POWER QUALITY ENHANCEMENT IN DISTRIBUTION SYSTEM USING INVERTED SINE PULSE WIDTH MODULATION APPROACHES WITH DVR

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ABSTRACT:

This paper describes the enhancement of Power quality in a power system by reducing the harmonics using various modulation techniques in DVR(Dynamic Voltage Regulator. Application of power electronic equipments and nonlinear loads in recent years leads to harmonic interference problems in a power system. The harmonic currents generated by the loads will cause a voltage drop across source impedance which causes decrease in power quality. Inverters based on Voltage Source Converters (VSC) are widely used as a basic component in DVR. These controllers produce voltage harmonics due to switching operation of power electronic converter. The harmonics in the output voltage of power electronic converters can be reduced using Pulse-Width Modulation (PWM) switching techniques. In this paper, inverted sine PWM switching techniques have been developed for controlling of VSC based inverters which has lower Total Harmonic Distortion (THD) than conventional techniques and they are also used for power quality enhancement.

Keywords— PWM, Power Quality, Harmonics, VSC, DVR.

I.INTRODUCTION

The last decade has seen a marked increase on the deployment of end-user equipment that is highly sensitive to poor quality control electricity supply. Several large industrial users are reported to have experienced large financial losses as a result of even minor lapses in the quality of electricity supply.

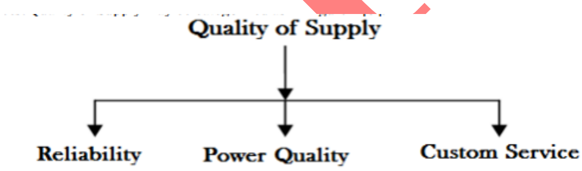

Fig.1 Quality of supply

A great many efforts have been made to remedy the situation, where solutions based on the use of the latest power electronic technology called custom power technology, installed at low-voltage distribution applications has emerged as a credible solution to solve many of the problems relating to continuity of supply at the end-user level. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power

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applications. Among these, dynamic voltage restorer (DVR) based on the VSC principle is used for power quality enhancement with various pulse width modulation techniques. PWM methods reduce the harmonics by shifting frequency spectrum to the vicinity of high frequency band of carrier signal. In the case of sinusoidal PWM (SPWM) scheme, the control signal is generated by comparing a sinusoidal reference signal and a triangular carrier. The SPWM technique however inhibits poor performance with regard to maximum attainable voltage and power. A novel PWM technique, called Inverted-Sine PWM (ISPWM), for harmonic reduction of the output voltage of ac-dc converters is presented. In addition, the control scheme based on ISPWM can maximize the output voltage for each modulation index.

2. MAIN POWER QUALITY PROBLEMS

2.1 .Voltage Sag:

A Voltage Sag is a momentary decrease in the root mean square (RMS) voltage between 0.1 to 0.9 per unit, with a duration ranging from half cycle up to 1 min. It is considered as the most serious problem of power quality. It is caused by faults in the power system or by the starting of large induction motor.

2.2. Voltage Swell:

Voltage swell is defined as an increase in the root mean square (RMS) voltage from 1.1 to 1.8 per unit for duration from 0.5 cycles to 1 min. Voltage swells are not as important as voltage sags because they are less common in distribution systems. The main causes for voltage swell are switching of large capacitors or start/stop of heavy loads.

2.3. Harmonics:

The fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency. The main causes for harmonic distortion are rectifiers and all non-linear loads, such as power electronics equipment including VSDs.

2.4. Voltage transients:

They are temporary and undesirable voltages that appear on the power supply line. Transients are high over-voltage disturbances (up to 20kV) that last for a very short time.

2.5.Flicker:

Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. The main causes are frequent start/stop of electric motors(for instance elevators), oscillating loads.

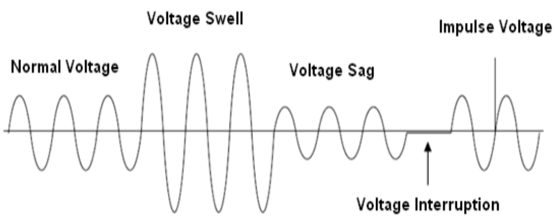

Fig.2 Waveform representing voltage sag, swell, impulse voltage

3. DYNAMIC VOLTAGE RESTORER (DVR)

The DVR is a powerful controller commonly used for voltage sags mitigation. The DVR employs the same blocks as the D-STATCOM, but in this application the coupling transformer is connected in series with the AC system

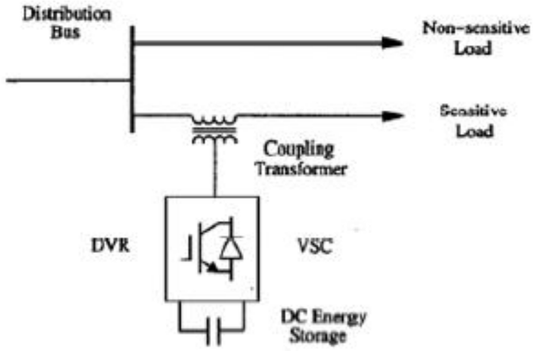

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Fig.3 Schematic representation of DVR

The VSC generates a three-phase AC output voltage which can be controlled in phase and magnitude. These voltages are injected into the AC distribution system in order to maintain the load voltage at the desired voltage level.

3.1.Features of DVR

- Voltages sag and swell compensation.
- Line voltage harmonics compensation.
- Reduction of transients in voltage.
- Fault current limitations.

4. PRINCIPLE OF DVR OPERATION

A DVR is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device and injection transformers. It is linked in series between a distribution system and a load that shown in figure. The basic idea of the DVR is to inject a controlled voltage generated by a forced commutated inverter in series to the bus voltage by means of an injection transformer. A DC to AC inverter regulates this voltage by using sinusoidal PWM technique. All through normal operating condition, the DVR injects only a small voltage to

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compensate for the voltage drop of the injection transformer and device losses. However, when the voltage sag occurs in distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical load.

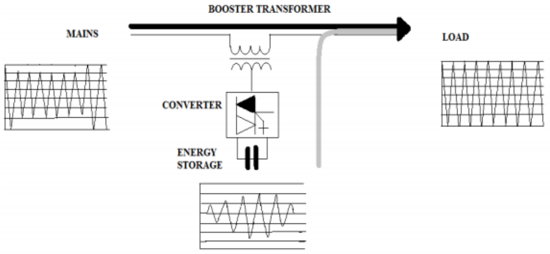

Fig.4. Principle of DVR System

Note that the DVR capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time. The predictable response time is about 25 milliseconds and which is much less than some of the traditional methods of voltage correction such as tap changing transformers.

5. BASIC ARRANGEMENT OF DVR

The DVR mainly consists of the following components.

i. An injection transformer
ii. DC charging unit
iii. Storage devices
iv. A voltage source converter(VSC)
v. Harmonic filter
vi. A control and protection system

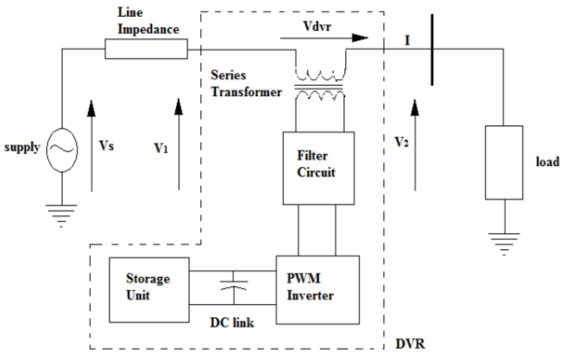

Fig.5. Schematic diagram of DVR

5.1 Series Voltage Injection Transformers:

In a three-phase system, either three single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose .The injection transformer comprises of two side voltages namely the high voltage side and low voltage side. Normally the high voltage side of the injection transformer is connected in series to the distribution system while power circuit of the DVR can be connected at the low voltage side. The basic function of the injection transformer is to increase the voltage supplied by the filtered VSI output to the desired level while isolating the DVR circuit from the distribution network. The transformer winding ratio is pre-determined according to the voltage required in the secondary side of the transformer (generally this is kept equal to the supply voltage to allow the DVR to compensate for full voltage sag). A higher transformer winding ratio will increase the primary side current, which will adversely affect the performance of the power electronic devices connected in the VSI. Three single phase or three-phase voltage injection transformers can be used for a three-phase DVR. In this case the high voltage of the injection transformer is connected to the distribution line and for single phase DVR one single-phase injection transformer can be connected. The single phase transformers can be used to inject the compensating voltages separately when three phase inverter is used. To evaluate the performance of the DVR the rating of the injection transformer is an important factor that need to be considered due to the compensation ability of the DVR is totally depend on its rating .The DVR performance is totally depend on the rating of the injection transformer, since it limits the maximum compensation ability of the DVR. Multilevel inverter topology is used in DVR allowing the direct connection of the DVR to the distribution system without using injection transformer.

5.2 Energy Storage:

The DVR needs real power for compensation purposes during voltage disturbances in the distribution system. In this case the real power of the DVR must be supplied by energy storage when the voltage disturbances exit. The energy storage such as a battery is responsible to supply an energy source in DC form. Energy storage consists of two types form. One using stored energy to supply the delivered power and the other having no significant internal energy storage but instead energy is taken from the faulted grid supply during the sags. A shunt–converter or the rectifier is the main sources of the direct energy storage which is supplied to DVR. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used as energy storage devices. It is supplies the real power requirements of the system when DVR is used for compensation. The application of the energy storage in DVR is depending on the designed rating required and total cost is also must be considered. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used as energy storage devices. It is supplies the real power requirements of the system when DVR is used for compensation lead acid batteries are popular among the others owing to its high response during charging and discharging. But the discharge rate is dependent on the chemical reaction rate of the battery so that the available energy inside the battery is determined by its discharge rate Storage systems with auxiliary supply is used to increase the system performance when the grid of DVR is weak. Flywheel Energy Storage as a preferred energy storage device, the system utilizes a single AC/AC power converter for the grid interface as opposed to a more conventional AC/DC/AC converter, leading to higher power density and increased system reliability. However the suitable of the type of energy storage depend on the DVR designed in term rated power and the total cost factor.

5.3 LC Filter:

Basically filter unit consists of inductor (L) and capacitor (C). In DVR, filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This can be achieved by eliminating the unwanted harmonic components generated by the VSI action. Higher orders harmonic components distort the compensated output voltage. The unnecessary switching harmonics generated by the VSI must be removed from the injected voltage waveform in order to maintain an acceptable Total Harmonics Distortion (THD) level. The switching frequencies of the VSI are usually up to several kHz for medium power level. The passive filters can be placed either in the high voltage or in low voltage side winding of the series injection transformer. If the filter is installed at the low voltage side it has the advantage of being closer to the harmonic source thus high order harmonic currents are avoided to penetrate into the series injection transformer. Harmonics currents will circulate into the series injection transformer if the filtering scheme is placed at the high voltage.

5.4 Voltage Source Inverter (VSI):

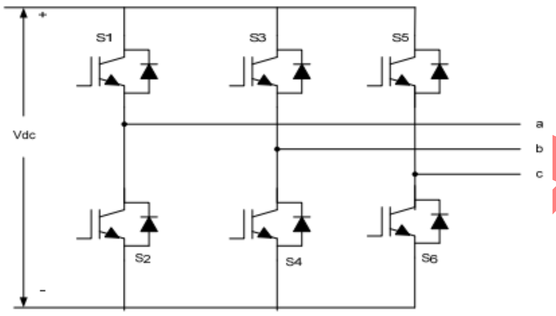

Fig.5.4. Voltage Source Inverter

The function of an inverter system in DVR is used to convert the DC voltage supplied by the energy storage device into an AC voltage. Voltage source inverter (VSI) of low voltage and high current with step up injection transformer is used for this purpose in the DVR compensation technique. Generally Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. Thus a VSI with a low voltage rating is sufficient. There are two basic three phase inverter topologies, the popular two-level inverter and the multilevel inverter. Multilevel inverters have recently emerged as an attractive alternative to PWM schemes so that the losses associated with fast switching can be eliminated. The implementation of the PWM in the two level inverter is simpler and its cost is cheaper than a multilevel inverter.

6. MODULATION TECHNIQUES

Pulse width modulation (PWM) control strategies development concerns the development of techniques to reduce the total harmonic distortion (THD) of the current. It is generally recognized that increasing the switching frequency of the PWM pattern reduces the lower-frequency harmonics by moving the switching frequency carrier harmonic and associated sideband harmonics further away from the fundamental frequency component. While this increased switching frequency reduces harmonics, resulting in a lower THD by which high quality output voltage waveforms of desired fundamental r.m.s value and frequency which are as close as possible to sinusoidal wave shape can be obtained.. One of the most important problems in controlling a VSI with variable amplitude and frequency of the output voltage is to obtain an output waveform as much as possible of sinusoidal shape employing simple control techniques. Harmonic reduction can then be strictly related to the performance of an inverter with any switching strategy.

6.1. Sinusoidal Pulse Width Modulation

Sinusoidal Pulse width modulation (PWM) techniques are effective means to control the output voltage frequency and magnitude. It has been the subject of intensive research during the last few decades. Especially, the space-vector PWM is used for three-phase converter applications. Here we mainly consider the carrier based PWM approaches that are often applied to the single phase applications. Figure.7 shows general scheme of PWM modulation. In order to produce a sinusoidal voltage at desired frequency, say f1, a sinusoidal control signal Vcontrol at the desired frequency (f1) is compared with a triangular waveform Vcarrier as shown in Fig.7, at each compare match point, a transition in PWM waveform is generated as shown in Fig.7. When Vcontrol is greater than Vcarrier, the PWM output is positive and When Vcontrol is smaller than Vcarrier, the PWM waveform is negative.The frequency of triangle waveform Vcarrier establishes the inverter's switching frequency fs. We define the modulation index mi as follows:

$$mi = Vcontrol / Vtri$$

Where Vcontrol is the peak amplitude of the control signal and Vtri is the peak amplitude of the triangle signal (carrier).

Also the frequency modulation ratio is defined as

$$mf = fs / f1$$

mf is the ratio between the carrier and control frequency. The fundamental component (Vout)1 of the H bridge output voltage (Vout)1 has the property as depicted in equation below in a linear modulation region:

$$(Vout)\ 1 = mi * Vd \quad mi \le 1.0$$

The equation shows that the amplitude of the fundamental component of the output voltage varies linearly with the modulation index. The mi value from zero to one is defined as the linear control range of sinusoidal carrier PWM.

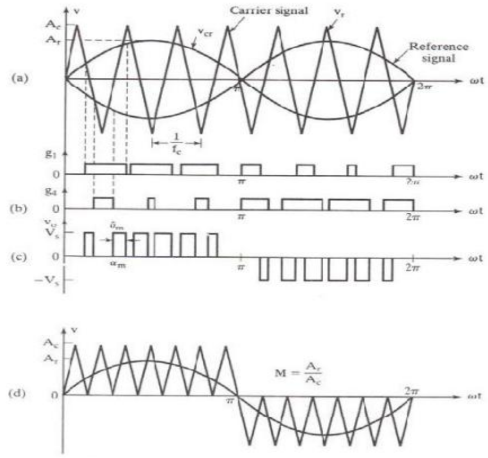

Fig.6.1. Sinusoidal Pulse Width Modulation

6.2. Proposed ISPWM Technique

The proposed ISPWM has new forms of carriers, carrier1 and carrier2, as shown in Fig.8 These waveforms have been generated by inversion of ISPWM carrier of in half-cycle of power frequency and half-cycle of carrier frequency, respectively. In each case, equivalent triangular carriers have been shown by dashed lines in Fig.8

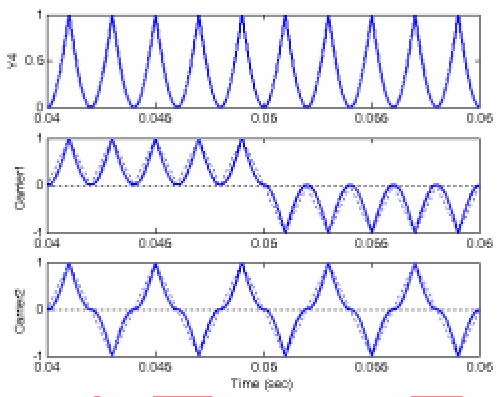

Fig 6.2.Proposed ISPWM Carriers

The firing control signals have been generated by comparing sinusoidal reference signal (with the frequency f and magnitude ma) with the inverted-sine carrier signal (with the frequency mf and magnitude 1 p.u.), as shown in Fig.8

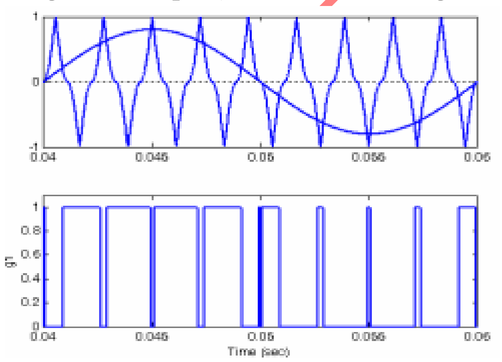

Fig.6.2(a). Firing pulse generation in proposed ISPWM

Considering angle θ_P as an intersection angle of carrier and reference signals, the following equations can be calculated

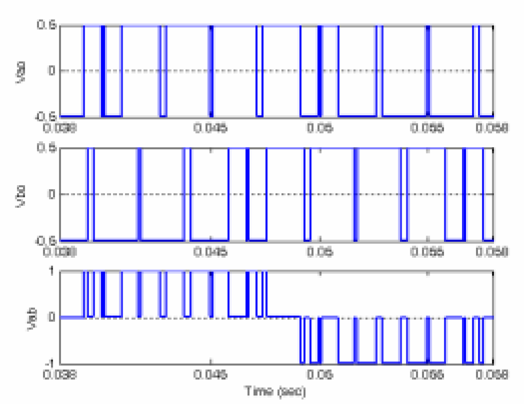

Fig 6.2(c).Phase and line output voltages for mf=9

:

$1-\text{Sin}\left[m_f\,\theta_p-\frac{\pi}{2}(p-1) \right] = m_a\sin\theta_p$, for p=1,3,5….

$1+\text{Sin}\left[m_f\,\theta_p-\frac{\pi}{2}(p-2) \right]= m_a\sin\theta_p$, for p=2,4,6…

Based on Fourier analyais, all harmonics of output voltage waveform can be calculated. When mf is an odd number, the half cycles of the phase voltage Vao are the same but with opposite sign and each half cycle is symmetrical with respect to half cycle midpoint. Therefore, $(m_f-1)/2$ angles should be determined using following equations.

$\frac{\pi}{2}-\theta_{(mf-1)/2}=\theta_{(mf+1)/2}-\frac{\pi}{2}=\frac{3\pi}{2}-\theta_{(3mf-1)/2}=\theta_{(3mf+1)/2}-\frac{3\pi}{2}....$

$\frac{\pi}{2}-\theta_{(mf-3)/2}=\theta_{(mf+3)/2}-\frac{\pi}{2}=\frac{3\pi}{2}-\theta_{(3mf-3)/2}=\theta_{(3mf+3)/2}-\frac{3\pi}{2}....$

$\theta_{mf}=\pi,\ \theta_{2mf}=2\pi$

Fourier expansion of the output waveform when m is also an odd number, consists of only odd harmonic orders.

$V_{a0}=A_1\text{Sin}\omega t+A_3\text{Sin}3\omega t+A_5\text{Sin}5\omega t+.......+A_n\text{Sin}n\omega t$

Where

$A_n=\frac{4}{\pi}\int_0^{\pi/2} V_{A0}\text{Sin}n\omega t\, d\omega t$

$A_n=\frac{4}{\pi}\frac{Vdc}{2}\left[\int_0^{\theta 1} sin\omega t d\omega t+\int_{\theta 1}^{\theta 2} sin\omega t d\omega t \pm\int_{\theta(mf-1)/2}^{\pi/2} Sin\omega t d\omega t\right]$

$A_n=\frac{1}{n}\frac{4}{\pi}\frac{Vdc}{2}(1-2\text{Cos}n\theta_1+2\text{Cos}n\theta_2-.....\pm 2\text{Cos}n\theta_{(mf-1)/2})$

Using the same method, Fourier series for V_{bo} can be expressed as follows:

$V_{b0}=A_1\text{Sin}(\omega t-\frac{2\pi}{3})+A_3\text{Sin}3(\omega t-\frac{2\pi}{3})+A_5\text{Sin}5(\omega t-\frac{2\pi}{3})+....+A_n\text{Sin}n(\omega t-\frac{2\pi}{3})$

It is obvious that the line voltage V_{ab} has no triple harmonics. In addition, if m_f is equal to 3k for k=1, 2…then the line lowest harmonic orders are m_f-2, m_f+2, $2m_f$-2 and $2m_f$+2 (e.g., for m_f=9 the order of these harmonics are 7, 11, 17 and 19).

6.2.1. Advantages of inverted sine PWM

1. It has a better spectral quality and a higher fundamental component compared to the conventional sinusoidal PWM (SPWM) without any pulse dropping.
2. The ISCPWM strategy enhances the fundamental output voltage particularly at lower modulation index ranges.
3. There is a reduction in the total harmonic distortion (THD) and switching losses.
4. The appreciable improvement in the total harmonic distortion in the lower range of modulation index attracts drive applications where low speed operation is required.
5. Harmonics of carrier frequencies or its multiples are not produced.

6.3 Trapezoidal Inverted Sine PWM(TISPWM)

In this technique the gate signals are generated by comparing a inverted sine carrier wave with a modulating trapezoidal wave. In this proposed scheme, a unipolar trapezoidal signal with an amplitude of Am and frequency fm is taken as reference. High frequency inverted sine carriers with frequency fc and amplitude Ac are compared with the trapezoidal reference. Both the carriers are in phase with each other. The frequency ratio is chosen to be 24 and the modulation index is varied from 0.6 to 1 in steps of 1

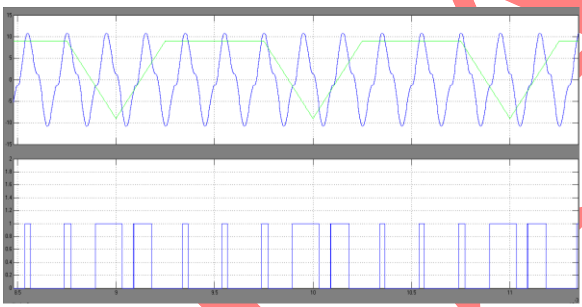

Fig 6.3 Firing Pulse Generation by Using TISPWM

6.4 Sawtooth Inverted Sine PWM (SISPWM)

This modulation is termed as naturally sampled PWM, which compares low frequency inverted sine reference waveform against high frequency sawtooth carrier waveform. This modulation is illustrated in the figure 12

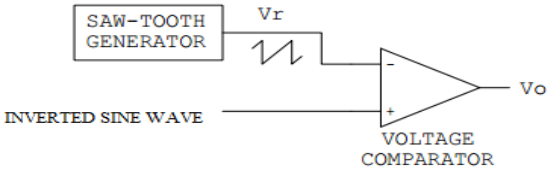

Fig 6.4 Sawtooth inverted sine PWM

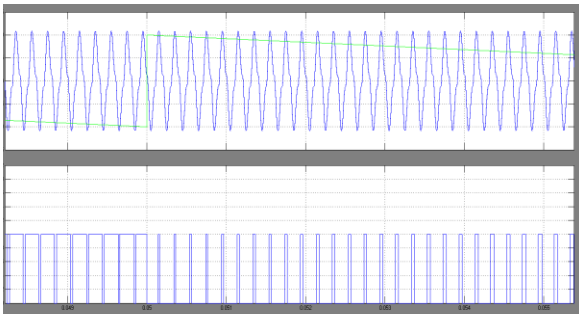

Fig 6.4(a) Firing pulse generation by using sawtooth inverted sine PWM

7. TOTAL HARMONIC DISTORTION (THD)

The Total Harmonic Distortion (THD) is mathematically given by

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} H_n{}^2}}{H_1}$$

Where H1 is the amplitudes of the fundamental component, whose frequency is w_o

Hn is the amplitudes of the nth harmonics at frequency nw_o.

$$h_n = \frac{4E}{n\pi} \sum_{k=1}^{s} \cos n \propto_k$$

Let $H_{(n)} = h_n$ and $H_1 = h_1$

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} H_n{}^2}}{H_1}$$

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} \left(\frac{1}{n} \sum_{k=1}^{s} \cos(n \propto_k)\right)^2}}{\sum_{k=1}^{s} \cos \propto_k}$$

Therefore, output voltage THD of the presented waveform can be calculated. Theoretically, to get exact THD, infinite harmonics need to be calculated. However, it is not possible in practice. Therefore, certain number of harmonics will be given. It relies on how precise THD is needed. Usually, n = 63 is reasonably accepted.

8. SIMULATION

8.1. Simulation without DVR for a Distribution System

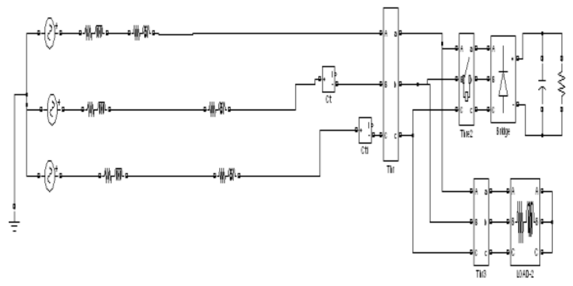

Fig.8.1 Simulation block diagram without DVR for distribution system

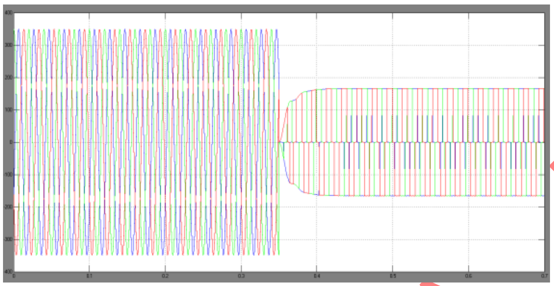

Fig.8.1(a). Three phase Load voltages

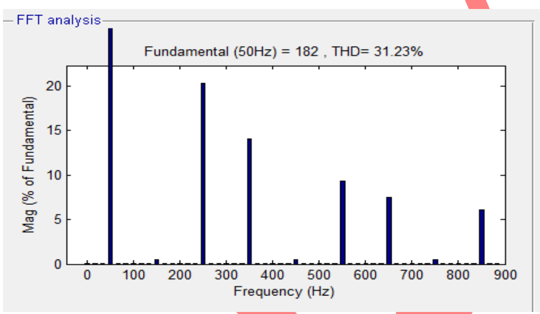

Fig.8.1(b). FFT Analysis

8.2. Simulation with DVR for a Distribution System

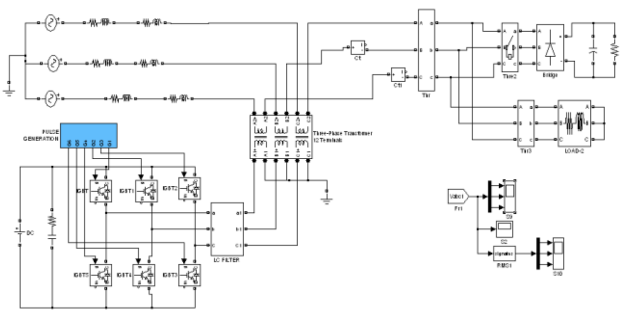

Fig.8.2.Simulation block diagram with DVR for distribution System

8.2.1 Simulation result with sine PWM

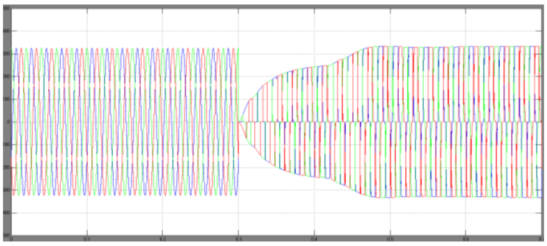

Fig.8.2.1(a). Three phase load voltages by using sine PWM

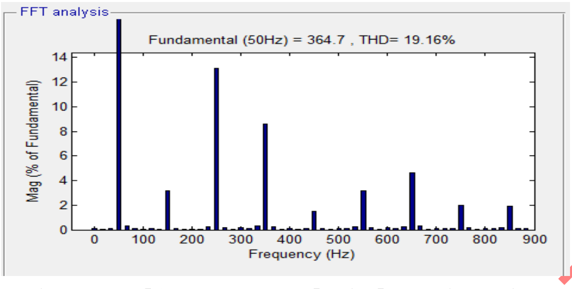

Fig 8.2.1(b). FFT Analysis by using sine PWM

8.2.2 Simulation result with inverted sine PWM

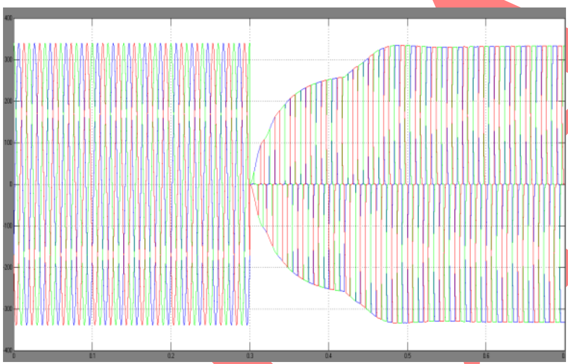

Fig 8.2.2(a).Three phase load voltages by using inverted sine PWM

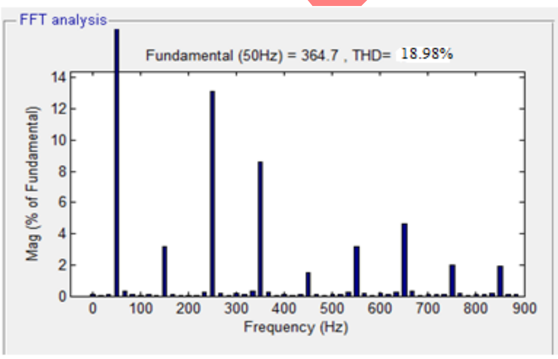

Fig 8.2.2 (b). FFT Analysis by using inverted sine PWM

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8.2.3 Simulation result by using trapezoidal inverted sine PWM

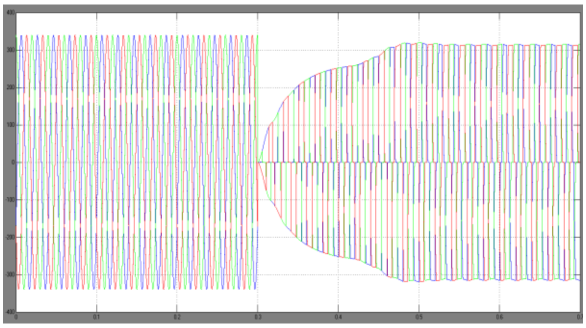

Fig 8.2.3(a) Three phase load voltages by using trapezoidal inverted sine PWM

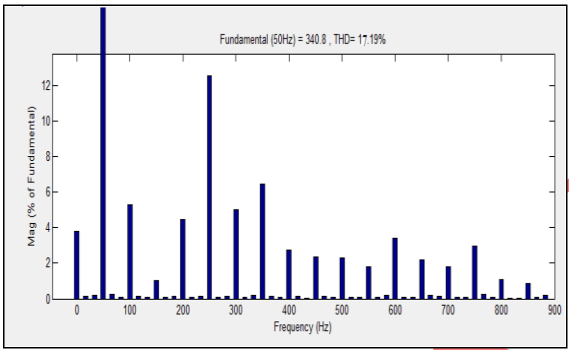

Fig 8.2.3(b) FFT Analysis by using trapezoidal inverted sine PWM

8.2.4 Simulation result by using Sawtooth inverted sine PWM

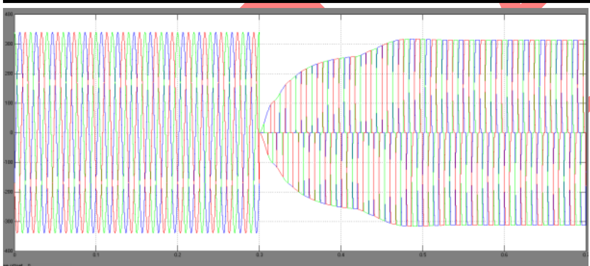

Fig 8.2.4(a) Three phase load voltages by using sawtooth inverted sine PWM

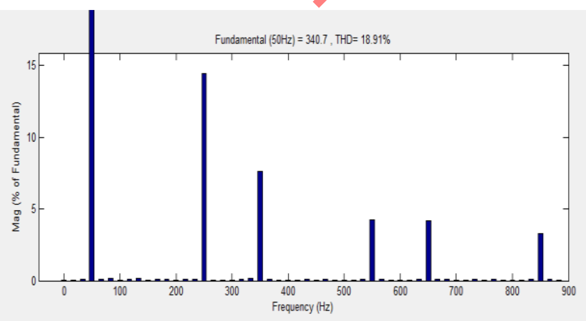

Fig 8.2.4(b) FFT Analysis by using sawtooth inverted sine PWM

9. COMPARISON OF TOTAL HARMONIC DISTORTION FOR ALL MODULATION TECHNIQUES

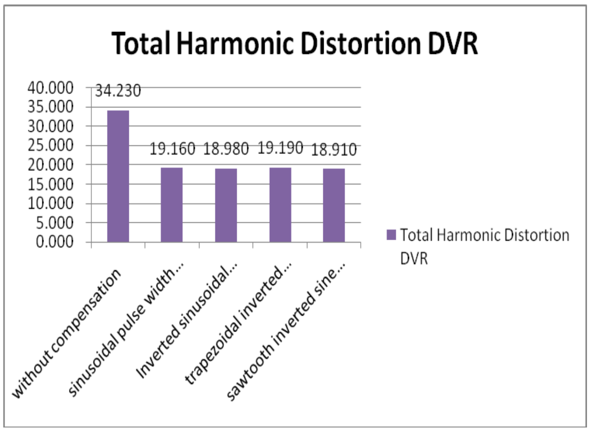

Fig 9 Bar chart representation of THD for all modulation techniques

10. CONCLUSION

Harmonics produced by the nonlinear loads which are connected in distribution system are harmful. In this paper a novel PWM technique called inverted sine PWM to reduce harmonics and increase power quality using DVR (Series Compensator) is considered. By doing FFT analysis it is observed that the Total Harmonic Distortion (THD) of the power system is reduced after the application of inverted sine PWM techniques in DVR compared to conventional PWM technique. The simulation results show the output voltage across a sensitive load without and with DVR. The simulations results show voltage regulation and no appreciable reduction of THD with inverted sine PWM techniques.

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