving the transformer into saturation. As a result, high transient magnetizing inrush currents are produced in the transformer. One of the solutions for mitigating these currents is energizing the transformer by controlling the circuit breaker making instants in a way that the magnetic flux produced in the windings corresponds to the prospective flux in the core. This strategy was applied on a 100 MVA, 230/138 kV, three-phase three-limbed core type transformer, with the results showing that transformer inrush currents can be almost completely eliminated.

Yu Hsing Chen (2008) et al. Unexpected voltage sags or outages events often interrupt the operation of manufacturing processes, or even lead to equipment damages. Numerous critical loads rely on the uninterruptible power supply (UPS) system to uphold the power during these events and maintain the normal operation. As disturbances occur in the utility, the UPS should take over the load within 1 − 5ms to prevent any interruptions. However, the start-up process of UPS can cause the significant inrush current phenomenon on the load transformer due to the magnetic saturation. The inrush current could result in reduced line voltages, and even trigger the UPS's overcurrent protection. To prevent the inrush current, this paper proposes a flux linkage offset compensation technique based on the synchronous reference frame (SRF) to regulate the flux linkage of the transformer. The proposed technique can be integrated with the existing voltage control and the PWM of the

UPS inverter without any additional sensors. The proposed technique can provide a very smooth and timely transition without the risk of inrush current for critical loads under power outages and voltage sags.

J. Pontt (2007) et al. Maintenance and operation of electrical systems in mining facilities fed by long Over Head Lines (OHL's) require configurations with two or more power transformers for ensuring high reliability and availability. This work presents the methodology developed for the study of an actual problem related with the connection of three power transformers operating in parallel, addressing the phenomenon of sympathetic interaction when the DC-component of inrush transient currents of the incoming transformer generate additional saturation in the already connected transformers. Nonexpected operation and tripping of electrical protective devices may be caused by the asymmetrical voltages and prolonged transient harmonic overvoltages, affecting the reliability of the whole electrical systems. Simulation and experimental results of an actual power system validate the methodology proposed for the study and design of mitigation methods.

l.sainz (2004) et al. This paper studies the effects of symmetrical and unsymmetrical voltage sags on a three-phase three-legged transformer and a three-phase transformer bank by considering that fault clearing is produced instantaneously in all the phases. The transformer model includes saturation and the parameters have been obtained from experimental measurements. The influence of the sag type, depth, duration and initial point-on-wave on the inrush current peak value is studied. The current peak has a periodical dependence on sag duration and the initial point-on-rave, and a linear dependence on depth. Unsymmetrical sag scan result in current peaks as high as those of symmetrical sags. A voltage sag is a short-duration reduction in rms voltage which can result in a mal-operation of the equipment Transformer saturation is caused precisely by the sudden variation in voltage at the voltage recovery, and it involves high inrush currents.

J.C. Gomez (2000) et al. More than 50% of the today power quality problem related with voltage sags and interruptions. Equipment manufacturers or manufacturer associations give the voltage sag equipment susceptibility. The curves approximately follow the equation $\int v^2 dt$ = constant, relating this concept to the specific energy of the current-limiting fuses. The upstream impedance determines the relationship between voltage and current integrals. There are several fuse types, which allows the selection to be made for the voltage sag duration reduction, using the fuse energy control characteristic. Also the effect of protected system particularities, like as motor starts, transformer connections and hot cold load pickup can be considered.

Sang Yun (2000) et al. This paper presents a reduction method of voltage sag using feeder transfer in power distribution systems. The proposed method is carried out using the switching for the sectionalizing points of distribution networks. It consists of two main sequences. First, we fine the weakness points for voltage sag. Second, we transfer the customer of weakness points to other source during the fault current exist. The reliability evaluation using the risk assessment model of voltage sag was performed for case studies. The Monte Carlo method and the historical reliability data in KEPCO (Korea Electric Power Corporation) are used for simulations.

C. S. Chang (2000) et al. Recently, due *to* the influx of digital computers and other types of electronics controls, utilities are paying more attention on voltage sag reduction. Solid-state Fault Current Limiters (FCLs) have been proposed as a means for sag reduction in the literature. However, not all FCL configurations are suitable for sag reduction. This paper presents the shortcomings (transient complications) introduced by the Thyristor Controlled Resonant FCL proposed by G. G. Karady in the literature. In addition, two modified versions of the Resonant FCL, with sag reduction and fault current limiting capabilities, are proposed for use on distribution systems. Sensitivity analysis is then performed on the modified FCLs to determine the effects of component and network parameters on the current limiter performances.

CHAPTER 3

PRESENT WORK

3.1 VARIOUS APPROACHES FOR MITIGATION OF INRUSH CURRENT

A number of methods which is used for mitigation of inrush current on the transformer, but very few of them are used in present days. The most conservative methodology is to control the applied voltage on the transformer by the help of electronic devices such as thyristors or by reactor starting technique. The control of applied voltage should be in such a way that the transformer flux should not flow beyond the saturation level of the magnetisation curve. Another method for inrush reduction is to apply the voltage on the transformer at the necessary point on sine wave, this method will prevent the flux of the transformer to develop beyond the saturation level. However the above mentioned methods can cause problems for the achievement of sag compensation, because the applied voltage, which is important for compensating the sag voltage may get affected by the above discuss methods used for inrush reduction. One more approach for inrush mitigation is that, modifying the shape of applied voltage by applying definite form factor to avoid the saturation level on the transformer. The form factor method can be used in two ways, the constant form factor method, in which a first half cycle of applied voltage magnitude is reduced by 50% and the another one is adaptive form factor method, in which the applied voltage on the transformer is adjusted depends on the measurement of flux obtained from first cycle. The decrease in the voltage may reduce the efficiency of the sensitive loads. The form factor methods is assumed to maintain the compensator voltage sinusoidal, then the line voltages inside industrial installations always holds major of harmonic distortion, in some circumstances the voltage THD might reach 8% owing to high attentiveness of nonlinear loads.

3.2 STUDY OF INRUSH IN TRANSFORMER

As we all know the transformer inrush will occur when the unloaded transformer is energized. At the same time the large amount of change will occur in the injected voltage to the magnetic core. As in case of three phase transformers, each phase of the transformer will have three different peak values of inrush current because of the change of the voltage angle at the switching time. The transformer inrush current is the function of several approaches like the terminal voltage switching angle, the remaining flux of the magnetic core, design of the transformer, impedance of the system etc.

Typical systematic formulas for the measurement of inrush current in transformer and amount of decay are resulting from single-phase transformer theory. The inrush current on a three phase transformer can be measured systematically created on the analytical formulas for a single-phase transformer and an experimental scaling factor. This factor explanations for the number of phases, core construction and coupling of transformer.

Bertagnolli suggests a quite simple equation created on a persistent exponential decay of the inrush current:

$$\hat{i}(\mathrm{n}) = \frac{\sqrt{2}U}{\sqrt{R_W^2 + \omega^2 L_{air-core}^2}} \left(\frac{2B_N + B_R - B_S}{B_N}\right) \mathrm{e}^{\frac{-t_n}{\tau}} \tag{1}$$

$$\tau = \frac{2L_{air-core}}{R_W}$$

The analytical formula projected for by Specht is slightly more exact as the decay of the dc component of the flux (B_R) is measured only during saturation (B > BS):

$$i(\mathrm{n}) = \frac{\sqrt{2}U}{\omega L_{air-core}} \left(1 - \frac{B_S - B_N - \tilde{B}_R(\mathrm{n})}{B_N}\right) \tag{2}$$

$$\tilde{B}_R(\mathrm{n}) = B_R(\mathrm{n}-1) - B_N \frac{\tilde{R}_W}{\omega L_{air-core}} 2(\sin\theta - \theta\cos\theta)$$

Holcomb recommends an enhanced analytical equation:

$$\mathrm{i(t)} = \frac{\sqrt{2}U}{\sqrt{R_W^2 + \omega^2 L_{air-core}^2}} \left(\sin(\omega \mathrm{t} - \phi) - \mathrm{e}^{\frac{R_W}{L_{air-core}}(\mathrm{t}-\mathrm{t}_s)} \sin(\omega t_s - \phi)\right) \tag{3}$$

$$\phi = \tan^{-1}\frac{\omega L_{air-core}}{R_W}$$

Where t_s is a time period when the core initiates to saturate ($B(t) > B_s$). It is expected that the inrush current is different from zero only between t_s and t_0, where t_0 is the time when the inrush current touches zero at each cycle.

Equation (1) and (2) analyse only the use of the inrush current peaks, not the real waveform. Equation (3) can be used to estimate systematically an imprecise waveform of the inrush current.

The air-core inductance $L_{air\ core}$ of the winding can be calculated as:

$$L_{air-core} = \mu_0 N_{HV}^2 \frac{A_{HV}}{h_{eq\_HV}}$$

With h_{eq_HV} existence, the equivalent height of the winding with fringing effects. The equivalent height is achieved by dividing the winding height by the Rogowski factor K_R (<1). This factor is typically resolute empirically and is a function of the height, mean diameter, and radial width of a winding.

3.3 CONFIGURATION OF COMPENSATOR

The per phase equivalent circuit of the sag compensator are shown in figure 3.1. The output of the inverter is filtered by low pas filter that is inductor of transformer L_f and capacitor C_f which supress the dc component and PWM ripples from the output of inverter voltage v_m.

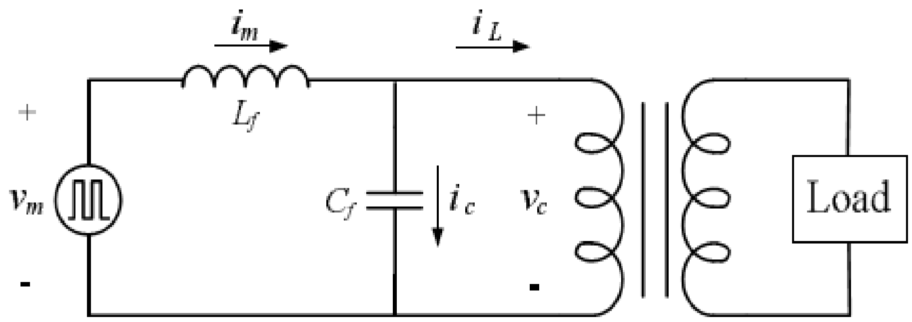


Fig. 3.1. Per phase equivalent circuit of the sag compensator

Following equations are dynamic equations of the equivalent circuit:

$$L_f \frac{d}{dt}\begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} = \begin{bmatrix} v_{ma} \\ v_{mb} \\ v_{mc} \end{bmatrix} - \begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} \quad (4)$$

$$C_f \frac{d}{dt}\begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} - \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{5}$$

Where $[i_{ma}\ i_{mb}\ i_{mc}]^T$ is the filter inductor current, $[v_{ma}\ v_{mb}\ v_{mc}]^T$ is the inverter output voltage, $[i_{La}\ i_{Lb}\ i_{Lc}]^T$ is the load current and $[v_{ca}\ v_{cb}\ v_{cc}]^T$is the compensation voltage. Equation (4) and (5) are shifted into the synchronous reference frame as (6) and (7).

$$\frac{d}{dt}\begin{bmatrix} i_{mq}^e \\ i_{md}^e \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_{mq}^e \\ i_{md}^e \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} v_{mq}^e \\ v_{mq}^e \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} \tag{6}$$

$$\frac{d}{dt}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} i_{mq}^e \\ i_{mq}^e \end{bmatrix} - \frac{1}{C_f}\begin{bmatrix} i_{Lq}^e \\ i_{Ld}^e \end{bmatrix} \tag{7}$$

Where superscript "e" designates the synchronous reference frame illustration of this variable and ω is the angular frequency of the utility grid. Equation (6) and (7) expression the cross-coupling relations between compensation voltage and filter inductor current.

3.4 METHODS USED FOR CONTROL

The proposed control method is shown in a block diagram in which d axis controller is not shown for your simplicity. In the block diagram full state feedback controller with inrush current technique are used. Detailed explanation are given as bellow:

3.4.1 The Full State Feedback Scheme

The state feedback scheme contains feedforward control, feedback control, and the decoupling control.

Feedback Control

The feedback control is used to improve the accuracy of the compensation voltage, the robustness and the distribution rejection ability against the variation in the parameters as

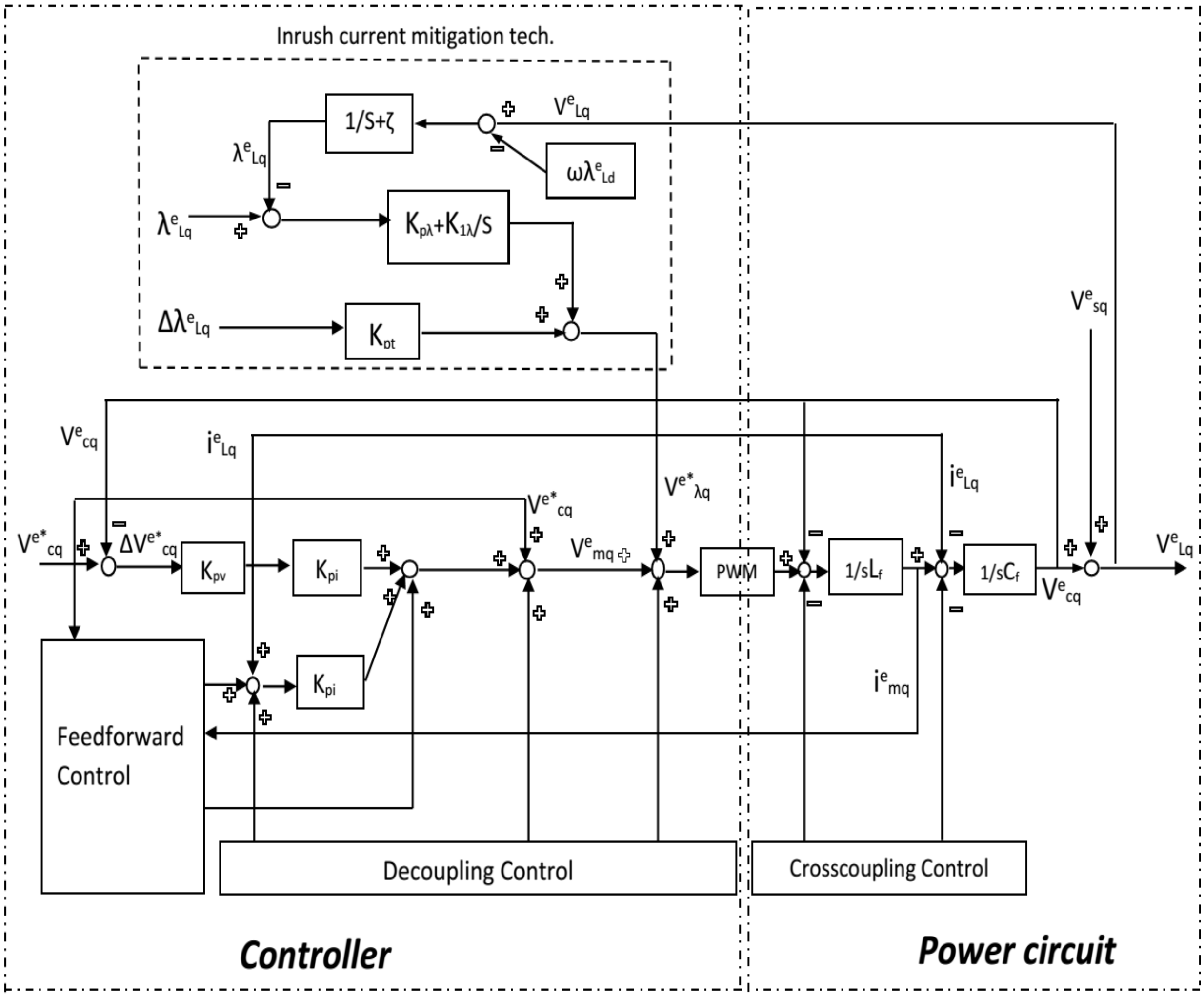


Fig.3.2. Block diagram of the proposed inrush current mitigation technique with the feedback control.

shown in block diagram. The voltage from the capacitor v^e_{cq} is the inner loop voltage control and the current from the inductor i^e_{mq} is the current control in the inner loop. The control of the voltage con be done by the propositional regulator with voltage command v^{e*}_{cq} respectively according to the requirement of the sag.

Feedforward Control

Feedforward control is added to the voltage control loop for enhancing the dynamic response of the voltage sag compensator and to compensate the sag voltage without making any further delay. The feedforward voltage command can be measured by joining the compensation voltage and the voltage drop across the filter inductor which is produced by the filter capacitor current.

Decoupling Control

In the block diagram the cross coupling terms and the decoupling terms is derived from the synchronous reference frame transformation and the external disturbance in the voltage compensator. These controls are used to enhance the preciseness and the distribution ability. These terms can be obtained by calculating the filter capacitor voltage, load current and the filter inductor current.

3.4.2 Inrush Current Mitigation Techniques

3.4.2.1 Flux Linkage Dc Offset

By integrating the line voltage, we can measure the flux linkage of the transformer as given in equation 8. Figure 6 shows delta/wye three phase transformer having single windings and is installed in downstream of voltage sag compensator. The linkage of the flux in the phase a-b windings is expressed as:

$$\lambda_{Lab}(\mathrm{t}) = \int v_{Lab}(\mathrm{t})\,\mathrm{dt} \tag{8}$$

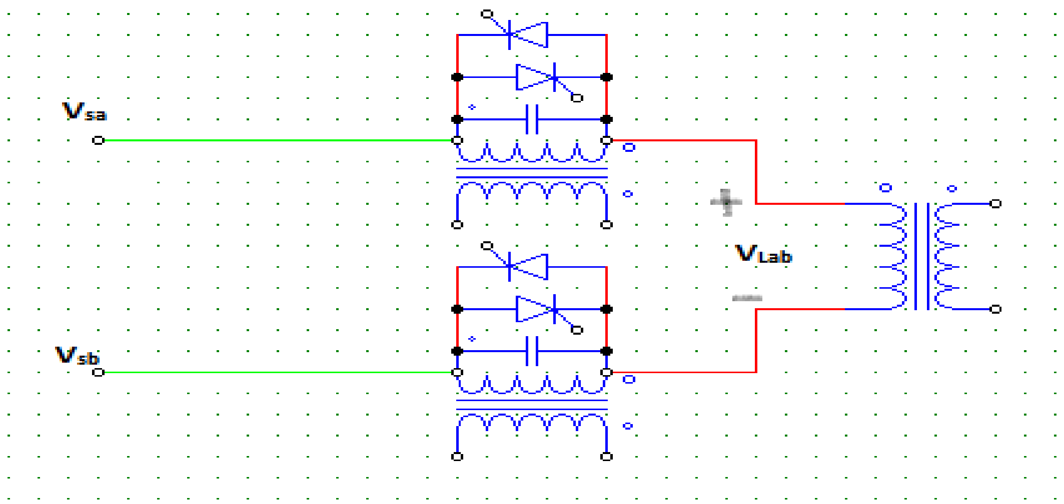


Fig. 3.3. Connection diagram of the projected system and delta/wye load transformer

Figure 3.4 shows the line-to-line voltage through the transformer winding and the causing flux linkage attained from the voltage sag incidence to completion of voltage compensation. When voltage sags happens ($t=t_{sag}$), the controller senses the sagged voltage and inserts the essential compensation voltage at $t = t_{detect}$. The flux linkage through the voltage compensation procedure can be direct as following:

$$\lambda_{Lab}(\mathrm{t}) = \lambda_{Lab}(\mathrm{t})\Big|_{t=t_{sag}} \int_{t_{sag}}^{t_{detect}} v_{Lab}(\mathrm{t})\,\mathrm{dt} + \int_{t_{detect}}^{t} v^{*}_{Lab}(\mathrm{t})\,\mathrm{dt} \tag{9}$$

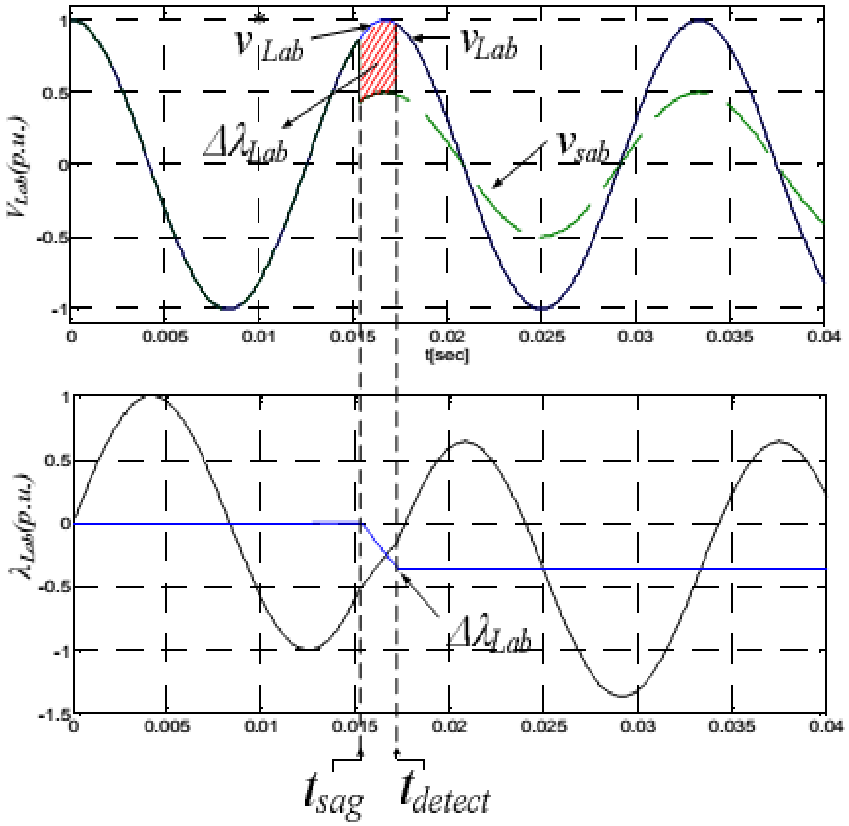


Fig. 3.4. Transformer voltage and corresponding transient flux linkage

Above equation can be rewritten as follows:

$$\lambda_{Lab}(\mathrm{t}) = \lambda_{Lab}(\mathrm{t})\Big|_{t=t_{sag}} - \int_{0}^{t} v^{*}_{Lab}(\mathrm{t})\,\mathrm{dt}$$

$$+ \int_{t_{sag}}^{t_{detect}} (v_{Lab}(\mathrm{t}) - v^{*}_{Lab}(\mathrm{t}))\,\mathrm{dt} + \int_{0}^{t} v^{*}_{Lab}(\mathrm{t})\,\mathrm{dt} \tag{10}$$

Where V^{*}_{Lab} (t) is the pre-fault load voltage distinct as follows:

$$v^{*}_{Lab}(\mathrm{t}) = \hat{V}^{*}_{Lab}\sin(\omega \mathrm{t} + \Phi^{*}_{Lab})$$

Where $\tilde{V}^{*}_{Lab}$ is the magnitude of load voltage, ω is the grid frequency, and Φ^{*}_{Lab} is the phase angle. Thus, next the voltage compensation is finished, the flux linkage can be stated as follows:

$$\lambda_{Lab}(\mathrm{t}) = \Delta\lambda_{Lab}(\mathrm{t})\Big|_{t=t_{\mathrm{detect}}} + \frac{\hat{V}^{*}_{Lab}}{\omega}\sin(\omega \mathrm{t} + \Phi^{*}_{Lab} - \frac{\Pi}{2}) \tag{11}$$

Where

$$\Delta\lambda_{Lab}(\mathrm{t})\Big|_{t=t_{\mathrm{detect}}} = \lambda_{Lab}(\mathrm{t})\Big|_{t=t_{sag}} - \lambda^{*}_{Lab}\Big|_{t=t_{sag}}$$

$$+\int_{t_{sag}}^{t_{\mathrm{detect}}} (v_{Lab}(\mathrm{t}) - v^{*}_{Lab}(\mathrm{t}))\,\mathrm{dt} \tag{12}$$

$$t_{sag} \le t \le t_{\mathrm{detect}}$$

By the above equation no. 12 the flux linkage DC offset $\Delta\lambda_{Lab}$ which is obtained by the voltage sags on the transformer windings, also the flux magnitude is dependent on the penetration and the duration of sags. Various voltage sags may happen the DC offset which can saturate the core of the transformer above the knee may cause inrush current. Usually the magnetic saturation knee is 1.10 to 1.15 p.u. of state-study flux linkage.

3.4.2.2 Design the Flux Linkage Estimation

The single phase transformer under no load condition is shown in figure 3.5, where R_1 and L_{l1} is the primary side equivalent resistor of copper loss and the equivalent leakage inductance respectively. R_c and L_m is the equivalent resistor of core loss and magnetic inductance.

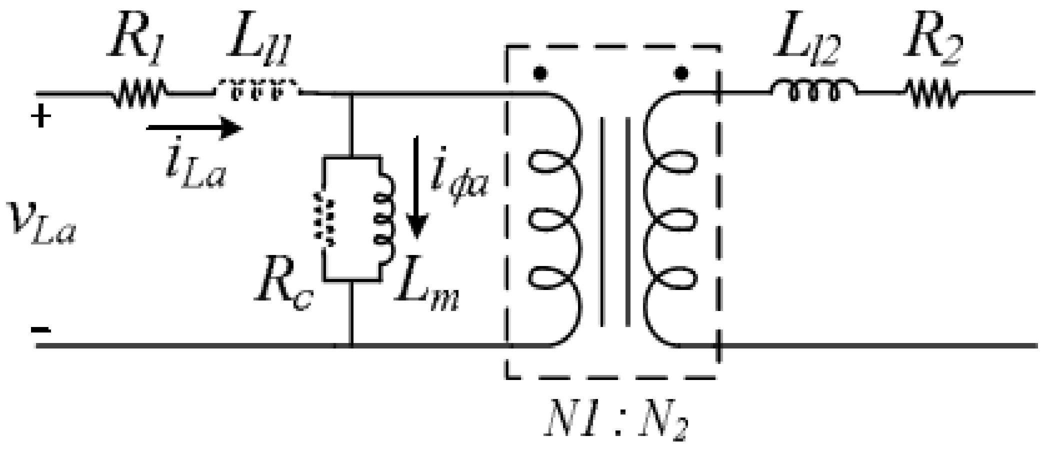


Fig. 3.5. Equivalent per phase circuit model of the transformer

This dynamics of the transformer equivalent circuit in Fig. 3.5 can be stated as:

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = L_m \frac{d}{dt} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} + R_1 \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{13}$$

Note that for explanation the leakage inductances and the core losses are ignored.

The above equation can be written as:

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} \lambda_{La} \\ \lambda_{Lb} \\ \lambda_{Lc} \end{bmatrix} + \frac{R_1}{L_m} \begin{bmatrix} \lambda_{La} \\ \lambda_{Lb} \\ \lambda_{Lc} \end{bmatrix} \tag{14}$$

Where

$$\begin{bmatrix} \lambda_{La} & \lambda_{Lb} & \lambda_{Lc} \end{bmatrix}^T = L_m \begin{bmatrix} i_{La} & i_{Lb} & i_{Lc} \end{bmatrix}$$

The changing aspects of the transformer flux linkages can be converted into the synchronous reference frame as:

$$\begin{bmatrix}\lambda_{Lq}\\ \lambda_{Ld}\end{bmatrix}^e = \int\left(\begin{bmatrix}v_{Lq}\\ v_{Ld}\end{bmatrix}^e + \begin{bmatrix}0 & -\omega\\ \omega & 0\end{bmatrix}\begin{bmatrix}\lambda_{Lq}\\ \lambda_{Ld}\end{bmatrix}^e - \zeta\begin{bmatrix}\lambda_{Lq}\\ \lambda_{Ld}\end{bmatrix}^e\right)dt \tag{15}$$

Where the damping ratio, $\zeta = R_1/L_m$, selects the transient of the flux linkage. Figure 3.6 pictures the flux linkage estimator in the synchronous reference frame causing from the equation (15).

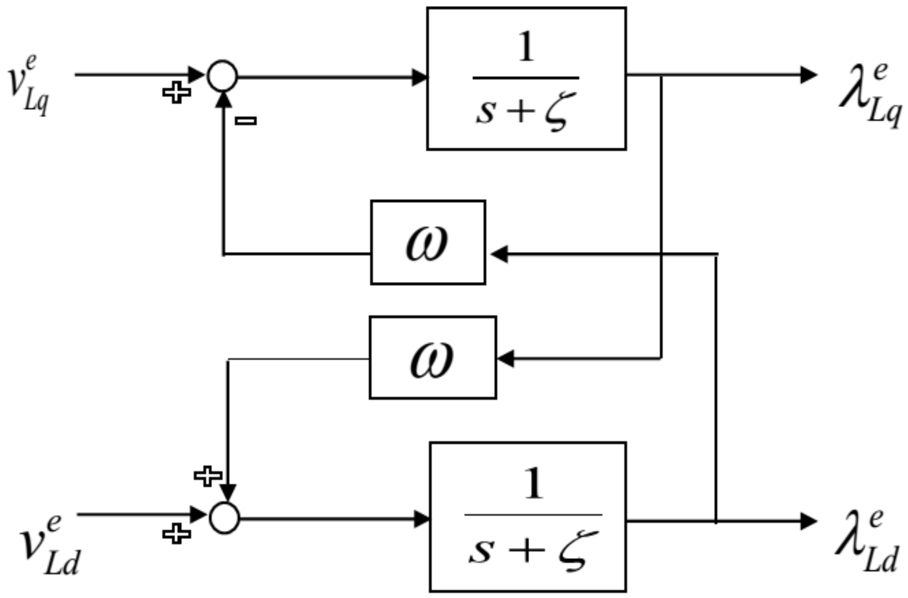


Fig. 3.6. The flux linkage estimator under the synchronous reference frame.

The flux linkage estimator, as obtainable in Fig. 3.6, is applied the projected inrush mitigation method. The projected inrush mitigation method holds feedback control and feedforward control.

In the feedback control loop, the flux linkage λ^e_{Lq} is created by the integration of load voltage v^e_{Lq}. The irregularity of the flux linkage can be proposed by the difference between λ^{e*}_{Lq} and the flux linkage λ^e_{Lq}. The error is controlled by a proportional-integral (PI) regulator.

To rapidity up the dynamics reaction of the inrush current modification, the error between the predictable flux linkage DC offset and the flux linkage command ($\Delta\lambda^{e}_{Lq.} = \lambda^{e*}_{Lq} - \lambda^{e}_{Lq}$) is applied as a feedforward control term. The command is multiplied by a proportional gain K_{pt} (=1/ΔT) to accelerate the DC offset compensation during the compensator start transient. The control gain K_{pt} is selected according to the tolerant of inrush current and the time responsibility of flux linkage DC offset compensation.

The summation $v^{e*}_{\lambda q}$ of feedback and feedforward command is added to the sag compensation voltage command v^{e*}_{mq} to produce the complete command voltage of the voltage sag compensator. Thus, the predictable control process designate the voltage sag compensator to attain an unresolved load voltage following and escape the inrush current occurs on the load side transformer.

3.4.2.3 Controlling the Magnitude of Voltage

The magnitude of applied voltage is so controlled that the transformer flux does not reach beyond the maximum value of the flux (λ_m) as shown in fig 3.7.

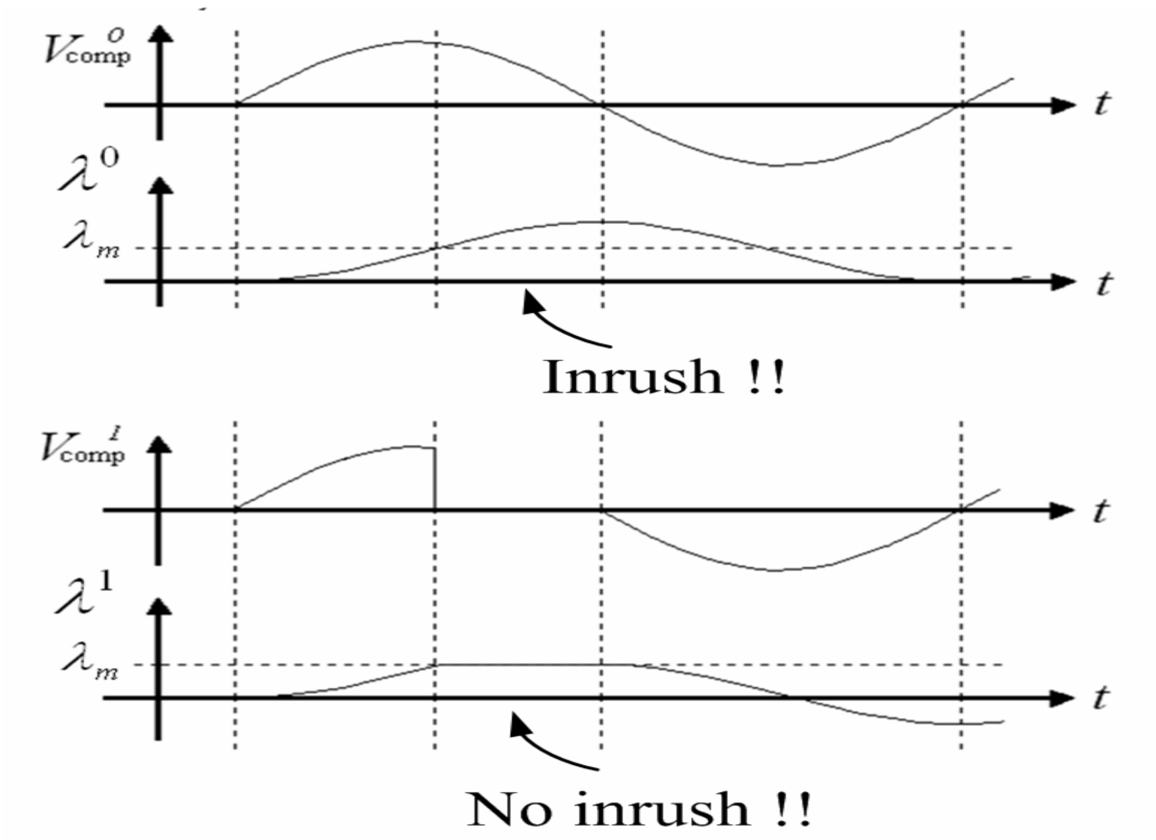


Fig 3.7. The compensation voltage and developed flux linkage

We can achieve that much of flux by cutting down the injected voltage at the time when the linkage flux will reach its maximum value (λ_m). Now assuming the original command voltage of the compensation, its flux linkage and magnetizing current are as V_{comp^o}, λ_o and i_o respectively. Now the adjusted compensation voltage command, its projected flux and current are V_{comp^1} and λ_1 and i_1 respectively.

CHAPTER 4

SIMULATION AND RESULTS

In the simulation diagram of we compare the results of the two Simulink models that is without inrush mitigation technique and with inrush mitigation technique for analysing the inrush current in the load transformer. So, MATLAB/SIMULINK is being used for the simulation purpose of both the systems. The SIMULINK diagram and blocks used in the system are detailed below.

4.1 SIMULATION WITHOUT INRUSH MITIGATION TECHNIQUE

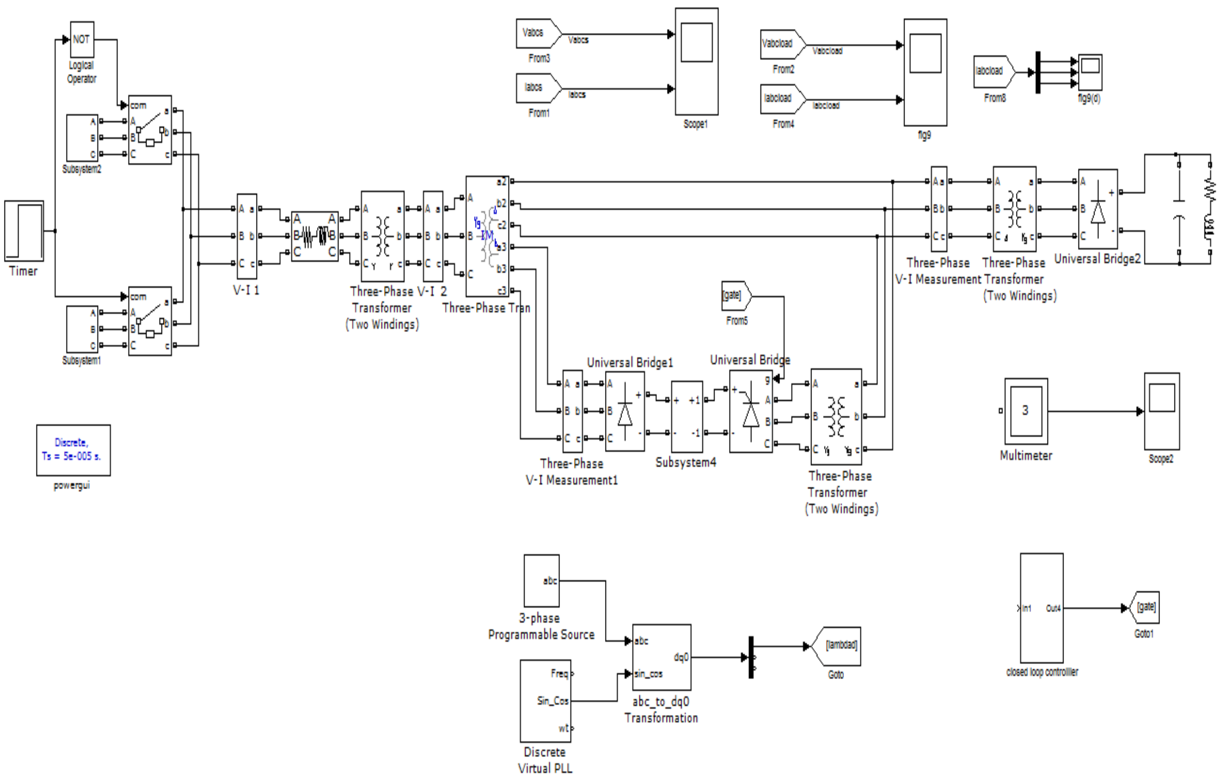


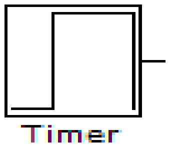
Fig 4.1 Equivalent circuit diagram of without mitigation tech.

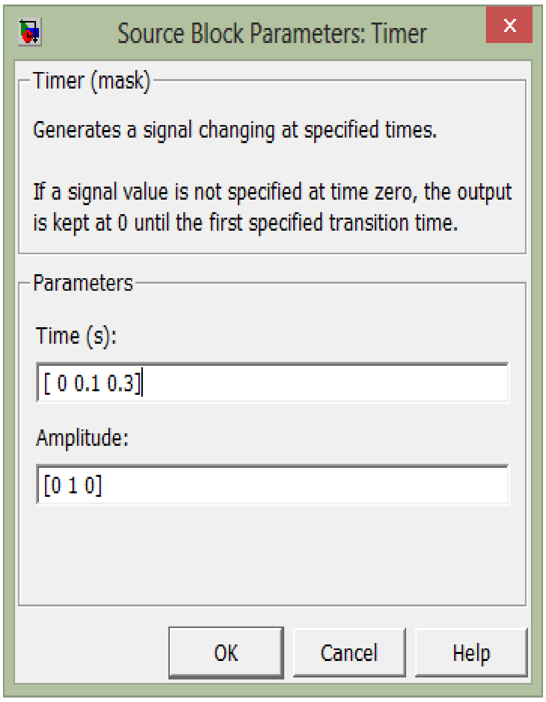
Following are the blocks which are used for the simulation of the above system model:

- Timer
- Three phase source
- Three phase transformer
- Three winding transformer
- Three phase V-I measurement.

- Current measurement.
- Voltage measurement.
- Rectifiers
- Inverters
- Filters
- Three phase load
- Power gui
- Scope

Timer:

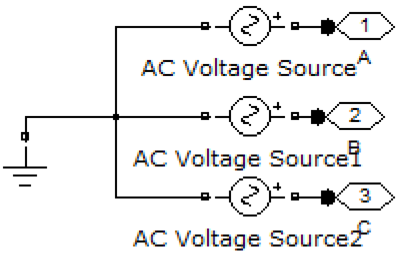


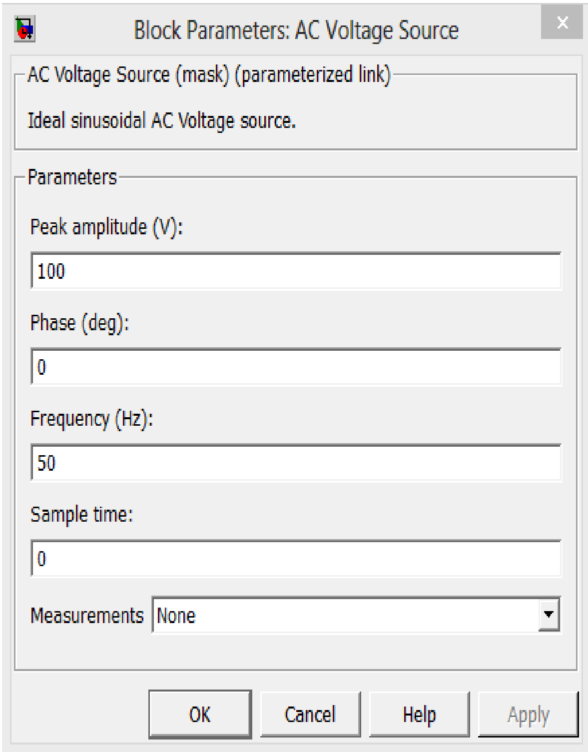


A timer block is used to generate a signal like 0 and 1 amplitude which is used to control the power switches like circuit breakers and other switching blocks. If a signal 0 is generated by timer this means that switch is off and if 1 is generated by timer that means switch is on. The amplitude of this block can be changed by steps.

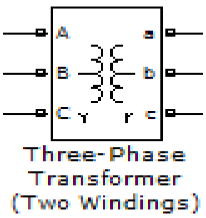
Three phase source:

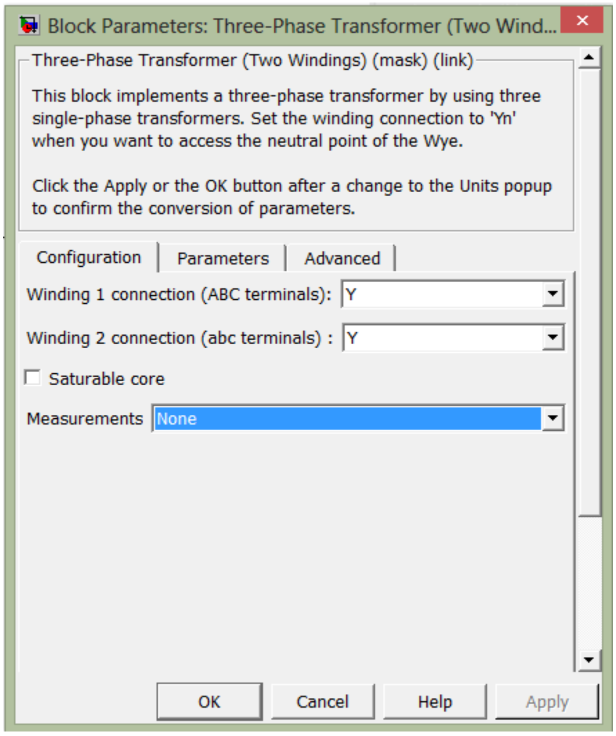
This block i.e. three phase source block provides three phase supply. It is connected in star and neutral is grounded as shown. Each phase is 120 apart from each other. It can be set to provide the supply what is needed by the circuit or the experiment for which the model is being simulated. In the above simulation this three phase source is set to supply 500 kv of the power.





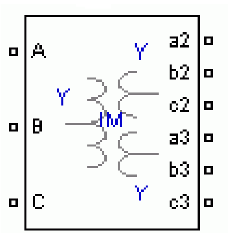
Three phase two winding transformer:

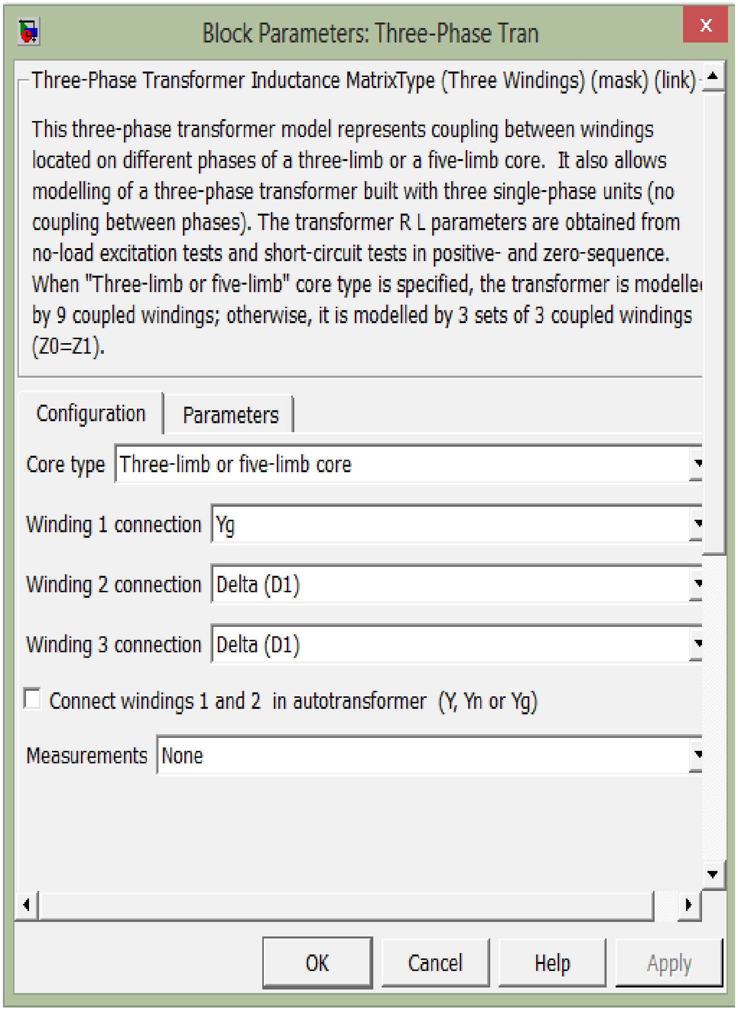




It is a three phase transformer which is formed by the combination of three single phase transformer connected together. To simulate saturable core transformer there is an option of checking and unchecking the box as to that the saturation of the core is required by the experiment or not. As the connection type of the block is changed and applied the block's diagram updates itself. If the Y connection with neutral winding 1 is selected there will be change in diagram and N will appear for the neutral connection. Similarly for winding 2, if neutral is needed them it will appear there. If at the start there is no values set for the flux and the other values then it will take default value and will always start in steady state and not in transient state. In this simulation model we are using Y connection with accessible neutral winding for the measurement purpose.

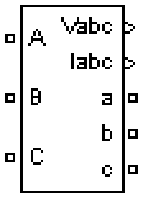
Three winding transformer:

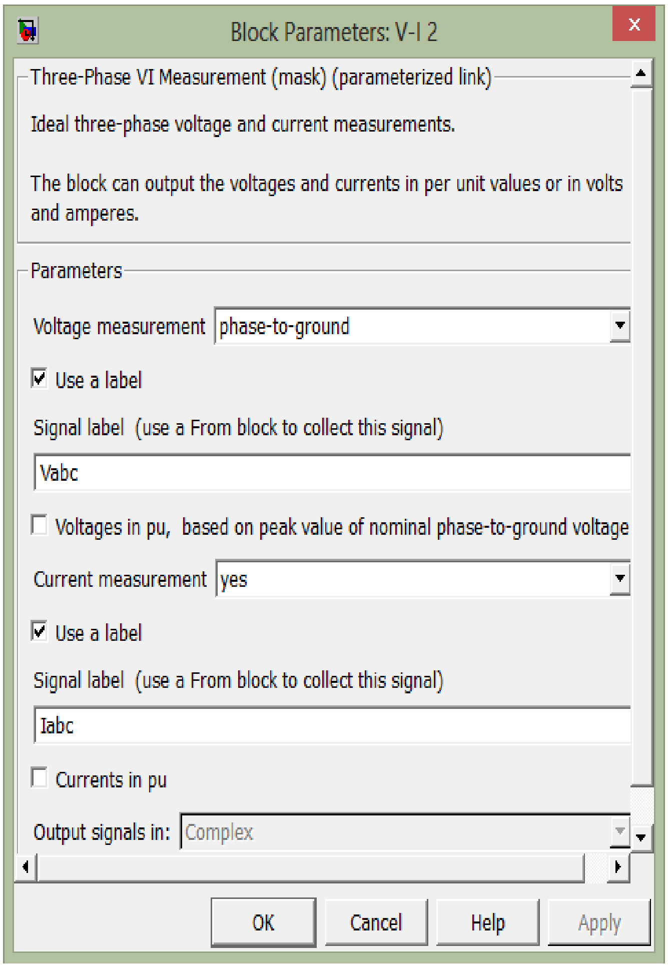




This block is three phase transformer which contains three windings. Three single phase transformers are used to make this block. Three limb or five limb core are used to make this block. In this block each winding is star connected.

Three phase V I measurement:





It is used to measure three phase current and voltage instantaneously and can acts as a virtual bus also depending upon the requirement. When it is connected in series with three-phase elements, returns the three phase-to-ground or phase-to-phase peak voltages and currents. It measures voltage and current and can provide the output value in per unit values. It is also acting as a bus as there are components which cannot be directly connected. The voltage and current phasors can be measured by using the powergui block, in this block settings can be done to use phasors to get the phasor outputs.

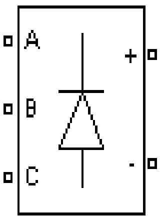
Current measurement:

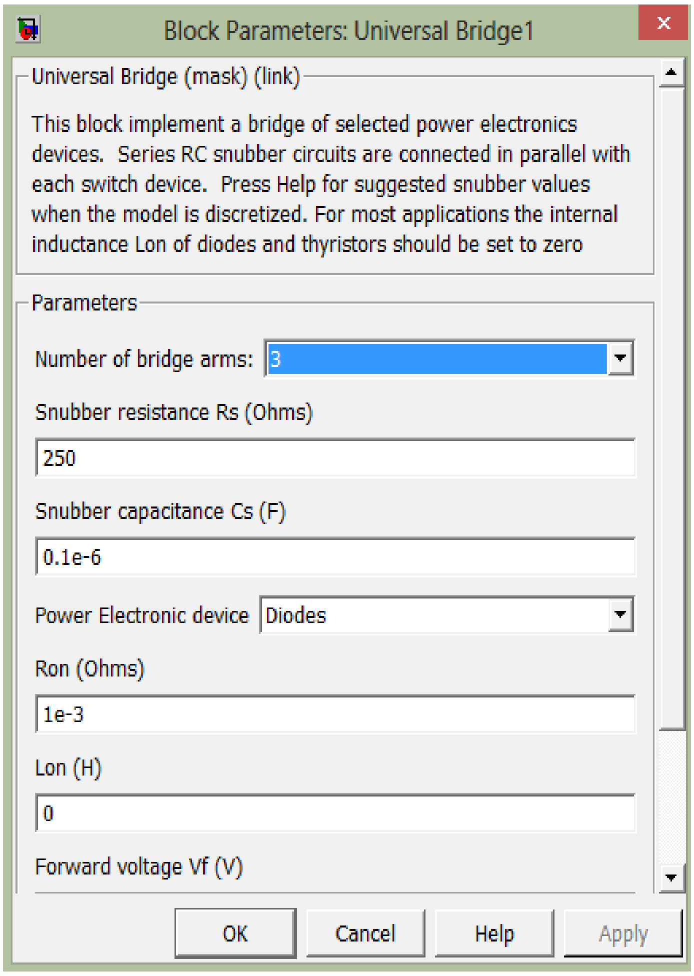
The Current Measurement block is used to measure the instantaneous current flowing in any electrical block. The Simulink output provides a Simulink signal that can be used by other Simulink blocks. The output of this block specifies the format of the output signal when the block is used in a phasor simulation for any network. The Output signal parameter is disabled when the block is not used in a phasor simulation and used in any other method. The phasor simulation is activated by a Powergui block placed in the model.

Voltage measurement:

The Voltage Measurement block measures the instantaneous voltage between two electric nodes in the model. The output provides a Simulink signal that can be used by other Simulink blocks. The output of this block specifies the format of the output signal when the block is used in a phasor simulation for any network. The Output signal parameter is disabled when the block is not used in a phasor simulation and used in any other method. The phasor simulation is activated by a Powergui block placed in the model.

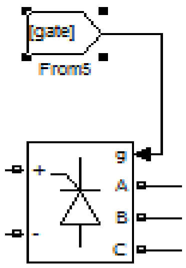
Rectifier:

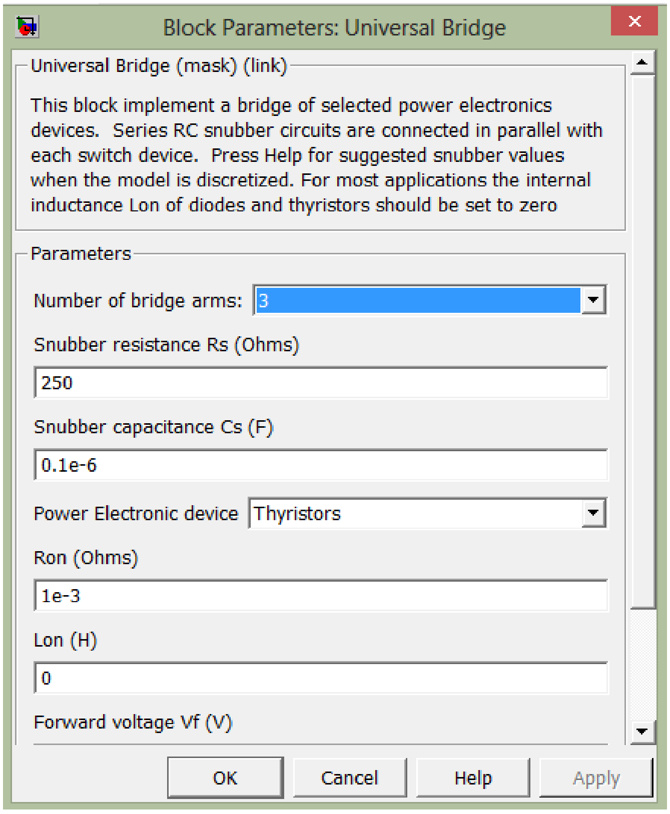




The control rectifiers are used to change the ac into dc. These rectifiers are simple and less expensive and the efficiency of these rectifiers are 95%. Rectifiers are also called ac dc converters and are used extensively in industrial applications, especially in variable speed drives, ranging from fractional horsepower to megawatt power level.

Inverters:

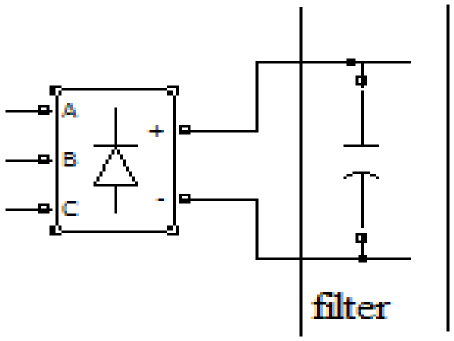




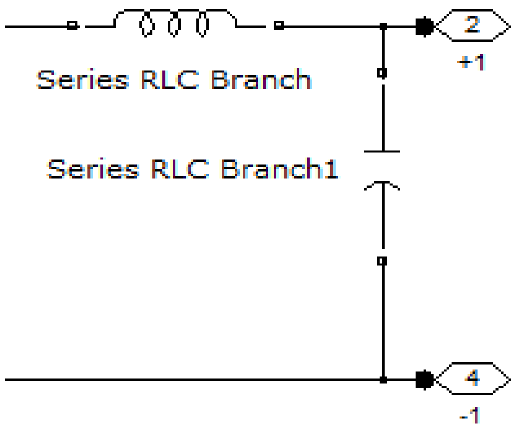
A device which converts dc power into ac power at desired voltage and frequency is called inverter. Some industrial application of inverters are for adjustable speed ac drive, induction heating, computers and hvdc transmission system.

Filters:

A rectifier would deliver an output voltage that must be as smooth as possible in practice, however, output voltage for rectifier contains dc components plus ac components or ac ripples. The ac components contain several dominant harmonics. These harmonics remain more in single phase rectifier with R load. The ac components does no useful work. These ac components nearly causes more ohmic losses in this circuit leads to decrease efficiency of the system. The filters are used to filter out the unwanted ac components present in the rectifier output.



In the above filter it offers direct short circuit to ac components, these are therefore not permitted to reach the load. However dc get stored in the form of energy in capacitor and this permits the maintenance of almost constant dc output voltage across the load.



The non-sinusoidal output current from inverter circuit holds harmonics. For decreasing these harmonics in the supply current ac filters are used at the output terminal of the inverter circuit.

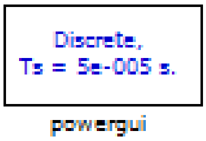
Power gui:

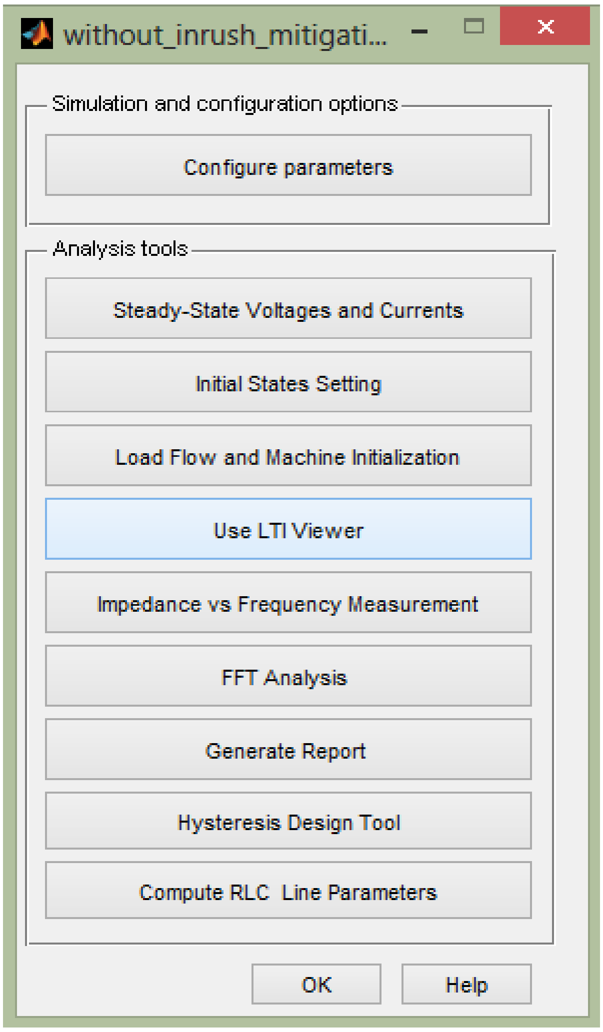
The Powergui block is necessary for simulation of any Simulink model containing Sim Power Systems blocks. This particular block is used to store the equivalent Simulink circuit that represents the state-space equations of the model. The Powergui block allows you to choose one of the following methods to solve your circuit:

- Continuous method, it uses a variable step Simulink solver.
- Ideal Switching continuous method.
- Discrete method, used for discretization of the electrical system for a solution at fixed time steps.

- Phasor solution method.

Simulation type can be easily specified in the powergui block configurations. To choose whether one of the above mentioned methods are used for solving the circuit. Here for our simulation circuit we are using discrete method to solve the circuit.





Scope:

Scope block is used to display the output with respect to the time of the simulation block. This block has so many different axis and with the same time range and a fixed y axis. The amount of time and the time range can be adjusted using the scope block. The window in which the results are about to be shown can be easily moved, modified and can be adjusted according to the requirement of simulation. Scope can be used to view the output as it is required by the user and mostly it is always helpful in determining the exactness or accuracy of the output. Here, in this simulation we can see different scopes used in the different areas of simulation. To measure current, to measure voltage and measure different aspects of output scope can be successfully used.

4.2 RESULTS OF SIMULATION WITHOUT MITIGATION TECHNIQUE

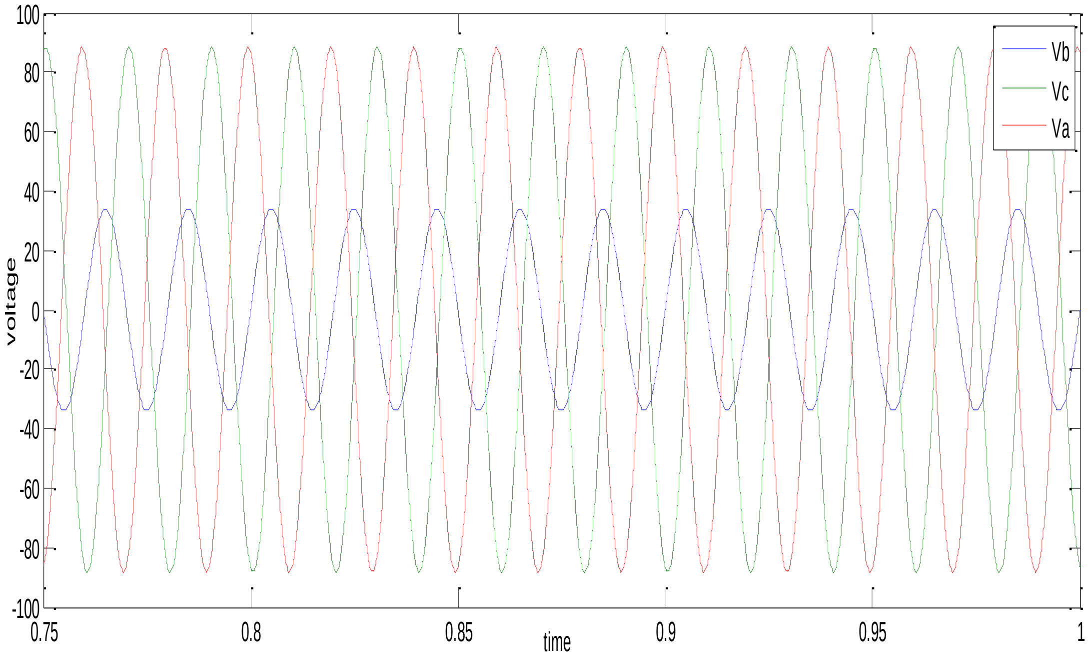


Fig. 4.2. Source voltage

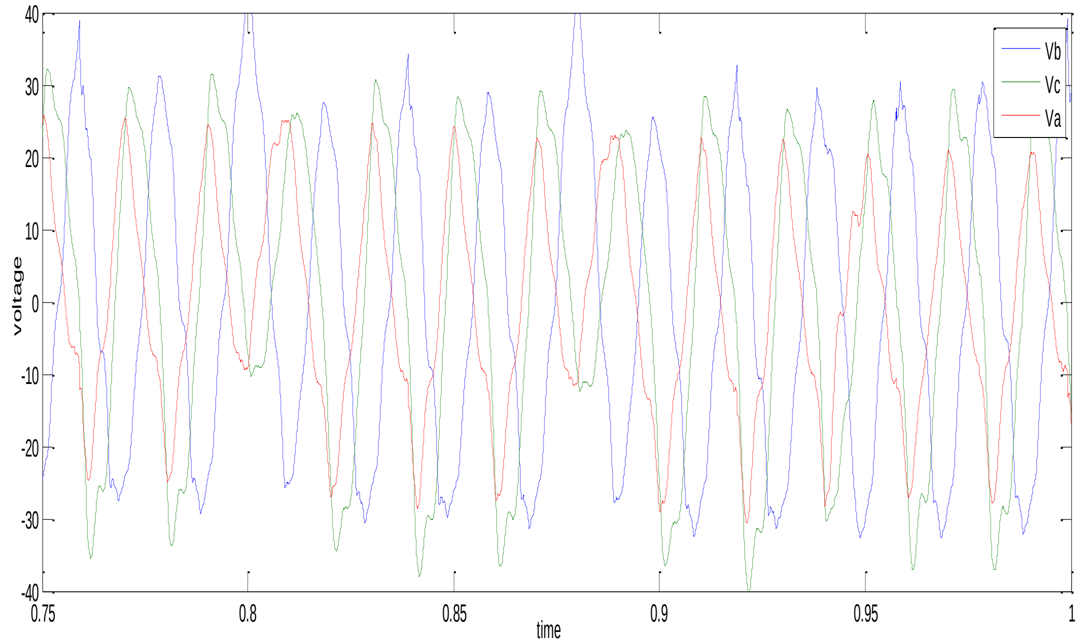


Fig. 4.3. Load voltage

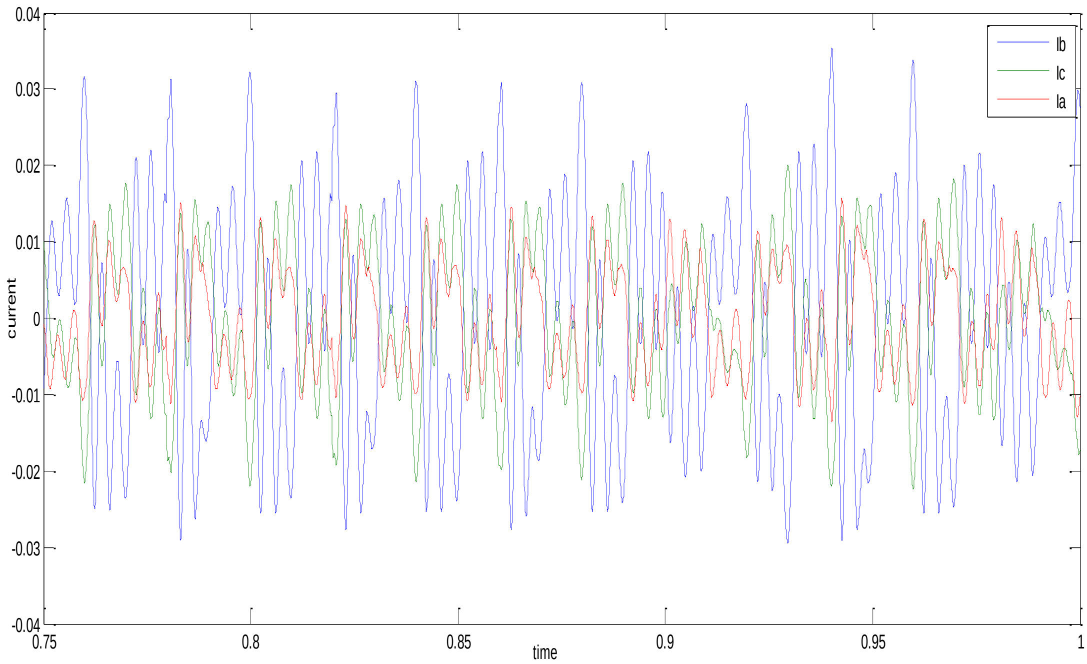


Fig. 4.4. Load current

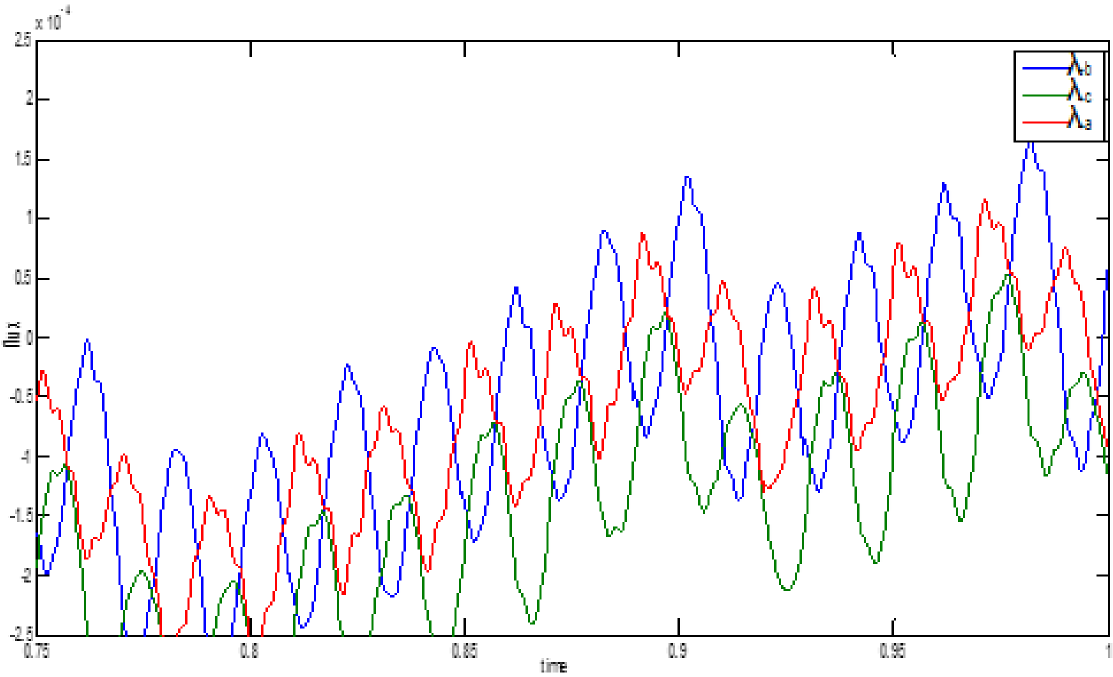


Fig. 4.5. Flux linkage of load transformer

4.3 SIMULATION DIAGRAM WITH INRUSH MITIGATION METHOD

In this simulation diagram mitigation of inrush current technique has been implemented which occur during voltage sag compensation.

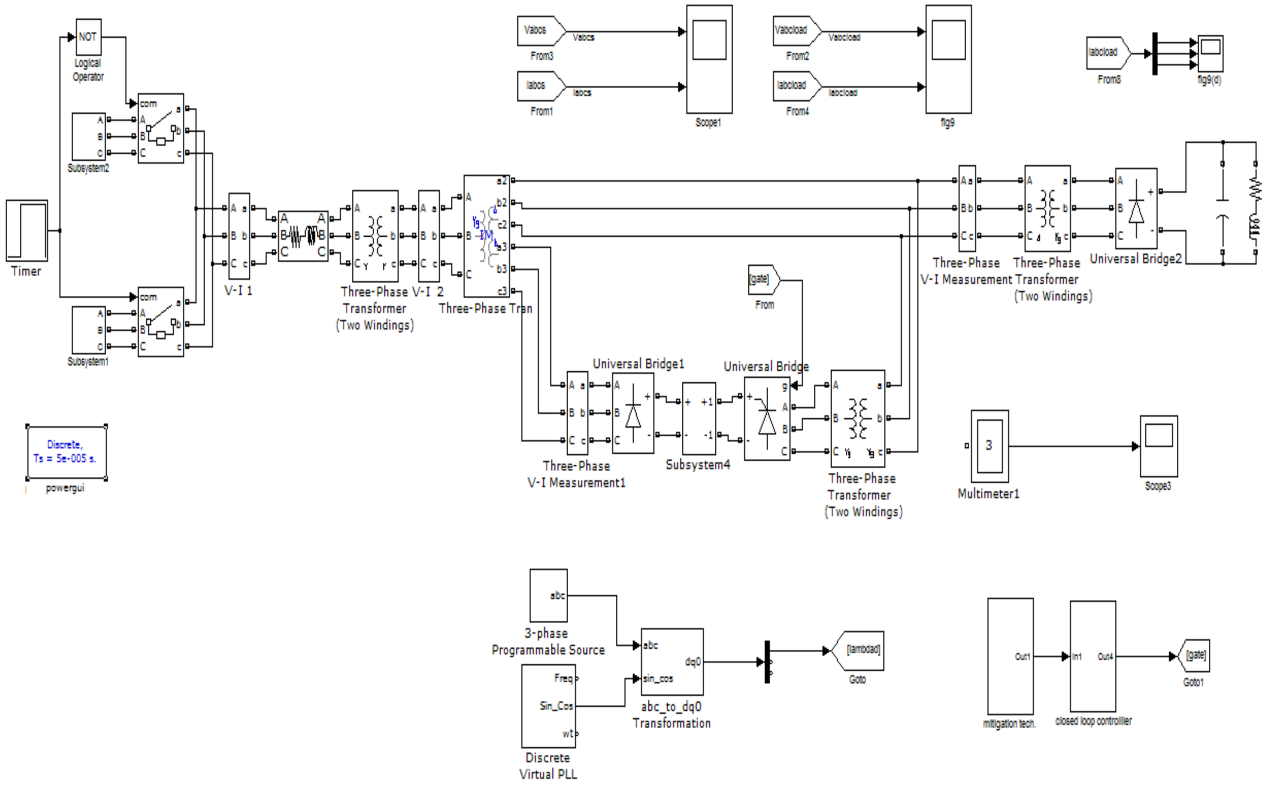


Fig 4.6 Equivalent circuit diagram of inrush mitigation tech.

Following are the blocks which are used for the simulation of the above system model:

- abc_to_dq0 Transformation
- Discrete virtual PLL
- PWM generator

Abc_to_dq0 Transformation:

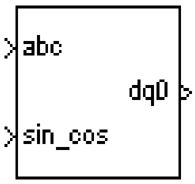
This block is used for abc to dq0 transformation that means the three phase signal is transformed to dq0 axis (direct, quadrature axis and zero sequence quantities).

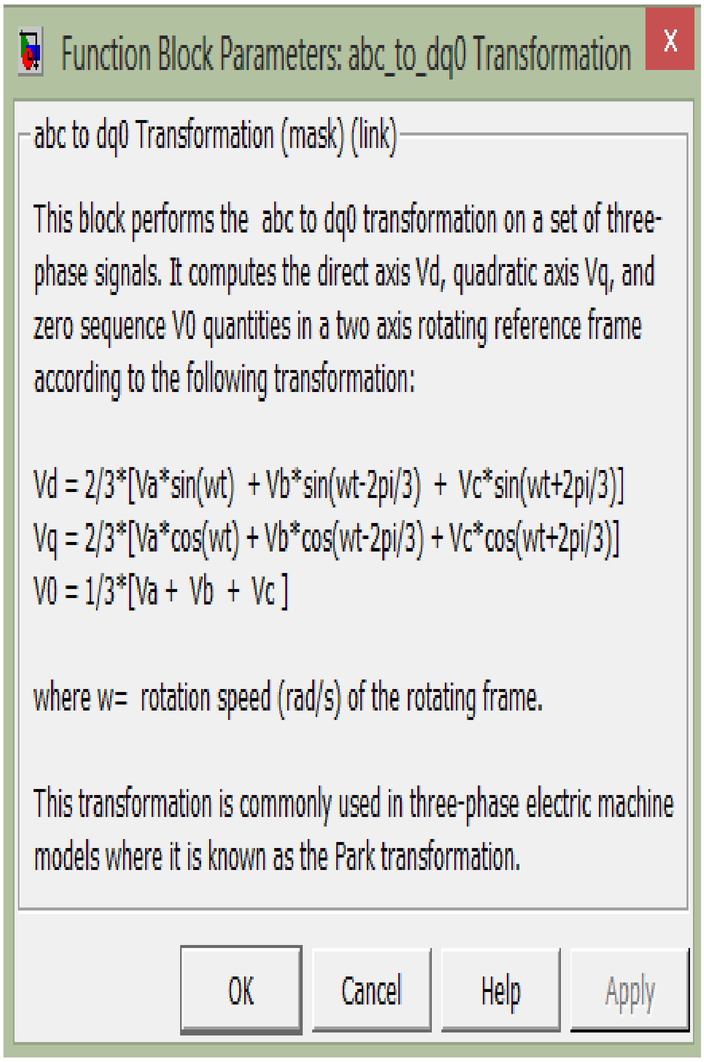
The transformation can be done as

$$V_d = \frac{2}{3}(V_a \sin(\omega t) + V_b \sin(\omega t - {}^{2\Pi}\!/_{3}) + V_c \sin(\omega t + {}^{2\Pi}\!/_{3}))$$

$$V_q = \frac{2}{3}(V_a \cos(\omega t) + V_b \cos(\omega t - {}^{2\Pi}\!/_{3}) + V_c \cos(\omega t + {}^{2\Pi}\!/_{3}))$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$

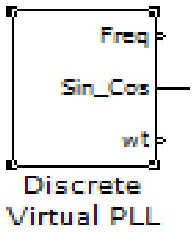


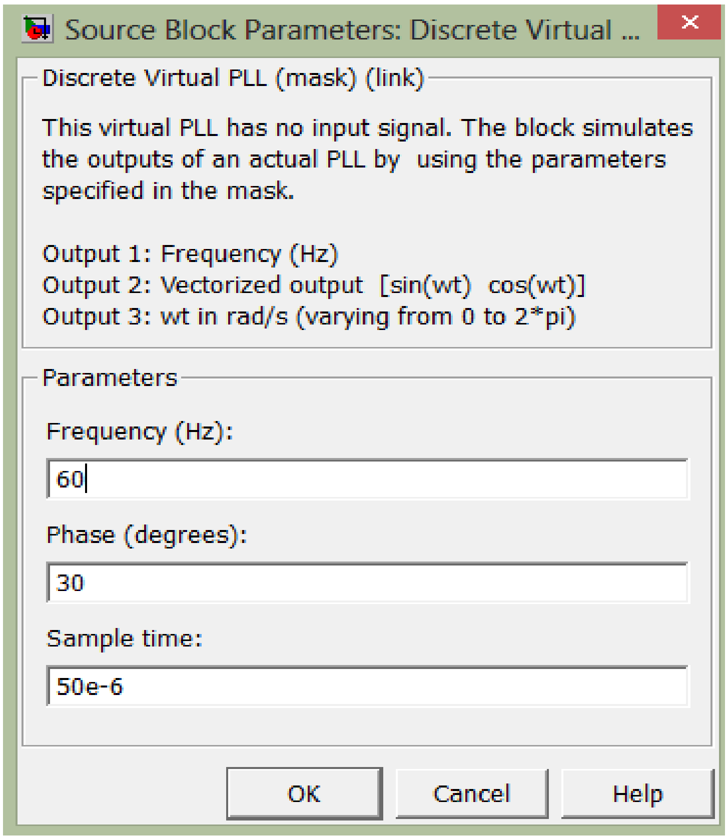


The transformation is necessary for the machines contain inductance terms which varies with the field and the field varies with the time as rotor rotates.

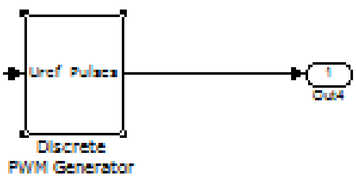
Discrete virtual PLL:

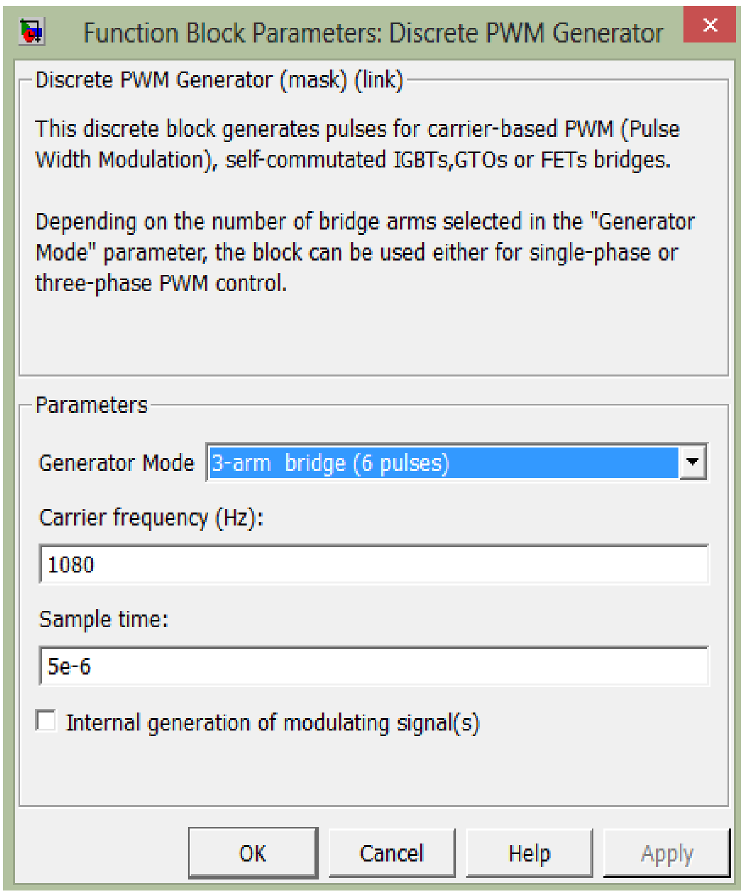
This block provides sin cos pulse as per the requirement.





PWM generator:





The PWM generator block is used to control the frequency and the phase of the output voltage. By comparing the reference wave with the carrier wave results the controlled output voltage.

4.4 SIMULATION RESULTS WITH INRUSH MITIGATION TECHNIQUE

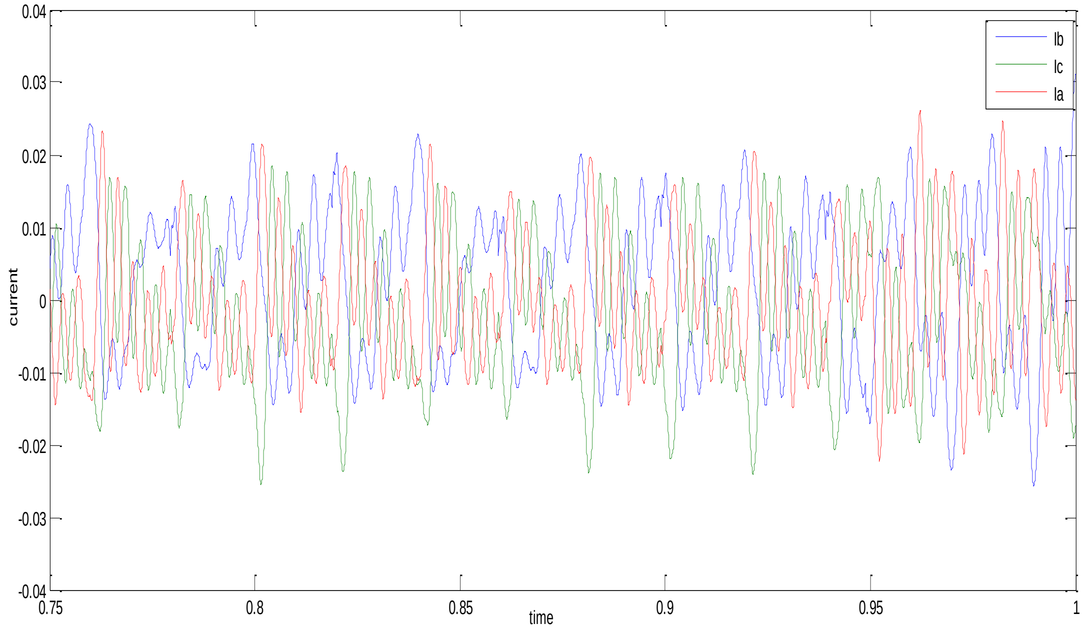


Fig. 4.7. Load current

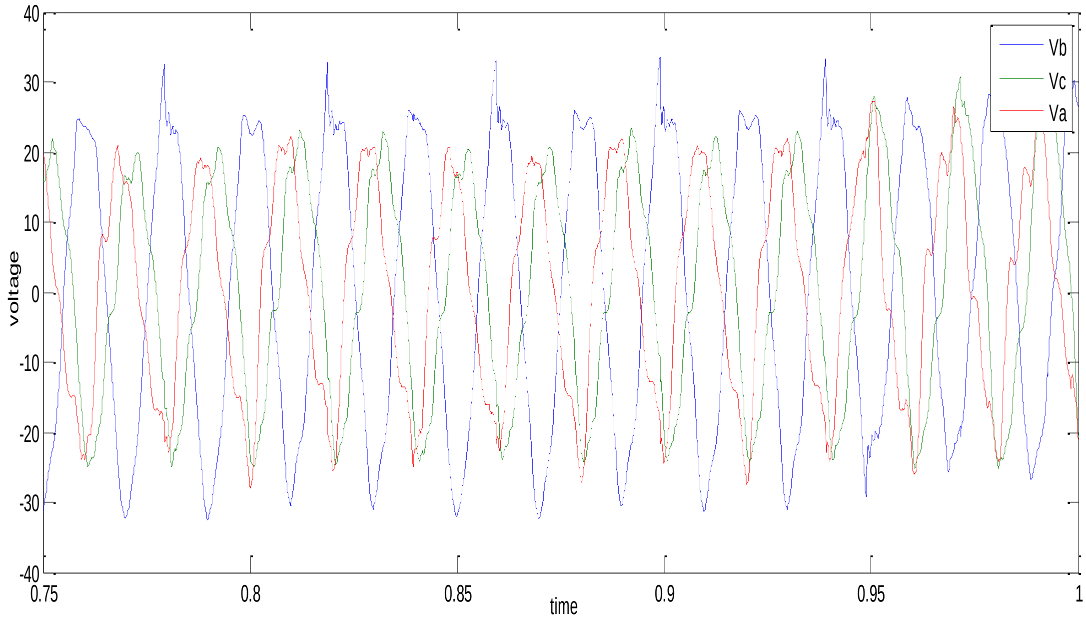


Fig. 4.8. Load voltage

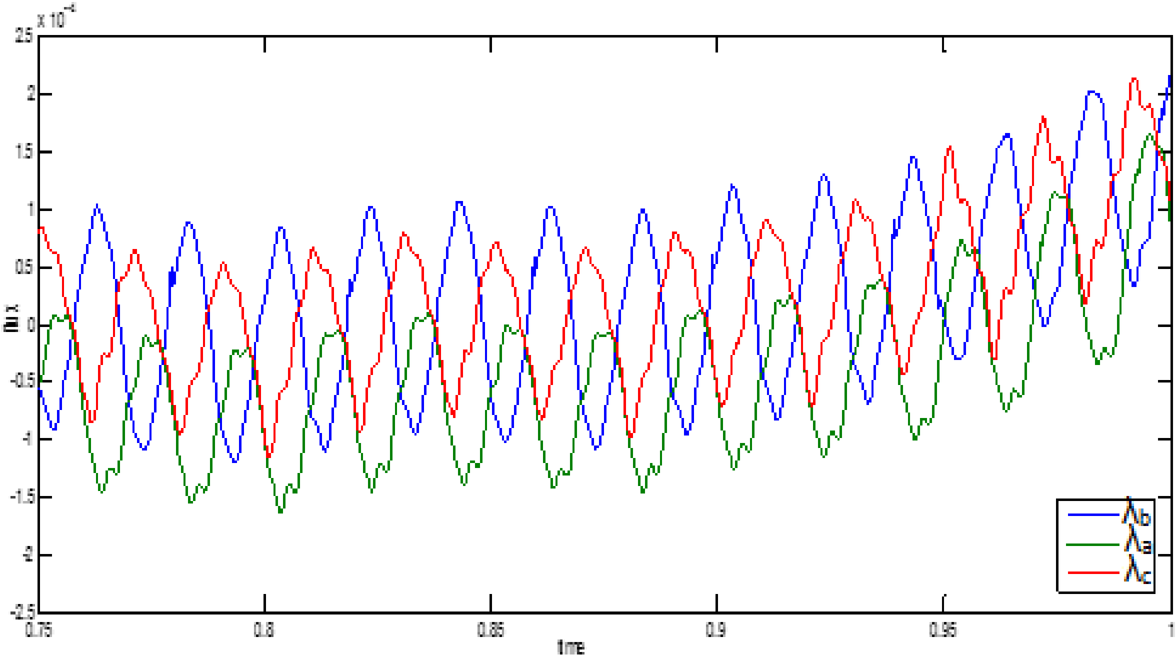


Fig. 4.9. Flux linkage of load transformer

CHAPTER 5

CONCLUSION & FUTURE SCOPE

5.1 CONCLUSION

In this paper a technique used for mitigation of transformer inrush current including with full state feedback controller to eliminate the inrush current effect at the time of voltage sag restoration in the power system. The controller provides to control the voltage, the current and the flux linkage. The method used for controller is based on the synchronous reference frame which allows the compensator to inject the sag voltage very quickly and prevents the inrush current for sensitive loads. When the voltage sag happens, the controller calculates the transient flux linkage on the bases of pre fault voltage and calculates the required voltage in real time for fast compensation and elimination of flux linkage dc offset created by voltage sag. The technique used for removal of voltage sag and the inrush current is shown in the simulation results. The projected technique can also be joined with the inrush reduction technique of the coupling transformer obtainable by the Cheng et al. and the simulation results display that these two approaches take result at different steps of the voltage injection without interfering each other. The combination of these two approaches confirms a fast and perfect voltage sag compensation with minimum danger of inrush current.

5.2 FUTURE SCOPE

Various technique for mitigation of inrush current and voltage sag restoration is beyond the study of present scope and can be studied in future. The voltage restoration equipments like use of dynamic voltage restorer (DVR) and FACT devices may also be implemented in future however inrush can be controlled by adjusting the wave shape of alternating voltage.

CHAPTER 6

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