DESIGN AND SIMULATION OF A NONLINEAR LOAD MODEL USED TO SIMULATE VOLTAGE NOTCHES AND HARMONICS CAUSED BY A 6-PULSE THREE-PHASE RECTIFIER

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Abstract – Harmonics and voltage notches are always present in electrical power systems. Harmonic distortion is harmless as long as its level is within the limit. However, with the recent rapid advancement of power electronics, i.e. nonlinear loads, the use of the variable speed drives are increasing day by day. Harmonics produced by non-linear loads are a potential risk if they are not evaluated, predicted, and controlled. The power electronic switching devices like thyristor used in the rectifier circuits inject harmonic distortion to the utility grid in different applications. The harmonic distortion causes different problems in the power system. To minimize the unwanted effects of harmonic distortion, IEEE Std 519-1992 recommends the amount of harmonics that is acceptable in the power system. IEEE Std 519-1992 suggests that an individual harmonic distortion to be under 3% and the total harmonic distortion, THD, to be under 5% of the fundamental component. Harmonic distortion can be mitigated using different methods. Based on the system configuration either active filters, passive filters, or phase shifting methods are used. In medium voltage high power applications, generally, phase shifting method is better suited. In addition to harmonic distortion in AC side, AC-DC converter produce ripple in DC side. DC ripple can be mitigated by the use of filter circuits. However, when phase shifting method is used in AC side for harmonic mitigation, a method called pulse multiplication can be used in DC side to mitigate DC ripple.

Keywords- Harmonics; Voltage notches; Total Harmonic Distortion (THD); Power Factor (PF);

INTRODUCTION

The distribution system is one of the main and important components of the entire power system network. However, it suffers from a number of challenges such as the deterioration of the fundamentals responsible for maintaining power quality and which can result in things like voltage notches, swells, sags and harmonics. In their designs therefore, high-quality ac power conversion aims to enhance power utilization efficiency of the ac power supply, minimize power loss, and improve regulation. In order to enhance the power utilization efficiency of the ac distribution power supply, the demanded power factor correction (PFC) converter can shape the input current of offline power supplies to be in phase with the line voltage. Apart from that, the total harmonic distortion (THD) of the line current is also used in the determination of the quality of power source.

An expression of (THD) versus the power factor is shown in the equation below,

$$THD = (\cos^2\theta / PF^2 - 1)^{1/2} \qquad (1)$$

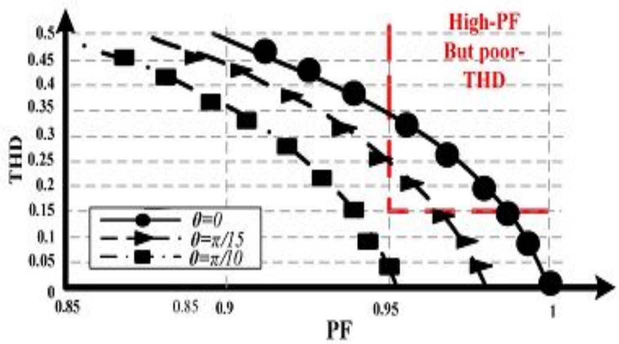


Figure 1: Diagram of THD versus PF [1]

It is worthwhile to observe that this relationship between PF and THD demonstrates that THD is never improved even if PF is high. This means that for high-quality power delivery, both the PF and the THD are important. The harmonic currents on the other hand would increase the power losses on the distribution network and hence would result in electrical equipment damages. Therefore, the THD needs to be decreased for high-quality power supply even if the PF is high. There are a number of safety standards that determine the maximum THD of electrical products in many countries, such as EN61000-3-2. In other words, improving THD becomes an essential requirement for electrical products.

In addition, the medium voltage high-power rectifiers find their use in various industrial plants. Application of 3-phase rectifiers are found for pipeline pumps in petrochemical industry, for steel rolling mills in metal

The current source inverters convert the dc current to three-phase ac current. Generally, diode rectifiers are voltage sources; on the other hand, thyristor rectifiers are current

Where power factor PF is the ratio of the real power to the apparent power, and θ is the phase angle between the line current and voltage. And Fig 1 below gives an illustration of the variation of THD and power factor.

industry, for pumps in water pumping stations, for fans in cement industry, for traction in locomotive industry, and in many other applications [1]-[2]

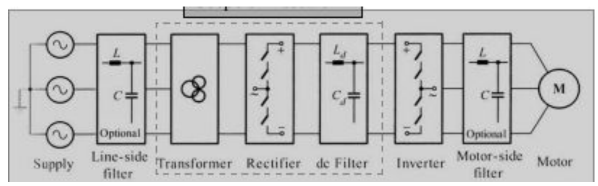


Figure 2: General block diagram of the MV drive [1]

The input is 3-phase utility voltage which is converted to dc voltage by the rectifier shown above. The dc voltage magnitude can be fixed or adjustable depending upon the power electronic switches that are used for switching. Multi-pulse silicon controlled rectifiers, SCR, multi-pulse diode rectifiers, or pulse-width-modulated (PWM) rectifiers are commonly used rectifier topologies.

For filtering the ripple from dc output, either a capacitor or an inductor can be used as dc filter. A capacitor can be used for providing a stiff voltage, while an inductor can be used for smoothing the current. Generally, the capacitors are used in voltage source drives while inductors are used in current source drives [2].

There are two types of inverters, voltage source inverter (VSI) and current source inverter (CSI). The voltage source inverters convert the rectified dc voltage to a three-phase ac voltage whereas

sources. There are various inverter topologies present for the MV drive and which could also be applied in the distribution networks.

Each of these topologies can have 6-pulse, 12-pulse, 18-pulse, 24-pulse, 30-pulse or higher number of pulses. Higher the number of pulses, lower is the total harmonic distortion, THD, on input ac currents and lower is the ripple on output dc currents .

II.HARMONIC DISTORTION

2.1 Introduction

Harmonic distortion is the distortion in the power system due to harmonics. Harmonics of a signal are the signals that are an integer multiple of the fundamental frequency. If the fundamental frequency is 60 Hz, the harmonics will have frequency of 2x60, 3x60, and 4x60 and so on. Harmonics in the electrical power system are unwanted effect due to various reasons. They produce undesirable effects in the power system. If the level of harmonics is above the limit, they must be mitigated to operate the power system satisfactorily**.**

Medium-voltage, high-power industrial drives consists of power electronic components like diodes, IGBTs, power thyristors etc. The switching frequency of thyristor in phase control mode is not very high but the switching frequency of IGBT in pulse width control mode can be as high as 10 kHz. Thus, these devices when switched at certain frequency produce harmonics. These devices are non-linear loads to the utility [2].

Harmonic distortion in the power system can give rise to a variety of problems including reduced power factor, deteriorating performance of electrical equipment, equipment overheating, the incorrect operation of protective relays, interference with communication devices etc. In some cases, circuit resonance causes dielectric failure of electric equipment and other type of severe damage [1]-[2].

The amount of total harmonic distortion produced by these power electronic drives should be under recommended value per IEEE standard 519-1992. Criteria specify that any individual harmonics should be equal or less than 3% and total harmonic distortion (THD) should be equal or less than 5% [4].

2.2 Production of Harmonics

If a load draws current that is proportional to the applied voltage and the shape of current waveform is identical to the shape of the voltage waveform, the load is called to be a linear load. Resistance heater, incandescent lamps, etc. are the examples of linear loads. But, if a load draws current that is not proportional to the applied voltage and the shape of current waveform is not identical to the shape of applied voltage, the load is referred to as a non-linear

Load. The examples of non-linear loads are computers, discharge lighting, variable speed drives etc. The majority of non -linear loads utilize semiconductors for power conversion e.g. rectifier.

In non-linear loads, the current waveform that are not sinusoidal contains harmonic current in additional to the sinusoidal fundamental current. The presence of harmonic component is responsible for the distortion of the sinusoidal shape of the current. Harmonic components are integer multiple of the fundamental component. In a 60 Hz system, 3^{rd} harmonics will have a frequency of 180 Hz; 5^{th} harmonics will have a frequency of 300 Hz; the 7^{th}harmonics will have a frequency of 420 Hz and so on.

A complex harmonic can be formed by adding all harmonics to the fundamental signal. Fig 2.1 shows an example of complex waveform consisting of the fundamental, 1st harmonic, and 3rd harmonic. The magnitude of the harmonic current in an idealized harmonic is given as the reciprocal of the harmonic number, i.e.:

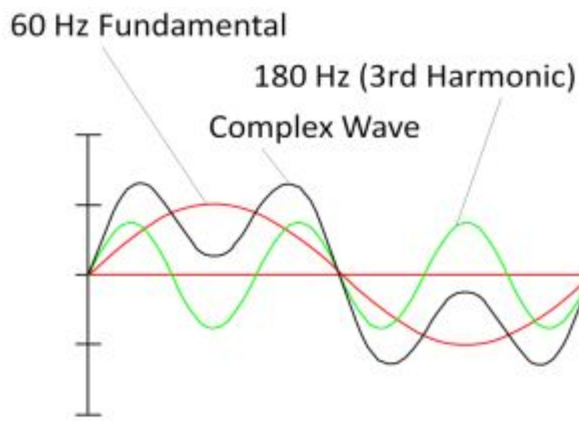


Figure 2.1: Complex Waveform [9]

AC to DC conversion using full-wave rectifiers generates harmonic currents. The idealized characteristic harmonic currents can be given by the formula:

$h = np \pm 1$ ……….. (2.1)

Where: h=order of harmonics

n=an integer 1, 2, 3…

p=number of current pulses per cycle

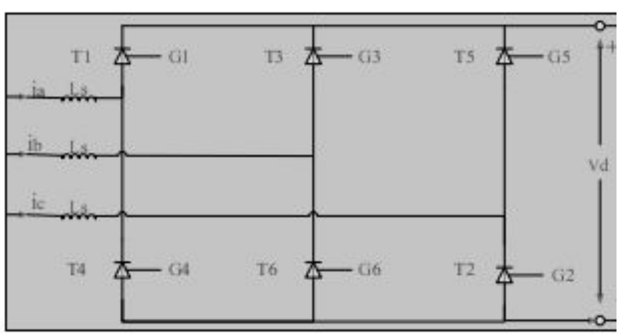


Figure 2.2: Three Phase 6-Pulse Rectifier Bridge [4]

Fig 2.3 illustrates an example of voltage notching at the terminals of the

$I = 1/h$ ……….. (2.2)

Thus,

2nd harmonic current should represent 50.00% of the fundamental current

3rd harmonic current should represent 33.33% of the fundamental current

2.3 Voltage Notching

Voltage notching is a phenomenon associated with the thyristor based phase-controlled rectifiers. Commutation notches can be present in diode rectifiers too but to a lesser extent than the notches associated with thyristor rectifiers. The voltage notching can impact the supply system and other equipment seriously. A 3-phase full-wave thyristor rectifier network supplying a DC load is shown in Fig 2.2.

thyristorrectifier. As the notching is at the input terminals, the circuit presents a minimal amount of inductance in the circuit without any source impedance. The voltage notches can be seen at the moments when the continuous line current commutates from one phase to another. During the commutation period though for a very short duration, the two phases are short-circuited through the rectifier bridge and he AC source impedance. The result is that the voltage, as illustrated, reduces to almost zero as the current increases, limited only by the source impedances.

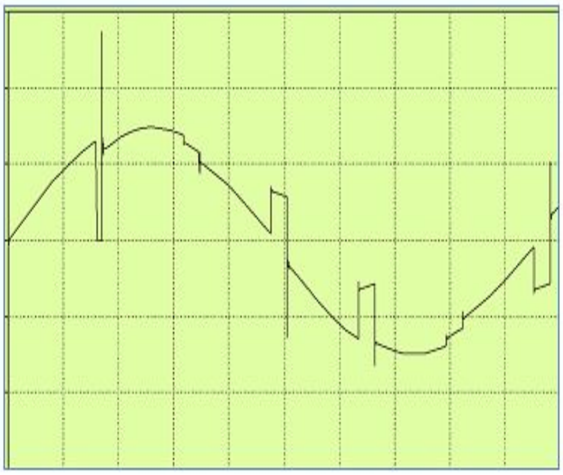


Figure 2.3 Example of Line Notching [4]

The number of notches is equal to the number of pulses. In this case, 6 notches can be seen as Fig 2.3 represents voltage notching for a 6-pulse rectifiers. The location of notches represents the firing instants of thyristors, as the phase angle of thyristor varies depending upon the needed output voltage. The disturbances associated with line notching reduce as we head towards a stiff source. An impedance of relatively low value with relatively high source circuit capacity is called a stiff source.

2.4 Effects of Harmonics

Harmonics produce many unwanted effects in the system. The most prominent effect is the increased equipment heating caused by increase in iron losses and copper losses. Single-phase nonlinear loads present increased the peak-to-peak voltage magnitudes, increasing the stress on the rectifiers.

Many electronic controls are based on zero crossing principle. Where voltage notching occurs such as in thyristor phase controlled load, additional zero crossing of the input signal may appear. The control loops can become unstable due to the combined effect of harmonic distortion and line notching. When the drives are at low speed and heavy load, the effect of line notching is more pronounced.

Isolation transformers and/or commutating reactors are often installed between the line and the rectifier to attenuate the voltage notches. The isolation transformer or commutating reactors are used for rectifier above 10 HP. This also helps reduce the effect of line notching and harmonics impressed on the drive. However, if the line notching or harmonics level are significant, thyristor misfiring can result. The result of thyristor misfiring is blowing of fuse or the circuit breaker tripping.

Increasing the number of pulse multiplication i.e. 12 -pulses, 18-pulses, or 24-pulses, reduces the effects of harmonics as well as line notching at the drive terminals [3].

2.5 Mitigation of Harmonics

In order to limit the harmonic currents and associated voltage distortion within the limits, the majority of nonlinear loads associated with bulk power often needs addition of mitigation equipment. Depending upon the solution desired, the mitigation may be an integral unit with nonlinear load or a discrete unit installed in the switchboard. On a system with multiple nonlinear loads, some harmonic cancellation occurs due to phase angle diversification between the multiple harmonic sources.

There are three major methods for mitigating the harmonics. The method utilized in any particular application depends upon the nature and magnitude of the mitigation needed and power system configuration.

2.5.1 Active Filters

Active filters are mainly used for mitigating triple harmonics in four-wire systems. The active filters monitor the load currents in 3-phases and neutral wire. The notch filter is used to remove the fundamental component. The remainder is the harmonic distortion current. This remainder distortion is phase reversed (180^0 out of phase) and injected into the load as harmonic cancellation current. Thus, the harmonic component is supplied to the load by active filter and the source supplies only fundament component.

2.5.2 Passive Filters

Passive filters are used to mitigate harmonic distortion for multiple applications. A passive filter consists of a capacitor, inductor and occasionally resistors. Their operation depends on resonance phenomenon. At series resonance, inductive reactance and capacitive reactance cancel each other leaving only resistive impedance in the circuit. The series filters are usually connected in parallel with the nonlinear load. These filter offer very low impedance to the harmonic frequencies that need to be mitigated. For example, for mitigating, 5^{th} and 7^{th} harmonic distortion, one set of filters would be needed to mitigate 5^{th} harmonics, and another set of filters would be needed to mitigate 7^{th} harmonics. Change in sources and load impedances have impact in the performance of passive filters. Since passive filters attract harmonics from other sources, the phenomenon must be taken into account in design.

2.5.3 Phase Shifting

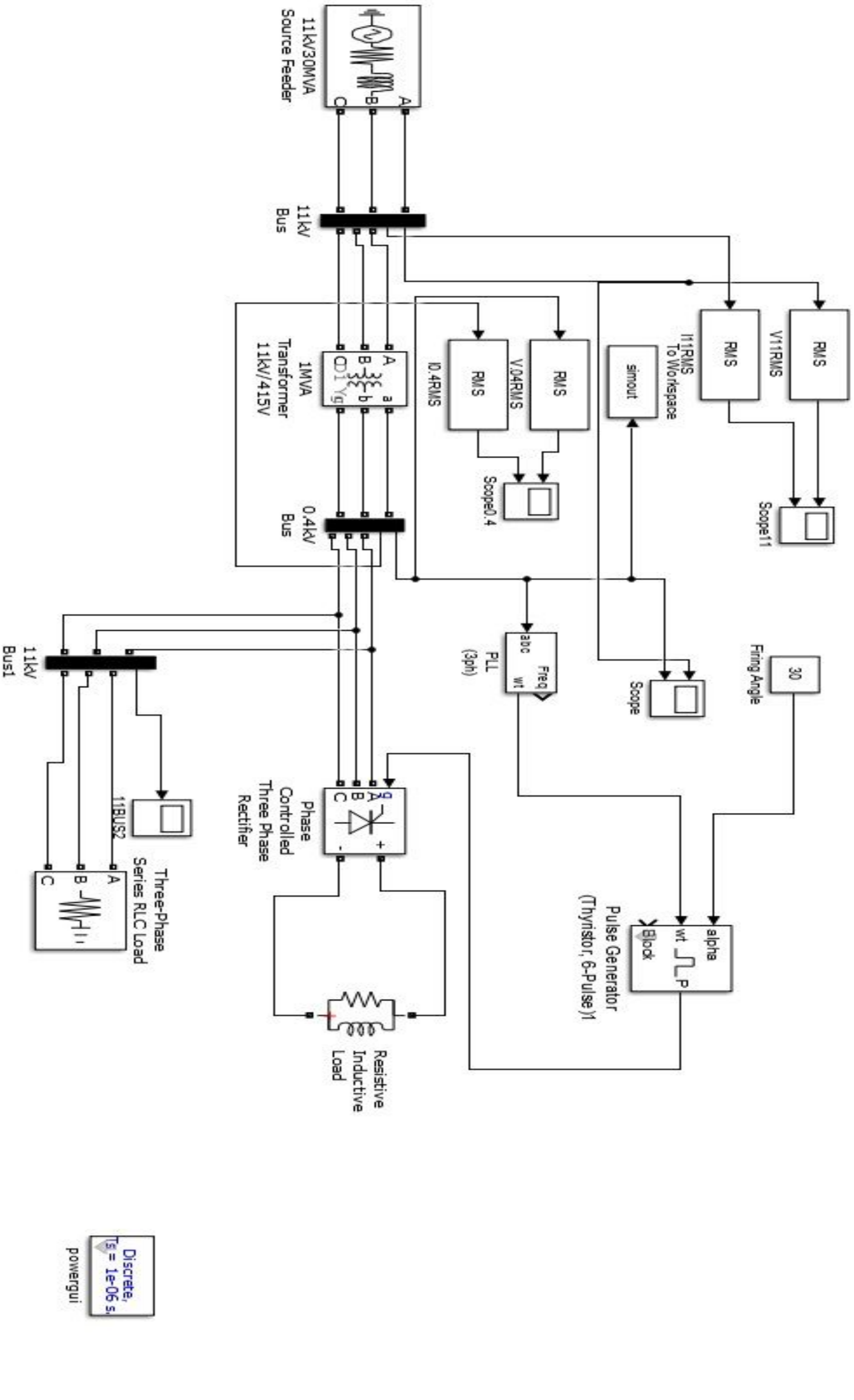
For high power operation, generally 400 HP motors or larger, phase-shifting technique is used to mitigate the input harmonic current. The phase-shifting is achieved by using multiple converters. The way multiple converters are connected together facilitate in canceling certain harmonics produced by one converter to those produced by other converter. Certain harmonics, determined by number of converter bridges used, are eliminated at the input i.e. primary side of the phase shift transformer.

The phase shifting technique is also called multi-pulsing. So the converter that utilizes phase shifting transformer for harmonics mitigation is termed as multi pulse drive, i.e. 6-pulse drive, 12-pulse drive, 18-pulse drive, 24-pulse drive etc. A single unit 3-phase rectifier is called 6-pulse rectifier. Thus, a 12-pulse rectifier will have 2x6-pulse rectifier, 18-pulse will have 3x6-pulse and so on. Phase-shifting not only reduce the harmonic input current but also reduces the ripple on the DC output of the rectifier

CIRCUIT ANALYSIS AND RESULTS

The model consists of 33 kV, 30 MVA, 50Hz three-phase source block feeding through a 33 kV/0.4 kV, 3 MVA delta/wye transformer to a 6-pulse controlled three phase rectifier connected to a 500 V, 20 kW resistive and 2 kVA inductive load. There is also a phase locked loop connected just before the 6-pulse controlled three phase pulse generator. Its main function is to generate an output signal or frequency that would be directly proportional to the input voltage. Both the input signal and output signals are then compared and adjusted through feedback loops until the output signal equals the input signal. To analyze various aspects of setup, values of voltages, firing angle, load impedance, and sampling time are changed to observe effects on THD and RMS

Design and simulation of a nonlinear load model used to simulate voltage notches and harmonics caused by a 6-pulse three-phase rectifier



WHEN VOLTAGE OF SOURCE IS VARIED

In this source voltage is varied and sampling time load impedance along with firing is kept constant.

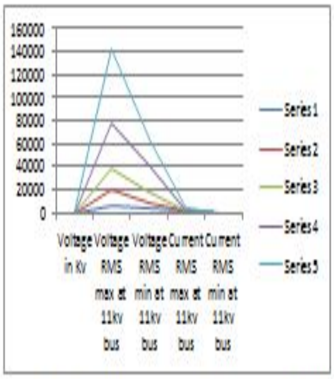


FIGURE 1 SHOWNING VOLTAGE AND CURRENT ON 11 KV BUS FOR CHANGE IN VOLTAGE

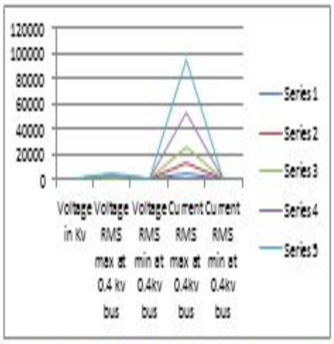


FIGURE 2 SHOWNING VOLTAGES AND CURRENT ON 0.4 KV BUS FOR CHANGE IN VOLTAGE

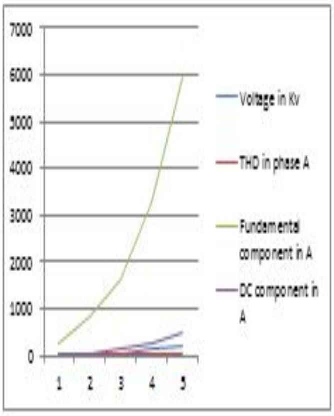


FIGURE 3 THD IN PHASE A FOR CHANGE IN VOLTAGE

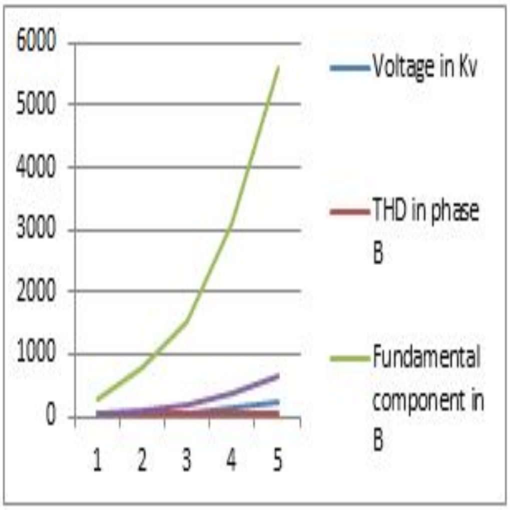


FIGURE 4 THD IN PHASE B FOR CHNAGE IN VOLTAGE

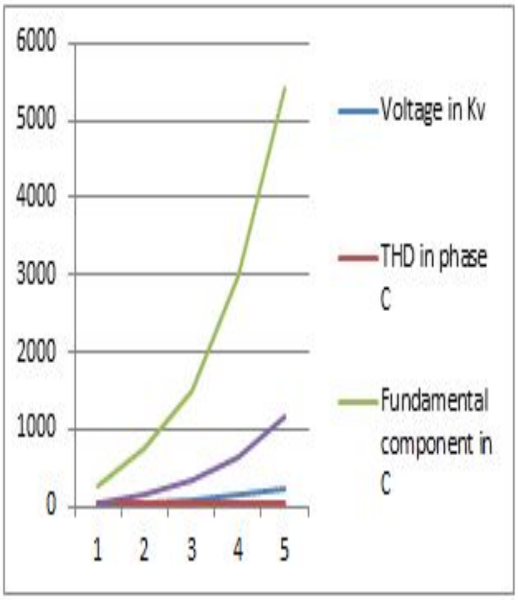


FIGURE 5 THD IN PHASE C FOR CHNAGE IN VOLTAGE

Here it is observed that THD independent of source voltage so for complete simulation THD in all the 3 phase remains constant

WHEN FIRING ANGLE IS CHANGED

Here we are taking source voltage constant at 11Kv load impedance at 1e-3 and sampling time at 1e-6, firing angle is varying

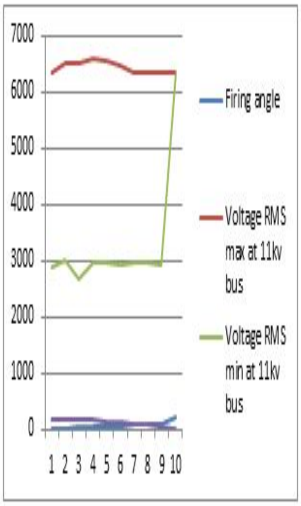
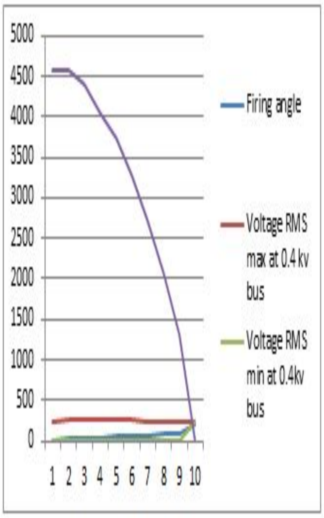


FIGURE 6 SHOWNING VOLTAGES AND CURRENT ON 11 KV BUS FOR CHANGE IN FIRINING ANGLE



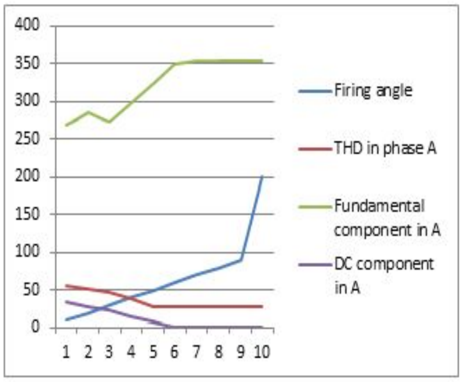


FIGURE 8 THD IN PHASE A

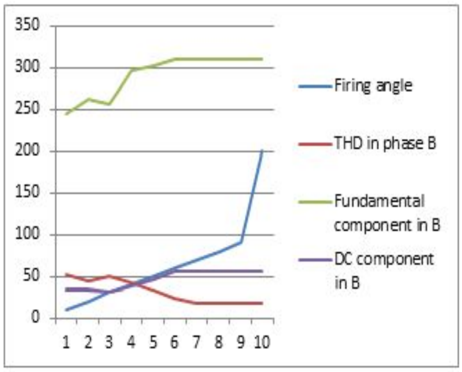


FIGURE 9 THD IN PHASE B

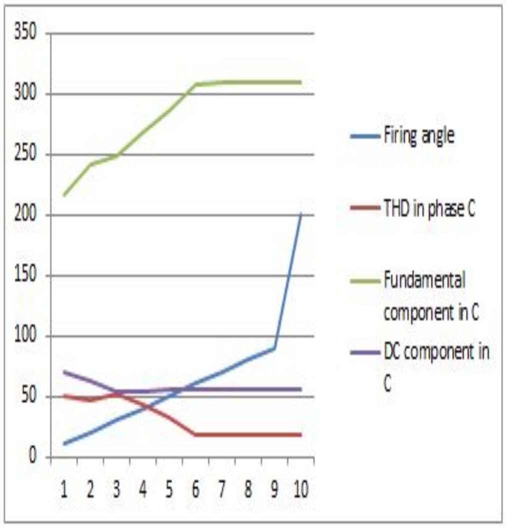


FIGURE 10 THD IN PHASE C

Here it is observed that with increase in firing angle THD decreases after after certain point THD stops decreeing and becomes constant.

WHEN LOAD IMPEDANCE IS VARIED

Here we are taking source voltage constant at 11Kv at sampling time at 1e-6, firing angle at 30' load impedance is varying

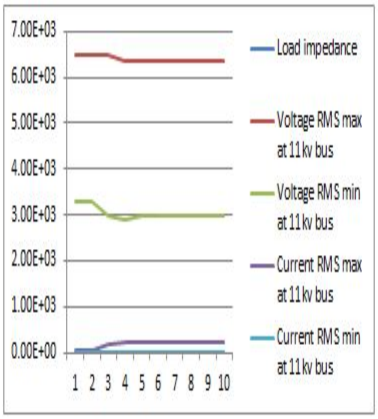


FIGURE 11 SHOWNING VOLTAGES AND CURRENT ON 11 KV BUS FOR LOAD IMPEDANCE VARIATION

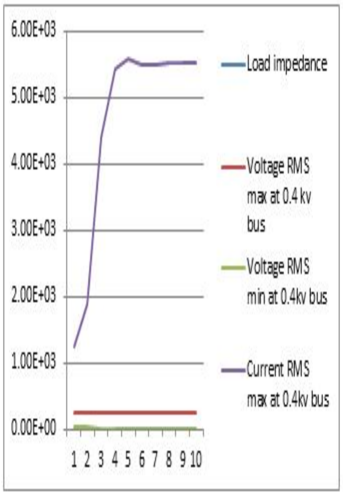


FIGURE 12 SHOWNING VOLTAGES AND CURRENT ON 0.4 KV BUS FOR LOAD IMPEDANCE VARIATION

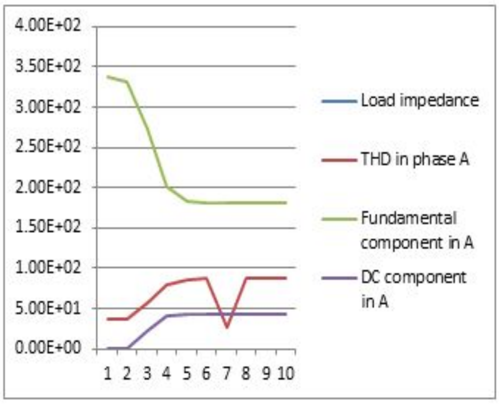


FIGURE 13 THD IN PHASE A

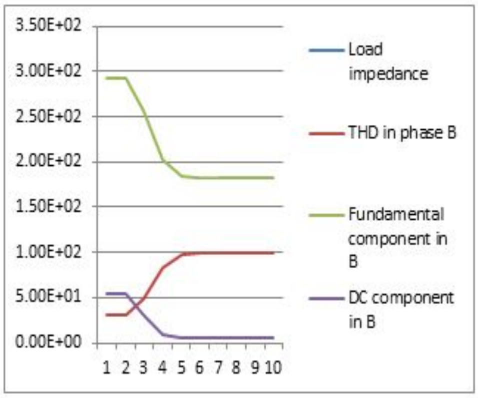


FIGURE 14 THD IN PHASE B

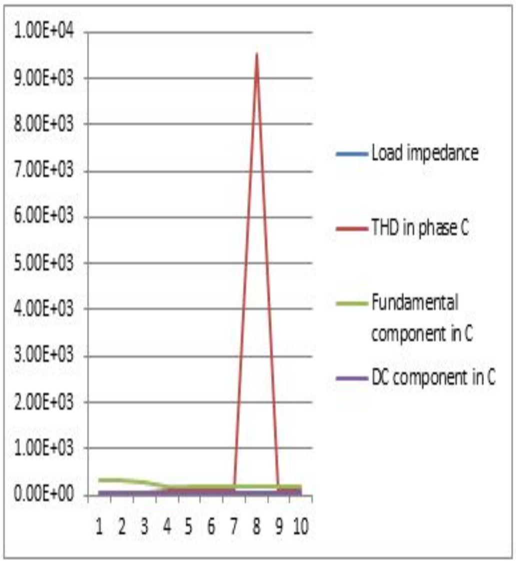


FIGURE 15 THD IN PHASE C

With increase in load impedance THD content increases linearly

WHEN SAMPLING TIME IS VARIED

Here source voltage is kept constant at 11kv firing angle at 30’ and load impedance at 1e-3 H and sampling time is varied.

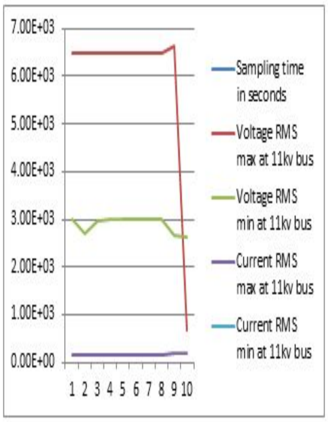


FIGURE 16 SHOWNING VOLTAGES AND CURRENT ON 11 KV BUS FOR SAMPLING TIME VARIATION

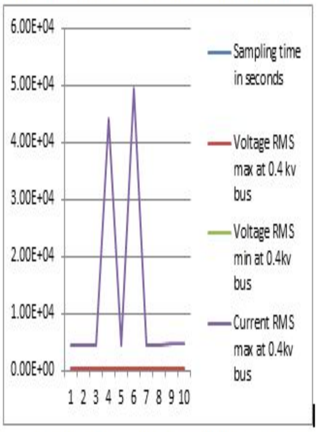


FIGURE 17 SHOWNING VOLTAGES AND CURRENT ON 0.4 KV BUS FOR SAMPLING TIME VARIATION

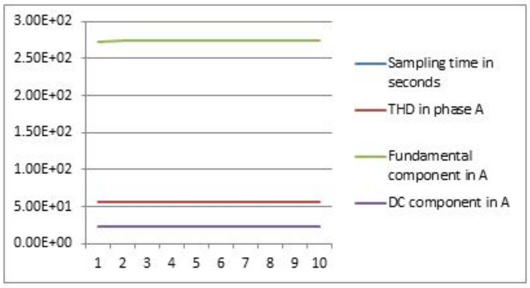


FIGURE 18 THD IN PHASE A

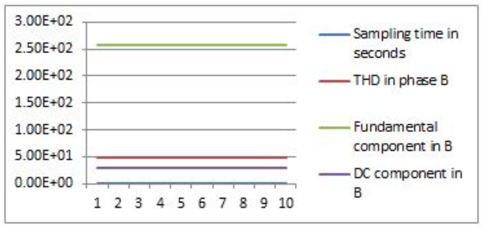


FIGURE 19 THD IN PHASE B

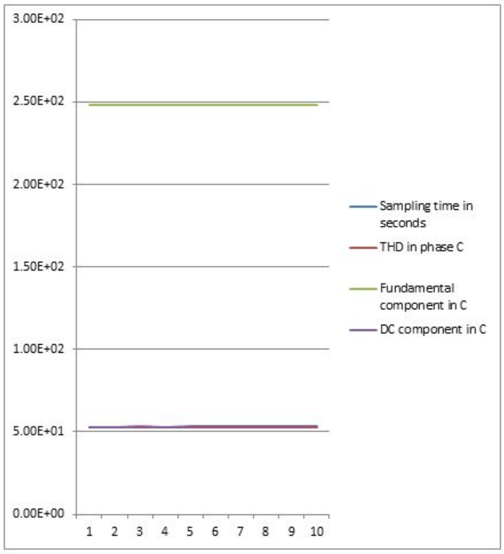


FIGURE 20 THD IN PHASE C

With increase in sampling time there is small incremental change in THD.

CONCLUSION

An analysis of how voltage notches and harmonics are generated using a six pulse three phase rectifier circuit have been presented in this paper. It can be seen that the need to maintain within standard limits certain parameters so as to have good Power quality in distribution systems cannot be over emphasized. Moreover, it is clear that total harmonic distortion (THD) becomes serious when the system runs into low power levels. When the THD is higher than the set limits, the entire system should be temporarily disabled until a time when the whole network has been normalized so as to avoid the generation of voltage notches and harmonics.

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Syed Mohd Adnaan has done master of technology from Lovely Professional University in Electrical engineering with major in power system. His research work lies in grid integration of renewable energy primary focusing on solar energy.