MITIGATION OF POWER QUALITY PROBLEMS AND HARMONICS COMPENSATION USING CAPACITOR-SUPPORTED DYNAMIC VOLTAGE RESTORER (DVR)

Amit Kumar[1] **Deepak Kumar**[2]
[123]School of Engineering, Gautam Buddha University, Greater Noida, India
abes.amit@gmail.com deepu1796@gmail.com

Abhay Yadav[3]
School of Engineering, Gautam Buddha University, Greater Noida, India
abhayadav@outlook.com

Abstract- *Power quality is an important issue in distribution network system. In present day, the industrial equipment is primarily based on electronic component such as rectifier, thyristors together with programmable sensing controllers and power electronic drives. These devices are very sensitive to instabilities and end up less tolerant to power quality issues. In the industrial and commercial equipment, voltage sags are serious and most common problems. By reactive power injection at the point of common coupling, balanced voltage is achieved. Several custom power devices are utilized to improve the quality of power but DVR is efficient and gives quick response, high reliability and cost is low. In this paper, we proposed a new scheme to control the self-supported dynamic voltage restorer (DVR) and different compensation techniques and operating modes are discussed.*

In this scheme, three phase harmonic filter (double tuned) is used to moderate harmonics, generated by voltage source converter (VSC). DVR operates within minimum energy rating. Capacitor is utilized as energy storage device during compensating the disturbance. Three phase programmable source is used to generate the disturbances within supply voltage. Through DVR, compensating the supply voltage harmonics the total harmonic distortion (THD) is minimized at load bus. By using a reduced-rating DVR, the reimbursement of the voltage dip, voltage swell, and harmonics is demonstrated. DVR works as enforced commutated VSC that inserts a dynamically required controlled voltage in series with the supply voltage through injection transformer for improving the load voltage. Parks Transformation is used to convert the voltages from rotating vectors to the stationary frame. The load voltage is sustained sinusoidal and in phase by inserting properly required compensation voltage through DVR. Extensive experiments are performed on MATLAB platform to analyze the performance of the proposed scheme.

Keywords- *Harmonics, Dynamic voltage restorer, voltage source converter, Power quality, voltage sag, synchronous reference frame theory.*

1. INTRODUCTION

Power quality complications are increased in present-day because the use of sensitive and precarious load equipment such as arc furnaces, food product manufacturing, and steel manufacturing processes [3], [23]. Sinusoidal waveform of the supply voltage is affected by many power quality abnormal conditions. Transients, voltage sag, voltage swell, interruption and other distortions affect the power system distribution network and performance of their equipment piece. Custom power expedients are used to afford fortification against the power quality complications [1], [33]. The quality of power is majorly affected by many factors such as non-linear loads, interruptions, transients, voltage sags, voltage swells, waveform distortion, voltage fluctuations, and long duration over voltage, capacitance switching and electrical noise [10]. The inductive loads which work on the principle of induction, causes poor power factor. The various type inductive loads are electric-arc and induction furnaces [16], [17]. Power electronic components, thyristor installation for D.C. motor control and in electro-chemical processes causes the power quality (PQ) disturbances. Electrical discharge lamps, welding machines, transformers, single phase and three phase motors cause the poor power factor [13]. Earlier active power factor correction (APFC), passive power factor correction (PPFC), hybrid filter, static compensator (STATCOM) techniques have been used to solve the poor power quality, power factor problem and minimization the overall losses [21].

Solid state Custom power devices are used in power system network to provide compensation and improve voltage profile

[9]. It is mainly of three types: a) DVRs - series connected b) distribution static compensator (DSTATCOM) shunt-connected [10] c) unified power quality conditioner (UPQC) - a permutation of series and shunt-coupled [2]–[6].

Westinghouse Corporation manufactured world's first DVR for the Electric Power Research Institute (EPRI) [12]. DVR is linked in series stuck between the supply and severe load at point of common coupling (PCC) [5]. Required compensating voltage can be injected using DVR to sustain supply voltage [14], [21]. It is solid state custom device that is used for mitigating voltage disturbances such as interruption, voltage sag, waveform distortion, voltage swell [8], [14]. It is also helpful in the distribution system for unsymmetrical fault by injecting voltage through the series transformer into the system [22] [36].

In paper [2], authors have discussed the power quality improvement by indirect control of capacitor supported DVR. Self-supported DVR controlling based on Reactive Power Theory (IRPT) [4] and Instantaneous Symmetrical Component Theory (ISCT) [10] are also related schemes in this area. In paper [5], authors have used DVR to restore a balanced sinusoidal voltage of preferred amplitude to deal with the phase of voltage unbalanced and distorted wave. There is no requirement of any active power for compensation after the injected voltage through DVR in quadrature [2], [3]. In steady state condition, the absorbed and supply power is zero. The DVR install at consumer point is used to compensate harmonics and regulate the terminal voltage. It provides protection to the consumer critical and sensitive loads [2], [4] and also full fill the power quality standard IEEE-519 [1]-[5].

2. Different Control Strategies in DVR

There are a number of strategies to enforce DVR for power quality improvement inside the distribution system and device. Other DVR applications that encompass strength power flow manipulate, reactive power reimbursement, in addition to restrained responses for PQ difficulties. Inverter is an imperative factor of the DVR. The overall performance of the DVR is without delay affected to the manage stratagem of inverter. The inverter control approach consists of two types of control. First is linear control and second is non-linear control.

Linear control utilized to controlling the DVR, the linear control method is taken as feed forward control which is computed the injected voltage between the pre-sag and during the sag voltage. This technique based on state space vector to give the quick time response by using close loop poles. The feedback control techniques based on state space vector, which can be installation closed-loop poles with the intention to make quicker time response [12]. Feed forward and feedback- control approach carried out by vector-control strategies. Multi-loop control method is a manipulate scheme within grid network voltage and load end side voltage, so it is able to improve voltage reimbursement effect. The feedback control in composite-control is design to consider double-loop, it is able to improve device stability [33]. The control technique within inductor current feedback and feed forward load contemporary is designed without series transformers consequently the sizes and price of the DVR is decreased.

Non-linear controlling approach is used in DVR and it has adaptive and self-organizing capability. This control approach can display the nonlinearity which is mainly based on enter input and output result is without any detail of mathematical model. Usually ANN controlling may be categorized into two types; first is feed-forward neural networks and second is feedback-neural network. Structure based ANN are local approximation neural networks and neuro-fuzzy network [25].

Non-linear control consist different types of control which are ANN control, fuzzy logic control and space vector pulse width modulation (SVPWM) control.

ANN control approach can display the nonlinearity which is mainly based on enter and output result is without the detail mathematical model. Normally ANN controlling may be categorized into two types; first is feed forward neural networks and second is feedback neural network. Structure based ANN are local approximation neural networks and Neuro-fuzzy network [36].

Fuzzy logic scheme is used for controlling the DVR for voltage injection. Its design view point deviates from all of the preceding approaches through information in controller layout. Data information is extracted from fuzzy set and used to controlling the DVR. It is an attractive choice while specific mathematical equations or formulations are not feasible. This control approach has an advantage because controller's capability is to lessen the mistake and transient over reach of PWM [34-38].

In 1980s, Japanese scholars described the SPWM manipulate method which is utilized to controlling the motor variable speed drives. It is used to generating the signals for eliminate the sag problems. The primary thinking is to implement a VSI space vector of the switch to become quasi circular rotating magnetic substance in place of the authentic SPWM, so enhanced overall performance of the exchange is established in low switching frequency situations [31]. For controlling and detection voltage sag of single phase in the distribution system, Instantaneous Value Comparison Method is generally used.

3. Operating Modes of DVR

There are three operating modes of DVR which are given as-

1. When voltage sag/swell on the line
2. Normal operation mode
3. In case of fault

When voltage sag/swell on the line: The DVR inserts the distinction among the pre-sag (Vpre-sag) and the sag voltage (Vsag), the requirement of actual power from the energy storing device together with the reactive power. Because of dc power storage and the voltage injection transformer ratio the most capability of DVR is restrained. The value of the inserted voltage may be controlled separately in case of three single phase DVR. The inserted voltages are complete synchronize at the required frequency and the phase angle [12].

Normal operation mode: In balanced condition that means any power quality problems is not occurs in distribution system or there is no sag appears with the system then dynamic voltage restorer will not produce supply voltage to the load. DVR will be not operating in a standby-mode when the energy storing device is fully charged [25] [30]. It operates in the self- charging mode. Battery and capacitor generally used as storage device for power and it can be charged either from the power source itself or through a different source.

In case of fault: In this condition, which occurs in the power distribute network then a bypass switch commonly used as crossbar switch may be initiated and it's going to pass the inverter circuit that allows protecting the electronic component of the inverter.

4. DVR Compensation Techniques

The DVR should make sure the unchanged load voltage with minimum power dissipation for injection. The characteristic of load determines the required control approach to inject compensation voltage. The techniques for injection of missing voltage can be divided into four groups.

1. Pre-sag compensation method
2. In-phase voltage injection method
3. Energy optimization compensation method
4. Voltage tolerance method with minimum energy injection

Pre-sag compensation method: In pre-sag compensation technique, the magnitude and the phase angle are compensated by the DVR. Vpre-sag shows the condition before the sag and Vsag is the sag voltage during the sag [25]. θsag is the angle between the Vpre-sag and Vsag. Vinj is injected voltage and θinj is injected angle which is inserted through transformer by the DVR. The variance of the sag and pre-sag voltage restores the magnitude and phase-angle to the normal condition as pre sag condition as shown in fig.1

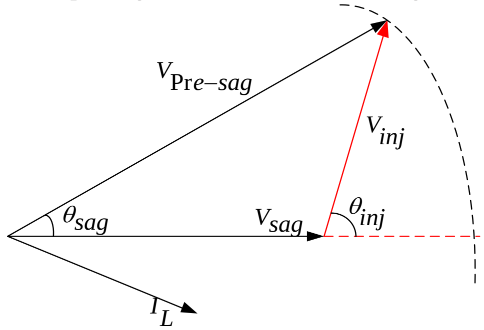

Fig.1. Phasor diagram of pre-sag compensation method

The dynamic voltage restorer injected voltage Vinj and phase angle θinj to be compensated may be calculated by this equation [12], [25].

$$V_{pre-sag} = V_L,\ V_{Sag} = V_S, \quad V_{DVR} = V_{inj} \tag{1}$$

$$V_{inj} = \sqrt{V_{Sag}^2 + V_{pre-sag}^2 - 2V_{Sag}V_{pre-sag}Cos\theta_{Sag}} \tag{2}$$

$$|V_{inj}| = |V_{pre-sag}| - |V_{sag}| \tag{3}$$

Alternative method to determine the Vinj by using this equation;

$$|V_{inj}| = |V_{pre-sag}| - |V_{sag}| \tag{4}$$

$$\theta_{inj} = \tan^{-1}\left(\frac{V_{pre-sag}Sin\theta_{pre-sag}}{V_{pre-sag}Cos\theta_{pre-sag} - V_{Sag}Cos\theta_{Sag}}\right) \tag{5}$$

Some non-linear loads are very sensitive for phase angle jumps. It is far the best strategy to restore the sensitive voltage for the load to getting desired phase angle and voltage magnitude because the nominal pre-sag voltage [24-26]. In single phase vector diagram, the perfect restoration is carried out. High capacity power storage devices are required when inserted active power is uncontrollable [12]. This method is requiring the active power during the reimbursement. If the variations in three phases are uneven in nature then cannot be restore and sustain the phase jump [28].

In-phase voltage injection method: This technique is utilized to reimburse any sort of voltage sag irrespective unbalanced phase jump. In case of disturbance, the active power is injected by DVR to the system [12].Vinj by DVR is in phase with Vsag. It is suitable for minimum required voltage in the DVR operation. The minimum value of Vinj is carry out when the active power is zero by having the phasor of Vinj is perpendicular to the IL phasor. In this method, the Vinj amplitude is minimum which is injected by DVR for certain voltage sags. The voltage magnitude is compensated and restores required voltage magnitude. Vinj is in-phase with supply voltage as present in figure 2.

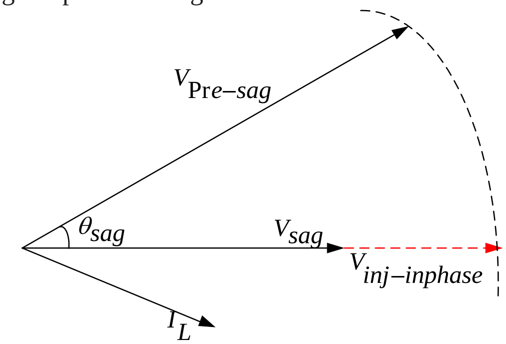

Fig.2. Phasor diagram of In-phase compensation method

It is very simple for execution and easy to manipulative the DVR compensating voltage, which is calculated by this equation.

$$V_{DVR} = V_{inj} \tag{6}$$

$$|V_{inj}| = |V_{pre-sag}| - |V_{sag}| \tag{7}$$

$$\angle V_{inj} = \theta_{inj} = \theta_S \tag{8}$$

The phase angle between pre-sag and load voltage are distinct but the maximum crucial standards for power quality, which is the constant value of load voltage, is satisfied. Active power is required at some point of reimbursement like that in Vpre-sag reimbursement technique [12].

Energy optimization compensation method: Pre-sag and in-phase compensation approach injects the active energy to loads. The I_L and load voltage are set in system and only alteration with phase of Vsag. This method makes the injection active power zero [12] [29]. So that it will decrease using real power the voltages are inserted at phase-angle of 90° to supply current as presented in figure 3.

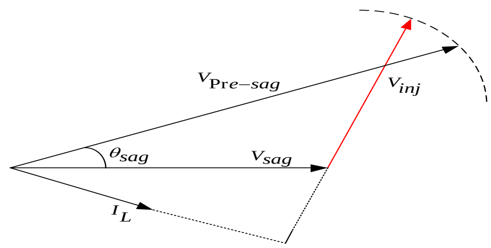

Fig. 3. Phasor diagram of energy optimization compensation method

Reactive power is generated during compensation through VSI. It keeps the apparent power at constant and decrease the reactive power of network. It is not requirement of active power during reimbursement and it is minimized the inserted energy. Therefore high capacity power storage device is not required when the requirement of real power is minimized. It increases the magnitude of Vinj and consequently the apparent power of the compensator. The restore voltage is achieved at the point of coupling where critical load is connected.

Voltage tolerance method with minimum-energy injection: The angle of phase and magnitude of improved load voltage inside the area of load voltage tolerance are present in Fig. 4. The phase-angle jump and voltage-drop on load may be tolerated by load. Normally the voltage value among 90%-110% of nominal voltage and phase angle variation between 5%-10% of ordinary state do not disturb the operation characteristics of loads [12], [32]. The significance and phase are controlling parameters of this technique to acquire the minimum power injection.

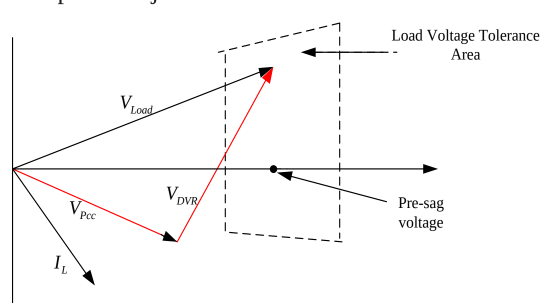

Fig. 4. Phasor diagram of voltage tolerance method

The voltage tolerance-area is dependent on load. Some loads are sensitive for phase-angle shift and other loads are sensitive to voltage magnitude variations. The operating point is determined by considering the load characteristic. The voltage tolerance method can sustain the load voltage in the tolerance area with minor change of voltage magnitude by injecting smaller active power than other methods.

5. Operation of DVR

The scheme of self-supported DVR is used to compensate, regulate and protect from sag, swell, distortion, or unbalanced condition in supply voltage [10]. This paper produces controlling and enactment of DVR validated through a minimal-voltage synchronous reference frame theory (SRFT) based controller scheme is used for DVR.

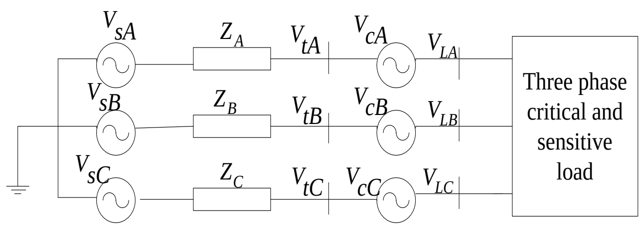

Fig. 5. Schematic diagram of self- supported DVR

The diagram of self-supported DVR is present in Fig. 5. Three phase voltage source V_{sA}, V_{sB}, V_{sC} denotes three-phase supply, Z_A, Z_B and Z_C represents the series source impedance. Terminal voltages (V_{tA}, V_{tB}, V_{tC}) denotes power quality abnormal conditions. DVR inserts required reimbursing injected voltages (V_{cA}, V_{cB}, V_{cC}) which pass through series injection transformer. Subsequently we achieve undistorted load voltages (V_{LA}, V_{LB}, V_{LC}) at load terminal. DVR practices a series injected transformer to introduce voltage $(Vinj)$ in series along with source voltage. In series injected transformer, low voltage side of transformer is connected with the VSC and high voltage side of transformer winding is associated with load [18], [15]. A capacitor VC_{dc} is used as storage device in DVR. The ripple filter consist the inductor(Lr), capacitor (Cr) and resistance (Rr) to eliminate the harmonics, ripples and higher switching frequency in VSC [16], [20], [23]. The main task of Harmonic filter (double tuned) is eliminating the harmonics which are presented in compensating voltage, generated by the VSC.

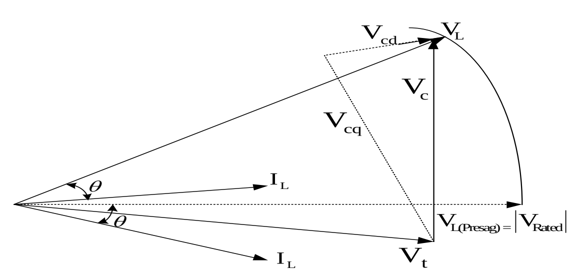

Fig. 6. Self- supported DVR phasor diagram for voltage sag compensation [2]

Fig. 6 represents the operation of DVR in the form of phasor diagram for compensation of voltage sag. This sag appears in supply voltage. In this figure V_L (pre-sag) and I_L represent load terminal voltage and current respectively, during pre-sag condition.

The supply voltage (V_s) is worse in magnitude of pre-sag circumstance after sag occurrence. The injected voltage (V_c) through the DVR is used to sustain the load voltage (V_L) at the evaluated magnitude. Injected voltage has two constituents, V_{cd} and V_{cq}. The voltage (V_{cd}) in-phase with current is to control dc bus voltage and satisfy the power loss in VSC. The voltage in quadrature (V_{cq}) with current is to normalize the load voltage at constant magnitude [2]. Proposed DVR takes out the requisite reference voltage to remunerate presence of harmonics and unbalanced source voltage [2], [23-27].

6. DVR Control Scheme

The offered control-scheme for VSC of DVR is based on SRFT or Parks Transformation. This scheme is used to compensate the harmonic current to achieved waveform sinusoidal, load voltage balancing and power factor improvement at load voltage bus [2-5]. Terminal voltage (V_t) at PCC are rehabilitated to rotating reference frame using abc-dq0 conversion by means of SRFT with unit vectors ($\sin\theta, \cos\theta$). For low pass filter (LPF) the synchronous frame variables $V_{d,}V_q$ are used as input variables to generate voltage reference in the synchronous frame [5]. When there is any disruption occurs in distribution network system [7], the source voltages turn into unbalanced voltage [22]. In circumstance of unbalanced positive and negative sequence constituents appear in system and both components prerequisite to be detected as a DC component and controlled and extracted through LPF after dq0 transformation [8], [9]. The components of dc voltage in term of direct and quadrature axes are [3], [19].

$$V^*_{Ld} = V_{tdDc} - V_{cd} \quad (9)$$

$$V^*_{Lq} = V_{tqDc} - V_{cq} \quad (10)$$

Where V^*_{Ld} and V^*_{Lq} represents the DC constituents of active and reactive voltage of mention load voltages in d-q frame. V_{tdDc} and V_{tqDc} represents the active and reactive power respectively, which consistent to the source side. V_{cd} and V_{cq} are discrete Proportional Integral (PI) controllers outputs corresponding towards required active voltage element for self–supporting DC bus voltage [28]. Reactive voltage element is required for voltage regulation at load terminal. V_{LP} is the computed magnitude of sensed voltage in per unit and V^*_{LP} is reference magnitude of the load voltage in per unit. The amplitude of load voltage at PCC is calculated from ac load voltages [5], [17].

$$V_{Lp} = (2/3)^{\frac{1}{2}}(V_{LA}{}^2 + V_{LB}{}^2 + V_{LC}{}^2)^{1/2} \quad (11)$$

Synchronous reference frame theory (SRFT) is established on instant values of the supply voltage [29]. It detects the unbalanced voltage conditions during the disturbances [15]. The control scheme generates three phase reference voltage toward the pulse width modulation (PWM) inverter. It attempts to sustain the load voltage at its orientation value. The voltage disturbances detected through evaluating the error among supply voltage and reference significance. Where, reference significance component is fixed at rated voltage [10].

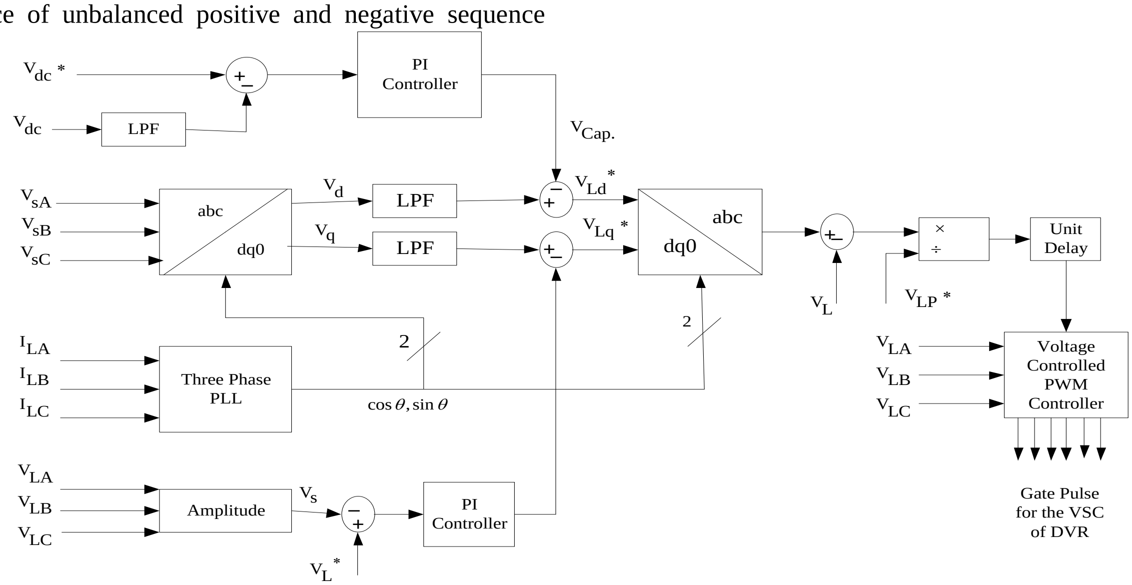

Fig.7. Control scheme of self-supported DVR

The basic capabilities of a DVR controller are the finding of voltage sag/swell activities in the system network and computation of the correcting voltage producing of triggering pulses to the sinusoidal pulse width modulation based dc-ac inverter [35]. The controller is also utilized to alteration the dc-ac inverter into rectification mode to charging the capacitor

within the dc power link inside the absence of voltage sags/swells. The dq0 technique offers the sag depth value and also produce phase shift information with begin and completion times [28], [32].
Low pass filter (LPF) is utilized to remove the harmonics and also for oscillatory components of voltages. The synchronous frame (SF) variables and are used as inputs for LPF to generate voltage references, when there is any disruption occurs with the system, [38] the voltages source go to the unbalanced condition. In this condition both the positive and negative sequence components appears in the system, and both constituents must to be detected as a direct current component and controlled. Both components extracted by using LPF after dq0 transformation [40].

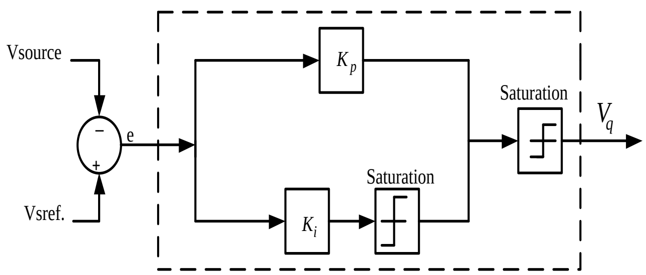

Fig.8. PI Controller

PI controller is used to improvement the tracking through minimizing the instant error which occurs in between the reference and real voltage and causes steady state error (e_{SS}) to become zero [34]. PI controller consists the two terms as K_p (proportional gain) and K_i (integral gain) and these values should be correct, PI controller produce an actuator command signal that attempts to drive the error to zero with proportional gain and steady state error (e_{SS}) with integral gain[38], [40].
The offered control-scheme for VSC of DVR is based on SRFT or Parks Transformation. This scheme is used to compensate the harmonic current to achieved waveform sinusoidal [34-38], load voltage balancing and power factor improvement at load voltage bus. Terminal voltage (V_t) at PCC are rehabilitated to rotating reference frame using abc-dq0 conversion by means of SRFT with unit vectors ($\sin\theta, \cos\theta$). For low pass filter (LPF) the SF variables $V_{d,}V_q$ are used as input variables to generate voltage reference in the synchronous frame [32].

The direct quadrature zero transformation is basically an extension of the Clarke-transform, which is applied on angle transformation to convert stationary reference-frame to a synchronous-rotating frame. The SRF can be allied to rotating with the voltage (e.g. utilized in VSC) or with the current (e.g. utilized in CSI) [25], [30].

$$V_d = \frac{2}{3}\left[V_a \sin(wt) + V_b \sin(wt - \frac{2\pi}{3}) + V_c \sin(wt + \frac{2\pi}{3})\right] \quad (12)$$

$$V_q = \frac{2}{3}\left[V_a \sin(wt) + V_b \cos(wt - \frac{2\pi}{3}) + V_c \cos(wt + \frac{2\pi}{3})\right] \quad (13)$$

$$V_0 = \frac{1}{3}\left[V_a + V_b + V_c\right] \quad (14)$$

Where V_d , V_q and V_0 are the direct axis voltage, quadrature axis voltage and zero axis voltage respectively, w is rotation speed (rad/sec) of the rotating frame, we have

$$V_a = \left[V_d \sin(wt) + V_q \cos(wt) + V_0\right] \quad (15)$$

$$V_b = \left[V_d \sin(wt - \frac{2\pi}{3}) + V_q \cos(wt - \frac{2\pi}{3}) + V_0\right] \quad (16)$$

$$V_c = \left[V_d \sin(wt + \frac{2\pi}{3}) + V_q \cos(wt + \frac{2\pi}{3}) + V_0\right] \quad (17)$$

Where V_a, V_b and V_c are the three phase supply voltage of phase A, B and phase C respectively.
Two PI controllers are used to determine the error between the reference and actual required DVR voltage. In-phase and quadrature components of injected essential voltage through DVR are computed using PI controllers [4], [33]. The DC bus voltage of DVR is controlled through a PI controller over detected (V_{dc}) and reference values (V_{dc}*). PI controller output is taken into account because the amplitude (V_{Cd}*) of the in-phase element of insertion voltages (V_{cAd}*, V_{cBd}*, V_{cCd}*). The amplitude (V_{LP}*) of quadrature element of injection voltages (V_{cAq}*, V_{cBq}*, V_{cCq}*) of DVR through over the amplitude of detected load voltage (V_{LP}) [2]. The sensed values of load voltages are used to obtain gating signals for the IGBT's (insulated gate bipolar transistors) of the VSC [36-38]. The carrier (triangular) frequency is fixed at 6 kilohertz. The compensation of power quality disturbances and harmonics in supply voltage through gate pulsate switch the IGBT's of VSC in DVR [2-5], [26].

7. MATLAB Based Simulation Model of DVR

Figure 4 shows the Simulink model of the DVR which are connected in the system. Three phase programmable voltage source is connected in series with source impedance. At the PCC voltage, the disturbances is analyzed and simulate through switched on an additional load. The load is considered resistive within lagging power factor. The VSC output passes through ripple filter and connected along with a transformer [11], [16]. The selection of DC bus capacitor is based on transitory energy necessity [27], and dc bus voltage is carefully chosen based on nearer injection voltage level [2], [3]. Ripple contented in dc voltage is decided by DC capacitor [4]. In the Appendix, system data are specified. The control scheme for the DVR which is demonstrated in MATLAB software is presented in Fig.3. The reference load voltages are derivative from sensed supply voltage (V_s), supply current (I_s), load voltage (V_L) and dc bus voltage of DVR.

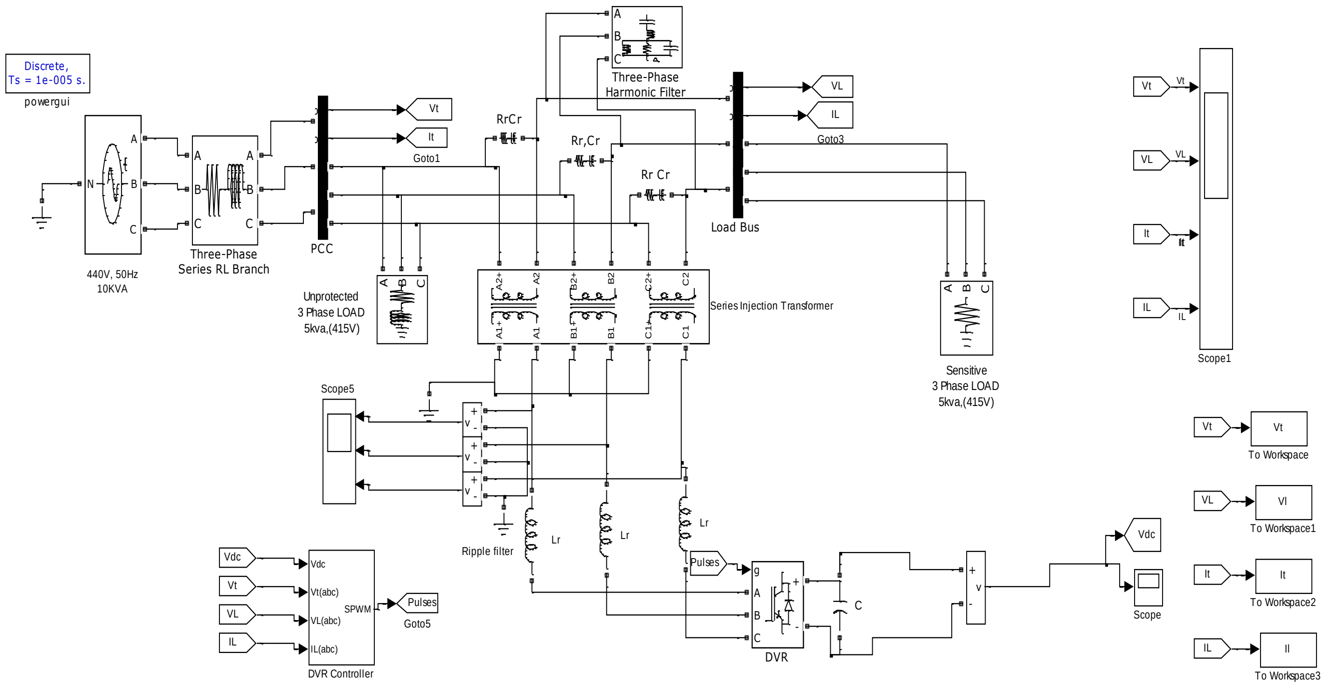

Fig. 9. MATLAB Simulink model of DVR connected system

8. Performance Of DVR System

The enactment of DVR for dissimilar supply conflicts is verified under numerous operative conditions. In the Simulink model of DVR, different two types disturbances are set on three phase balanced source which causes or effects unbalanced in three phases. First disturbance includes harmonic order 2, amplitude value is 0.3 p.u, phase shift 0^0 and sequence is zero. Second disturbance includes harmonics order 2, phase shift 0^0, amplitude 0.2 p.u, and sequence is negative. Three phase programmable source is used to generate disturbance and harmonics with supply voltage at the terminal-bus.

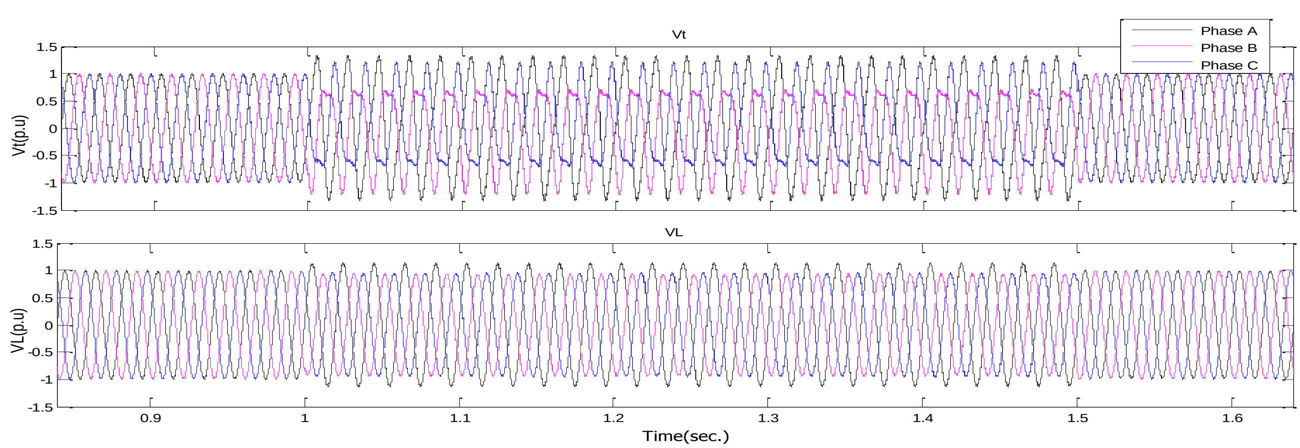

Fig. 10. Disturbance at Terminal voltage and balanced output at load voltage

Figure 10 shows the performance of terminal voltage and load voltage. Terminal voltage shows the disturbance or unbalanced condition for time period 1 second to 1.5 second, this time is set by three phase programmable source. X-axis shows the simulation running time and Y-axis shows the terminal voltage or load voltage in per unit. One per unit value is 440V. At the terminal, voltage waveform is not sinusoidal because of harmonic content and three phase A, B and phase C is unbalanced. After the compensation through DVR the load voltage waveform is sinusoidal achieved at load terminal. DVR injected voltage for time period of 1 second to 1.5 second.

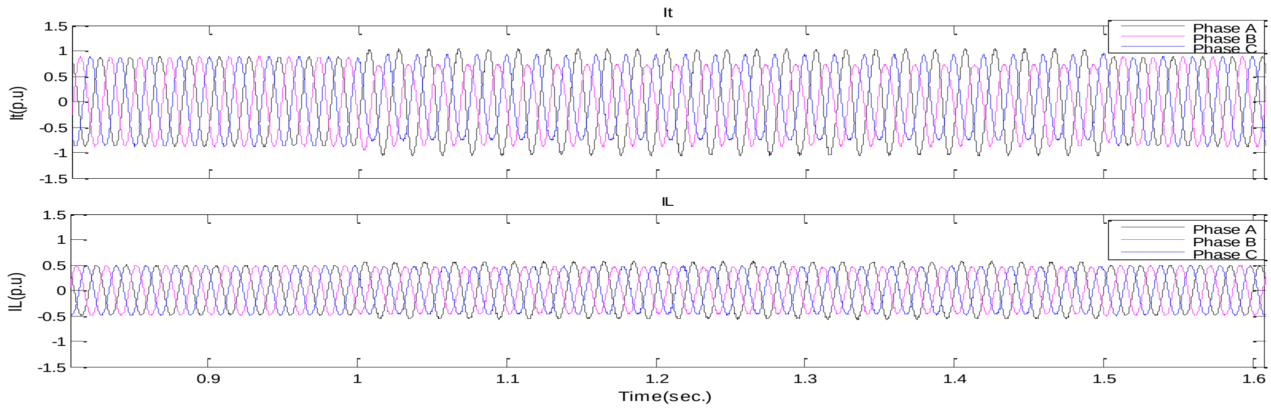

Fig. 11. Disturbance at terminal current and balanced at load current

Figure 11 shows the performance of terminal current and load current. Terminal current shows the disturbance or unbalanced condition for time period 1 second to 1.5 second, this time is set by three phase programmable source. X-axis shows the simulation running time and Y-axis shows the terminal current or load current in per unit. At the terminal, current waveform is not sinusoidal because of harmonic content and three phase A, B and phase C is unbalanced. In this figure the I_t represents terminal current at terminal point and I_L represents the load current at load terminal. After the compensation through DVR the load current waveform is sinusoidal achieved at load terminal. DVR injected voltage for time period of 1 second to 1.5 second.

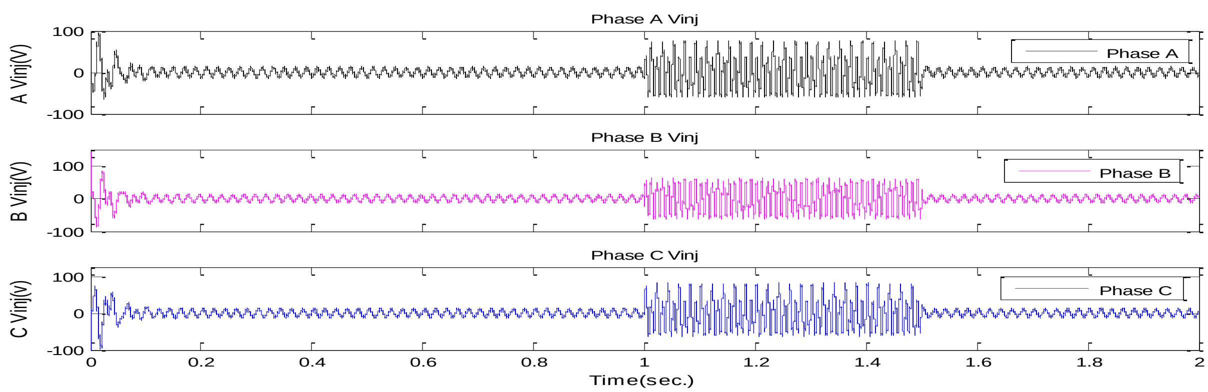

Fig. 12. Phase A, B and phase C injected voltage

Voltages of different phases which are injected by DVR of VSC is shown in figure 12. According the requirement of voltage to compensate and balanced the voltage at the load teminal at point of common coupling. Phase A, B and phase C injected voltage (Vinj) is inserted for the time period 1second to 1.5 second.

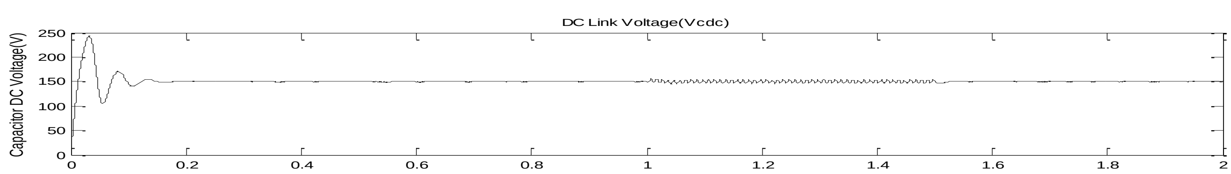

Fig. 13. DC-Link voltage waveform at inverter

The capacitor is used as energy storage device for DVR of VSC in Simulink model. Figure 13 presents the DC-link voltage as well as capacitor voltage waveform at inverter. The capacitor voltage value is fixed at 150V. DVR takes the energy from the source as capacitor during the abnormal condition for time period of 1second to 1.5 second which is shown in figure 13. Transient state condition occurs in DC-link voltage for approximate 0.1 second because of fluctuation occurs with the system.

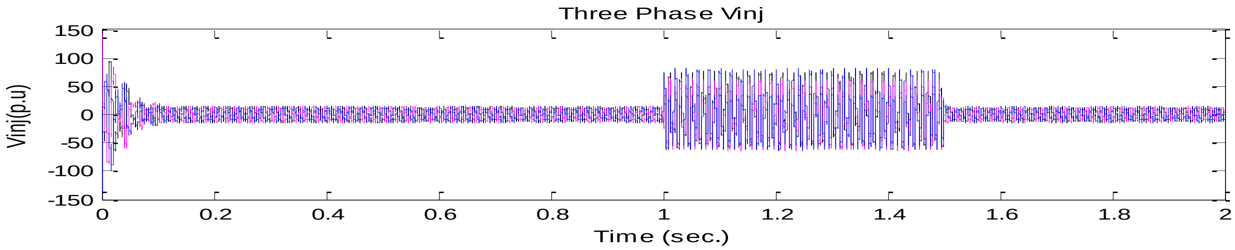

Fig. 14. Three Phase Injected Voltage

Figure 14 presents the three phase injected voltage during the disturbance condition which is set in programmable source. The X- axis shows the simulation running time and Y-axis presents the voltage which value is set at 150 V. Phase A, B and phase C as a three phase voltage inserted for time period 1 second to 1.5 second. Through this inserted voltage the unbalanced condition can be mitigating and compensating the harmonics which are present in supply voltage.

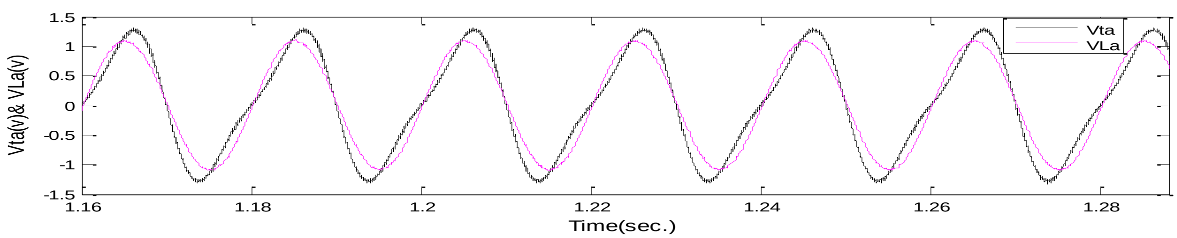

Fig. 15. Voltage at the terminal and load bus

Terminal voltage and load voltage variation shown in figure 15. The terminal voltage has the unbalanced condition and much amount of harmonics and load voltage has sinusoidal waveform with very low value of total harmonic distortion. At the load point the sinusoidal waveform is achieved which is denoted by pink waveform and load voltage is denoted by black waveform in figure 15. This figure shows that the terminal voltage of phase A and load voltage of phase A.

9. Fast Fourier Transform (FFT) Analysis Of Simulation Result

Fourier transform converts waveform data in the time domain into the frequency domain and vice-versa.

<u>FFT Analysis for Phase A</u>

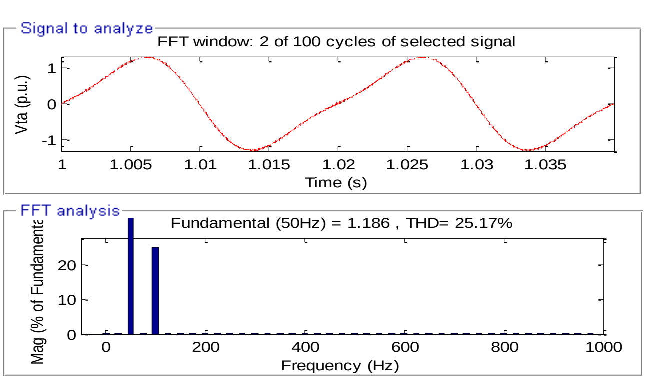

Fig. 16. Terminal voltage of Phase A at PCC along with Harmonic spectrum

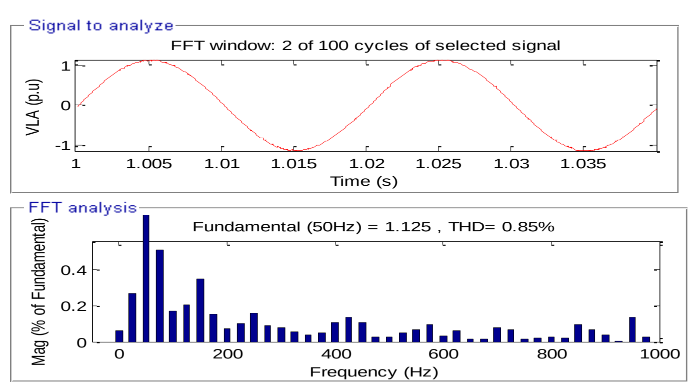

Fig. 17. Load voltage of Phase A along with compensating Harmonic spectrum

Figure 16 shows the FFT analysis for Phase A at terminal point (PCC). The waveform of terminal voltage of phase A presents the waveform is not sinusoidal and has the total harmonic distortion (THD) value is 25.17% which is very high. The fundamental (50 Hz) is 1.186 at the time of disturbance. The fundamental (50 Hz) shows the magnitude value.

<u>FFT Analysis for Phase B</u>

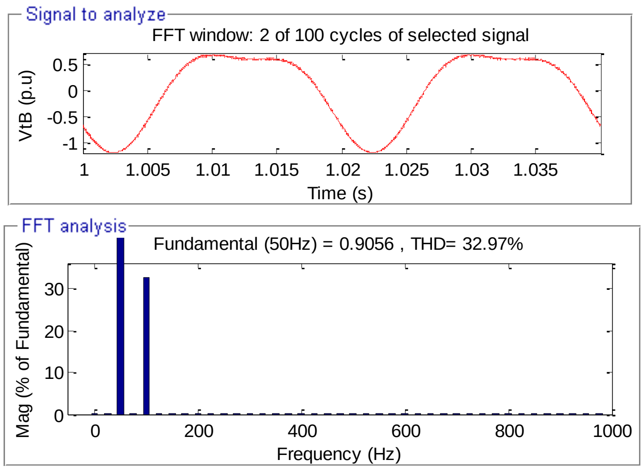

Fig. 18. Terminal voltage of Phase B at PCC along with Harmonic spectrum

Figure 18 shows the FFT analysis for terminal voltage of Phase B at terminal point (PCC). The terminal voltage at PCC is distressed through switching on a resistive load. The waveform of terminal voltage of phase B presents the waveform is not sinusoidal and has the total harmonic distortion (THD) value is 32.97% which is very high. The fundamental (50 Hz) is 0.9058 at the time of disturbance. This waveform achieved during the disturbance, and FFT analysis is done at 50 Hz frequency.

<u>FFT Analysis for Phase C</u>

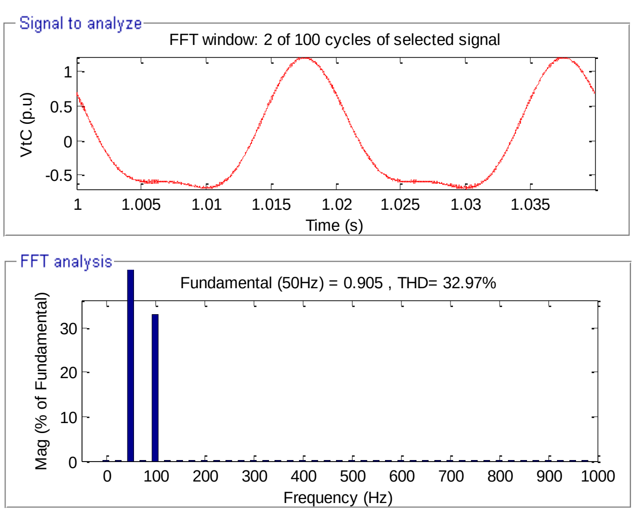

Fig. 20. Terminal voltage of Phase C at PCC along with Harmonic spectrum

Figure 17 presents the FFT analysis for magnitude value at 50 Hz frequency and THD value for load voltage of phase A at the load terminal. The waveform of load voltage of phase A presents the waveform is sinusoidal and has the total harmonic distortion (THD) value is 0.85% which satisfy the IEEE 519 standard. The fundamental (50Hz) is 1.125 is the restore magnitude after the compensation harmonics.

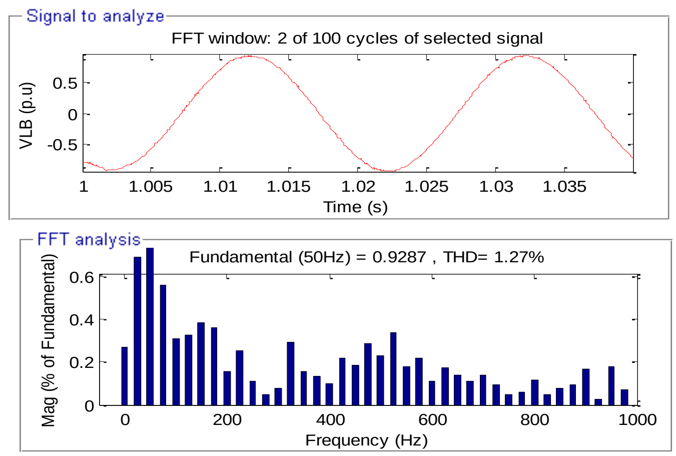

Fig. 19. Load voltage of Phase B along with compensating Harmonic spectrum

Figure 19 presents the FFT analysis for magnitude value at 50 Hz frequency and THD value for load voltage of phase B at the load terminal. The waveform of load voltage of phase B presents the waveform is sinusoidal and has the total harmonic distortion (THD) value is 1.27% which satisfies the IEEE 519 standard. The fundamental (50Hz) is 0.9287 is the restore magnitude after the compensation harmonics.

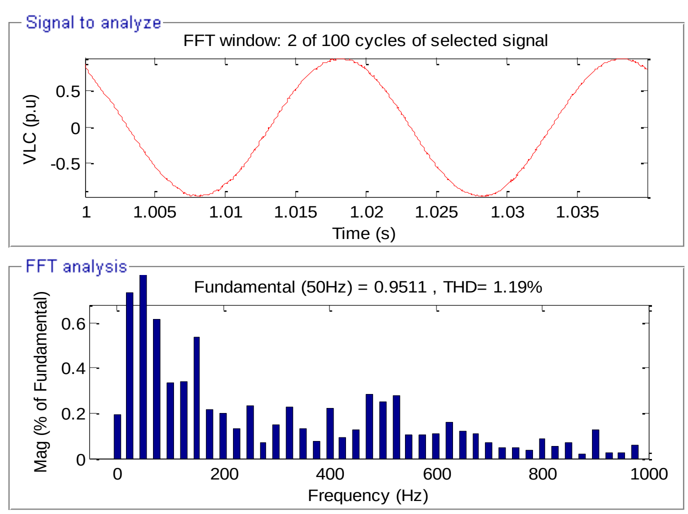

Fig. 21. Load voltage of Phase C along with compensating Harmonic spectrum

Figure 20 shows the FFT analysis for terminal voltage of Phase C at terminal point (PCC). The waveform of terminal voltage of phase C presents the waveform is not sinusoidal and has the total harmonic distortion (THD) value is 32.97% which is very high. The fundamental (50 Hz) is 0.905 at the time of disturbance. This waveform achieved during the disturbance, and FFT analysis is done at 50 Hz frequency.

Figure 21 presents the FFT analysis for magnitude value at 50 Hz frequency and THD value for load voltage of phase C at the load terminal. The waveform of load voltage of phase C presents the waveform is sinusoidal and has the total harmonic distortion (THD) value is 1.19% which satisfies the IEEE 519 standard. The fundamental (50Hz) is 0.9511 is the restore magnitude after the compensation harmonics.

Table 1: DVR Result Summary

Phase	**Dist. Mag(p.u.), peak**	**Restored Mag(p.u.), peak**	**(Vt) THD (%)**	**(V_L) THD (%)**
Phase A	1.186	1.125	25.17	0.85
Phase B	0.9056	0.9287	32.97	1.27
Phase C	0.905	0.9511	32.97	1.19

10. Conclusion

In this paper, the synchronous frame theory based control scheme is proposed. The performance of DVR has been endorsed by using MATLAB software through simulation. The reference voltages for DVR have been attained indirectly by take out the reference terminal voltage. Three-phase harmonic filter (double tuned) is used in this Simulink DVR model that reduces the harmonics generated by VSC. DVR control strategies, functions, configurations and their components are presented in this paper. DVR is utilized to mitigate voltage sag and compensate harmonics because of fast-response, compact in size and gives the efficient solution. This paper deliberated abc to dqo control algorithm to produce the pulses. SRFT based control scheme is design to exceptional voltage reimbursement abilities. Effectiveness of proposed method is examined using simulation through MATLAB/SIMULINK software. DVR performance in mitigating numerous power quality complications such as voltage dip, unbalanced conditions and voltage swell, and has been observed to be satisfactory and balanced voltage at the load terminal. SRFT based controller works satisfactory and compensate the harmonics and come across the power quality standards such as IEEE-519.

11. Appendix

The constraints of the system considered in table:

Parameter name	**Value**
Line Impedances	Ls 1mH, Rs 1 Ω
Load	5 kVA, 415V, pf:0.9lag
Ripple Filter	Cr 1 μF, Lr 3.1mH, R_r 1Ω
DC bus capacitance	Cdc 1000μF
AC line voltage	V_{L-L} 440V, 50Hz
PWM switching frequency	6kHz
Transformer	10kVA, 150V/300V

References

[1] A. Ghosh and G. Ledwich, : *Power Quality Enhancement using custom power devices* In: Kluwer Academic Publishers, London 2002.

[2] B. Singh, P. Jayaprakash, D.P Kothari, A. Chandra, K. A. Haddad, : *Indirect control of capacitor supported DVR for power quality improvement in distribution system* In: Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp.1-7, IEEE 2008.

[3] P. Jayaprakash, B. Singh, D.P. Kothari, A. Chandra, K. A. Haddad, : *Control of reduced-rating dynamic voltage restorer with a battery energy storage system* In: IEEE Transactions on industry applications, vol.50, no.2, pp.1295-1303, IEEE 2014.

[4] P. Kanjiya, V. Khadkikar, H. H. Zeineldin and B. Singh : *Reactive power estimation based control of Self-supported dynamic voltage restorer* In: Harmonics and Quality of Power (ICHQP) 15th International Conference, pp. 785-790, IEEE 2012.

[5] P. Kanjiya, B. Singh, A. Chandra and K. A. Haddad: *SRF theory revisited to control self-supported dynamic voltage restorer for unbalanced and nonlinear loads* In: IEEE transactions on industry applications, vol.49, no.5, pp.2330-2340, IEEE 2013.

[6] A. M. Rauf and V. Khadkikar,: *An enhanced scheme for dynamic voltage restorer* In: IEEE transactions on industrial electronics, vol.62, no.5, pp.2683 – 2692, IEEE 2015.

[7] M. U. Cuma, A. Teke, M. E. Meral, K. C. Bayindir and M. Tumay, : *Implementation of a non-linear adaptive filter based sag detection method for dynamic voltage restorers under unbalanced fault condition* In: journal of Power Electronics, vol.13, no.2, 20013.

[8] G. I. Nicolaescu, H. Andrei and S. Radulescu,: *Modeling and simulation of dynamic voltage restorer for voltage sag mitigation in medium voltage networks with secondary distribution configuration* In: International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp.52-58, IEEE 2014.

[9] F. B. Ajaei, S. Afsharnia, A. Kahrobaeian and S. Farhangi *: A fast and effective control scheme for the dynamic voltage restore*r In: IEEE Transactions on power delivery, vol. 26, no.4, pp.2398-2406, IEEE 2011.

[10] A. Ghosh, A. Joshi: *A new algorithm for the generation of reference voltages of a DVR using the method of instantaneous symmetrical componenets* In: Power Engineering Review, IEEE, vol.22, no.1, pp.63-65, IEEE 2002.

[11] Y. Prakash and S. Sankar,: *Power quality improvement using DVR in power system* In: Power and Energy Systems Conference: Towards Sustainable Energy (PESTSE), pp.1-6, IEEE 2014.

[12] S. Ali, Y. K. Chauhan and B. Kumar,: *Study and performance of DVR for voltage quality enhancement* In: Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference, pp.983-988, IEEE 2013.

[13] N. P. Kumar and Y. Pal*: Performance evaluation of three phase, three wire DVR for power quality improvement* In: Engineering and Systems (SCES), 2014 Students Conference, pp.1-6, IEEE 2014.

[14] I. Y. Chung, D. J. Won, S. Y. Park, S. I. Moon and J. K. Park: *The DC link energy control method in dynamic voltage restorer system* In: Electrical Power and Energy Systems 25 (2003) pp.523-531, Elsevier 2013.

[15] A.H.A. Hamza, M.S. El-Koliel, M.N. Ali, H. El-Eissawi and M.M. Hafez,: *Improvement of dynamic voltage restorer using proportional integral controller for mitigation of voltage sag*e In: Arab Journal of Nuclear Science and Applications, vol. 48, no.1, pp.44-52, 2015.

[16] S. P. Mishra, B. Biswal, J. P. Roselyn and D. Devaraj*: Simulation and analysis of DVR for mitigating voltage sags and swells* In: Procedia Engineering, vol.64, pp.341-350, Elsevier 2013.
[17] R. Omar, N.A. Rahim: *New configuration of a three phase dynamic voltage restorer for voltage disturbances mitigation in electrical distribution system* In: Arab Journal Science Eng., vol.37, pp.2205-2220, 2012.
[18] C. Gopinath, C. Yaashuwanth, R. Ramesh, J. R. Maglin and T. A. B. Raj : *Analysis and mathematical modelfor restitution of voltage using dynamic voltage restorer* In: Hindawi Publishing Corporation vol.2014 Article ID 845873, 2014.
[19] M.R. Banaei, S.H. Hosseini, S. Khanmohamadi and G.B. Gharehpetian,: *Verification of a new energy control strategy for dynamic voltage restorer by simulation* In: Simulation Modelling Practice and Theory, vol.14, pp.112-125, Elsevier 2006.
[20] A. O. A. Mathnani, H. Shareef, A. Mohamed, Mohd Alauddin Mohd Ali and M.A. Hannan: *Power quality improvement using DVR with two fast vector control* In: The 4th International Power Engineering and Optimization Conf.(PEOCO 2010), pp.376-381, IEEE 2010.
[21] A. M. Saeed, S. H.E. Abdel Aleem, A. M. Ibrahim, M. E. Balci and Essam E.A. El-Zahab: *Power conditioning using dynamic voltage restorers under different voltage sag types* In: Journal of Advanced Research, Elsevier 2015.
[22] A. Hanif, M. A. Choudhry,: *Dynamic voltage regulation and power export in a distribution system using distributed generation* In: Journal of Zhejiang University Science, vol.10, no.10, pp-1523-1531, 2009.
[23] M. Sadoughipour, B. Vahidi, G. H. Riahy*: Modeling and simulation of a dynamic voltage Restorer for voltage sag mitigation and harmonics elimination* In: Sci. Int.(Lahore), vol.26, no-2, pp.627-631, 2014.
[24] Parag Kanjiya, Bhim Singh and P. Jayaprakash: *A robust control algorithm for self-supported dynamic voltage restorer (DVR) In:* India International Conference on Power Electronics (IICPE), pp. 1-8, IEEE 2011.
[25] H. Ezoji, A. Sheikholeslami, M. Tabasi and M. M. Saeedina : *Simulation of Dynamic Voltage Restorer Using Hysteresis Voltage Control* In: European Journal of Scientific Research, pp. 152-162, vol. 27, EuroJournals Publishing 2009.
[26] Gregory Arthur de Almeida Carlos, Cursino Brandao Jacobina and Euzeli Cipriano dos Santos: *Investigation on dynamic voltage restorer with two dc links and series converters for three phase four wire system* In: IEEE Transactions on Industry Applications, pp. 1608- 1620, vol.52, IEEE 2016.
[27] Tarek I. El-Shennawy, Abdel-Mon'em Moussa, Mahmoud A. El-Gammal and Amr Y. Abou-Ghazala: *A Dynamic Voltage Restorer for Voltage Sag Mitigation in a Refinery with Induction Motors Loads* In: American Journal of Engineering and Applied Sciences, pp. 144-151, Science Publications 2010.
[28] J. G. Nielsen and F. Blaabjerg : *A detailed comparison of system topologies for dynamic Voltage restorers* In: IEEE Transactions on Industry Applications, pp. 1272-1280, vol. 41, IEEE 2005.
[29] S. R. Reddy, P. V. Prasad and G. N. Srinivas: *Performance comparison of DVR by various methods* In: Power India International Conference (PIICON), pp. 1-6, IEEE 2014.
[30] Carl Nagi-man Ho, Henry S. H. Chung and Keith T. K. Au: *Design and implementation of a fast dynamic control scheme for Capacitor- Supported Dynamic Voltage Restorers* In: IEEE Transactions on Power Electronics, pp. 237-251, vol. 23, IEEE 2008.
[31] V. Jayalakshmi and N.O. Gunasekar, *: Implementation of discrete PWM control scheme on dynamic voltage restorer for the mitigation of voltage sag/swell In:* Energy Efficient Technologies for Sustainability (ICEETS) International Conference, pp.1036-1040, IEEE 2013.
[32] N. P. Kumar and Y. Pal: *Performance evaluation of three phase, three wire DVR for power quality improvement* In: Engineering and Systems (SCES), 2014 Students Conference, pp.1-6, IEEE 2014.
[33] A. Ghosh, A. Joshi: *A new algorithm for the generation of reference voltages of a DVR using the method of instantaneous symmetrical component*s In: Power Engineering Review, IEEE, vol.22, no.1, pp.63-65, IEEE 2002.
[34] F. B. Ajaei, S. Afsharnia, A. Kahrobaeian and S. Farhangi : *A fast and effective control scheme for the dynamic voltage restorer* In: IEEE Transactions on power delivery, vol. 26, no.4, pp.2398-2406, IEEE 2011.
[35] M. U. Cuma, A. Teke, M. E. Meral, K. C. Bayindir and M. Tumay,: *Implementation of a non-linear adaptive filter based sag detection method for dynamic voltage restorers under unbalanced fault condition* In: journal of Power Electronics, vol.13, no.2, 20013.
[36] A. M. Rauf and V. Khadkikar, : *An enhanced scheme for dynamic voltage restore*r In: IEEE transactions on industrial electronics, vol.62, no.5, pp.2683 – 2692, IEEE 2015.
[37] Yash Pal, A. Swarup and Bhim Singh*: A Review of Compensating Type Custom Power Devices for Power Quality Improvement*" In: Power System Technology and IEEE Power India Conference, pp. 1-8, IEEE 2008.
[38] Chi-Jen Huang, Shyh-Jier Huang, and Fu-Sheng Pai : *Design of dynamic voltage restorer with disturbance-filtering enhancement*" In: IEEE Transactions on Power Electronics, vol. 18, no. 5, pp.1202-1210, IEEE 2003.
[39] D. Mahinda Vilathgamuwa, A. A. D. Ranjith Perera, and S. S. Choi: *Voltage sag compensation with energy optimized dynamic voltage restorer* In: IEEE Transactions on Power Delivery, vol.18, no. 3, pp.928-936, IEEE 2003.
[40] Belkacem Mahdad, Tarek Bouktir and Kamel Srairthe : *Impact Of Unified Power Flow Controller In Power Flow Regulation* In: Journal of Electrical Engineering, vol. 6, 2016.

Biographies

Mr**. Amit Kumar** received the B.Tech (Electrical & Electronics Engineering) degree from the ABES. Institute of Technology Ghaziabad, Uttar Pradesh Technical University (UPTU), India, in 2012 and the M.Tech degree from the Gautam Buddha University (GBU) Greater Noida, Gautam Buddh Nagar, India, in 2016. His area of interest includes power quality, power electronics, renewable energy, FACTS, active filters and HVDC.

Mr**. Deepak Kumar** received the B.Tech (Electrical & Electronics Engineering) degree from the NIET College Greater Noida, Uttar Pradesh Technical University (UPTU), India, in 2013 and the M.Tech degree from the Gautam Buddha University (GBU) Greater Noida, Gautam Buddh Nagar, India, in 2016. His area of interest includes power quality, power electronics, renewable energy, image processing and HVDC.

Mr**. Abhay Yadav** received the B.Tech (Electrical & Electronics Engineering) degree from the GNIT College Greater Noida, Uttar Pradesh Technical University (UPTU), India, in 2013 and the M.Tech degree from the Gautam Buddha University (GBU) Greater Noida, Gautam Buddh Nagar, India, in 2016. His area of interest includes power quality, renewable energy, image processing and HVDC.