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Research Paper

VOLTAGE SAG AND SWELL COMPENSATION BY USING DVR WITH A BESS

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Power quality problems become a major anxiety of industries due to enormous loss in terms of time and money. In this paper, different voltage injection schemes for Dynamic Voltage Restorer (DVR's) are analyze with a particular focus on a different technologies for DVR to compensate the voltage sag, swell and harmonics. One of the most powerful FACTS devices is the DVR to alleviate the voltage sag and swell. The SRF theory has been used for estimating the reference DVR voltages by converting voltage from rotating vectors to stator vectors form. A comparison of the DVR with different schemes has been performed with a PWM controlled VSC and SVPWM controlled VSC of DVR. In the simulink model the In-Phase compensation technique for voltage quality improvement is used.

Keywords: Dynamic Voltage Restorer (DVR), Power quality, Unit vector, SVPWM, Voltage harmonics, Voltage sag, Voltage swells

INTRODUCTION

Power quality problems in the present-day distribution systems are addressed in the literature due to the increased use of sensitive and critical equipment pieces such as communication network, process industries, and precise manufacturing processes. Power quality problems such as transients, sags, swells, and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Custom power devices are mainly of three categories such as series-connected compensators known as Dynamic Voltage Restorers (DVRs), shunt-connected compensators such as distribution static compensators, and a combination of series and shunt-connected compensators known as unified power quality conditioner. The DVR can regulate the load voltage from the problems such as sag, swell, and harmonics in the supply voltages. Hence, it can protect the critical consumer loads from tripping and consequent losses. The custom power devices

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are developed and installed at consumer point to meet the power quality standards such as IEEE-519.

Voltage sags in an electrical grid are not always possible to avoid because of the finite clearing time of the faults that cause the voltage sags and the propagation of sags from the transmission and distribution systems to the low-voltage loads. Voltage sags are the common reasons for interruption in production plants and for end-user equipment malfunctions in general. In particular, tripping of equipment in a production line can cause production interruption and significant costs due to loss of production. One solution to this problem is to make the equipment itself more tolerant to sags, either by intelligent control or by storing "ride-through" energy in the equipment. An alternative solution, instead of modifying each component in a plant to be tolerant against voltage sags, is to install a plant wide uninterruptible power supply system for longer power interruptions or a DVR on the incoming supply to mitigate voltage sags for shorter periods. DVRs can eliminate most of the sags and minimize the risk of load tripping for very deep sags, but their main drawbacks are their Standby losses, the equipment cost, and also the protection scheme required for downstream short circuits. Many solutions and their problems using DVRs are reported, such as the voltages in a three-phase system are balanced and an energy-optimized control of DVR is discussed. Industrial examples of DVRs are given in, and different control methods are analyzed for different types of voltage sags in. A comparison of different topologies and control methods is presented for a DVR in. The design of a capacitor-supported DVR that protects sag, swell, distortion, or unbalance in the supply voltages is discussed in. The performance of a DVR with the high-frequency-link transformer is discussed in. In this paper, the control and performance of a DVR are demonstrated with a reduced-rating Voltage Source Converter (VSC). The Synchronous Reference Frame (SRF) theory is used for the control of the DVR.

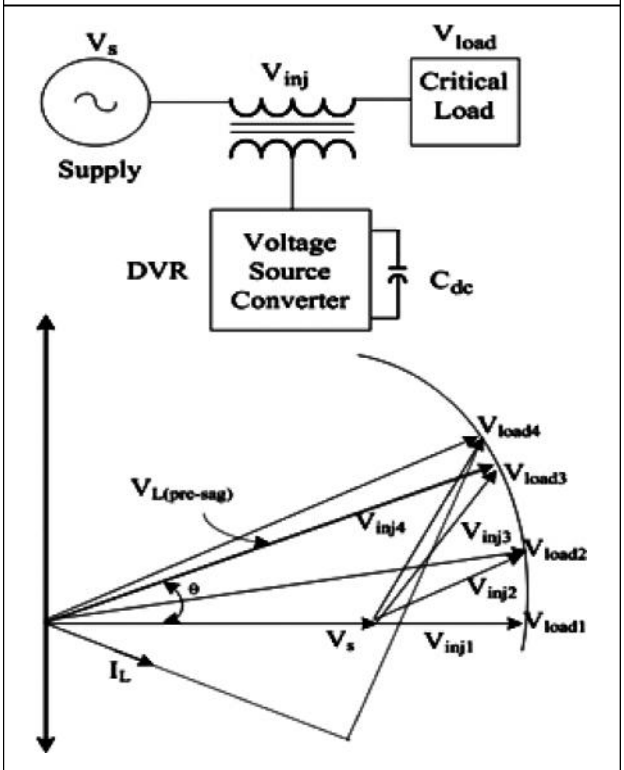
OPERATION OF DVR

The schematic of a DVR-connected system is shown in Figure 1a. Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as; DVR power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angel jump and some are sensitive towards change in magnitude and others are tolerant to these. Therefore the control strategies depend upon the type of load characteristics. The voltage V_{inj1} is inserted such that the load voltage V_{load} is constant in magnitude and is undistorted, although the supply voltage V_s is not constant in magnitude or is distorted. Figure 1b shows the phasor diagram of different voltage injection schemes of the DVR. $V_{L(pre\text{-}sag)}$ is a voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced to V_s with a phase lag angle of ¯. Now, the DVR injects a voltage such that the load voltage magnitude is maintained at the pre-sag condition.

According to the phase angle of the load voltage, the injection of voltages can be realized in four ways. V_{inj1} represents the voltage injected in-phase with the supply voltage. With the injection of V_{inj2}, the load voltage magnitude remains same but it leads *Vs* by a small angle. In V_{inj3}, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source. V_{inj4} is the condition, which may be an optimum angle considering the energy source. V_{inj4} is the condition where the injected voltage is in quadrature with the current, and this case is suitable for a capacitor-supported DVR as this injection involves no active power. However, a minimum possible rating of the converter is achieved by V_{inj1}. The DVR is operated in this scheme with a Battery Energy Storage System (BESS).

Figure 2 shows a schematic of a three-phase DVR connected to restore the voltage of a three-phase critical load. A three-phase supply is connected to a critical and sensitive load through a three-phase series injection transformer. The equivalent voltage of the supply of phase A V_{Ma} is connected to the Point of Common Coupling (PCC) V_{Ma} through short-circuit impedance Z_{Sa}. The voltage injected by the DVR in phase A V_{Ca} is such that the load voltage V_{La} is of rated magnitude and undistorted. A three-phase DVR is connected to the line to inject a voltage in series using three single-phase transformers T_r, L_r, and C_r represent the filter components used to filter the ripples in the injected voltage. A three leg VSC with Insulated-Gate Bipolar Transistors (IGBTs) is used as a DVR, and a BESS is connected to its dc bus.

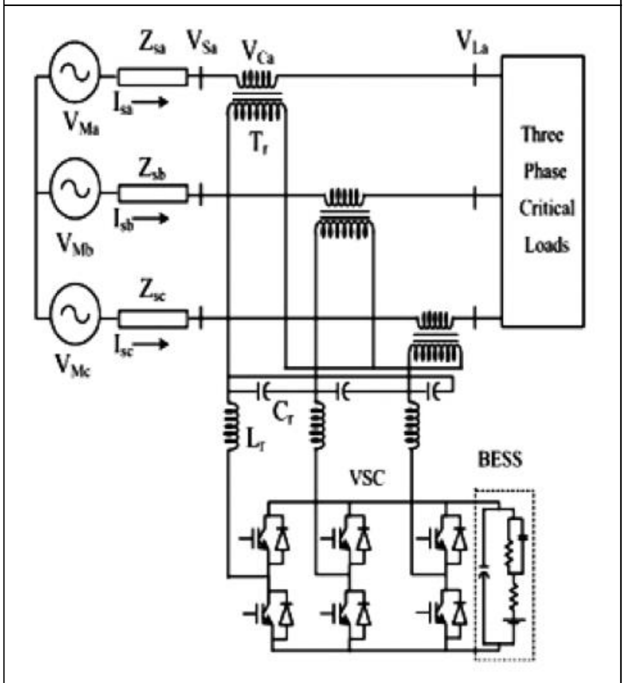
Figure 1: (a) Basic Circuit of DVR, (b) Phasor Diagram of the DVR Voltage Injection Schemes



CONTROL OF DVR

The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power.

Figure 2: Schematic of the DVR-Connected System



When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power and the DVR is with a self-supported dc bus. However, if the injected voltage is inphase with the current, DVR injects real power, and hence, a battery is required at the dc bus of the VSC. The control technique adopted should consider the limitations such as the voltage injection capability (converter and transformer rating) and optimization of the size of energy storage.

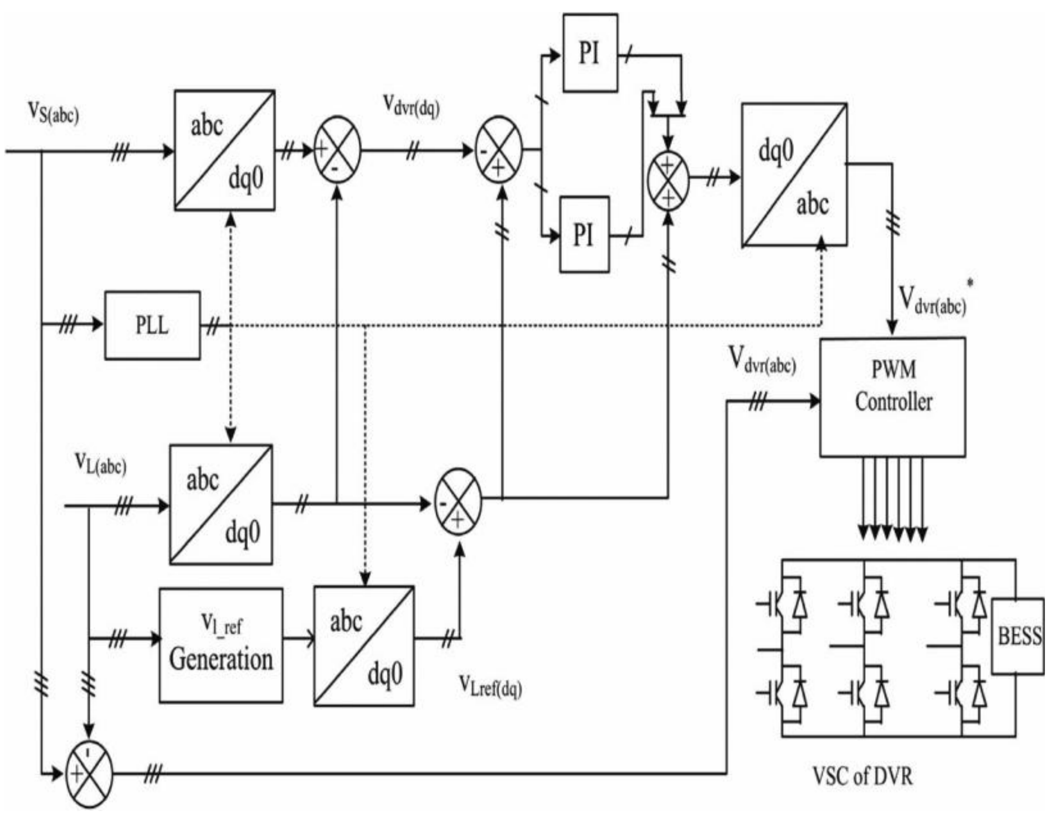
Control of DVR With PWM Technique and BESS for Voltage Sag, Swell and Harmonics Compensation

Figure 3 shows a control block of the DVR in which the SRF theory is used for reference signal estimation. The voltages at the PCC V_s and at the load terminal V_L are sensed for deriving the IGBT's gate signals. The reference load voltage V_L^* is extracted using the derived unit vector Load voltages (V_{La}, V_{Lb}, V_{Lc}) are converted to the rotating reference frame using *abc–dqo* conversion using Park's transformation with unit vectors (sin, ¯, cos, ¯) derived using a phase-locked loop as

$$\begin{bmatrix} v_{Lq} \\ v_{Ld} \\ v_{Lo} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{Lqref} \\ v_{Ldref} \\ v_{Loref} \end{bmatrix} \quad ...(1)$$

Similarly, reference load voltages (V_{La}^*, V_{Lb}^*, V_{Lc}^*) and voltages at the PCC V_s are also converted to the rotating reference frame.

Figure 3: Control Block of the DVR that Uses the SRF Method of Control



Then, the DVR voltages are obtained in the rotating reference frame as

$$v_{Dd} = v_{Sd} - v_{Ld} \quad ...(2)$$

$$v_{Dq} = v_{Sq} - v_{Lq} \quad ...(3)$$

The reference DVR voltages are obtained in the rotating reference frame as

$$v^*_{Dd} = v^*_{Sd} - v_{Ld} \quad ...(4)$$

$$v^*_{Dq} = v^*_{Sq} - v_{Sq} \quad ...(5)$$

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two Proportional-Integral (PI) controllers.

Reference DVR voltages in the *abc* frame are obtained from a reverse Park's transformation taking V_{Dd}* from (4), V_{Dq}* from (5), V_{Do}* as zero as

$$\begin{bmatrix} v^*_{dvra} \\ v^*_{dvrb} \\ v^*_{dvrc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v^*_{Dq} \\ v^*_{Dd} \\ v^*_{Do} \end{bmatrix} \quad ...(6)$$

Reference DVR voltages (V_{dvra}*, V_{dvrb}*, V_{dvrc}*) and actual DVR voltages (V_{dvra}*, V_{dvrb}*, V_{dvrc}*) are used in a pulse width modulated (PWM) controller to generate gating pulses to a VSC of the DVR. The PWM controller is operated with a switching frequency of 10 kHz.

Control of DVR with SVPWM and BESS for Voltage Sag, Swell, and Harmonics Compensation

Comparison of Sinusoidal PWM and Space Vector PWM

- In the Figure 4 below, U is the phase-to-center voltage containing the triple order harmonics that are generated by space vector PWM, and U1 is the sinusoidal reference voltage. But the triplen order harmonics are not appeared in the phase-to-phase.
- SPWM only reaches to 78% of square-wave operation, but the amplitude of maximum possible voltage is 90% of square-wave in the case of space vector PWM. The maximum phase-to-center voltage by sinusoidal and space vector PWM are respectively. voltage as well. This leads to the higher modulation index compared to the SPWM.

Vmax = Vdc/2: for Sinusoidal PWM; And

Vmax = Vdc/Ě3, where, V_{dc} is DC-Link voltage: for Space Vector PWM

SVPWM control strategy is to adopt a space vector of the inverter voltage to get better performance of the exchange is gained in low switching frequency conditions. Carrier based SVPWM allow fast and efficient implementation of SVPWM without sector determination. The technique is based on the duty ratio profiles that SVPWM exhibits (as shown in Figure 6). By comparing the duty ratio profile with a higher frequency triangular carrier the pulses can be generated, based on the same arguments as the sinusoidal pulse

Figure 4: Phase-to-Center Voltage by Space Vector PWM

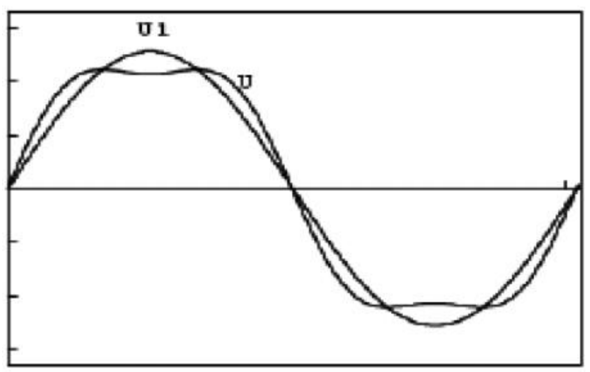
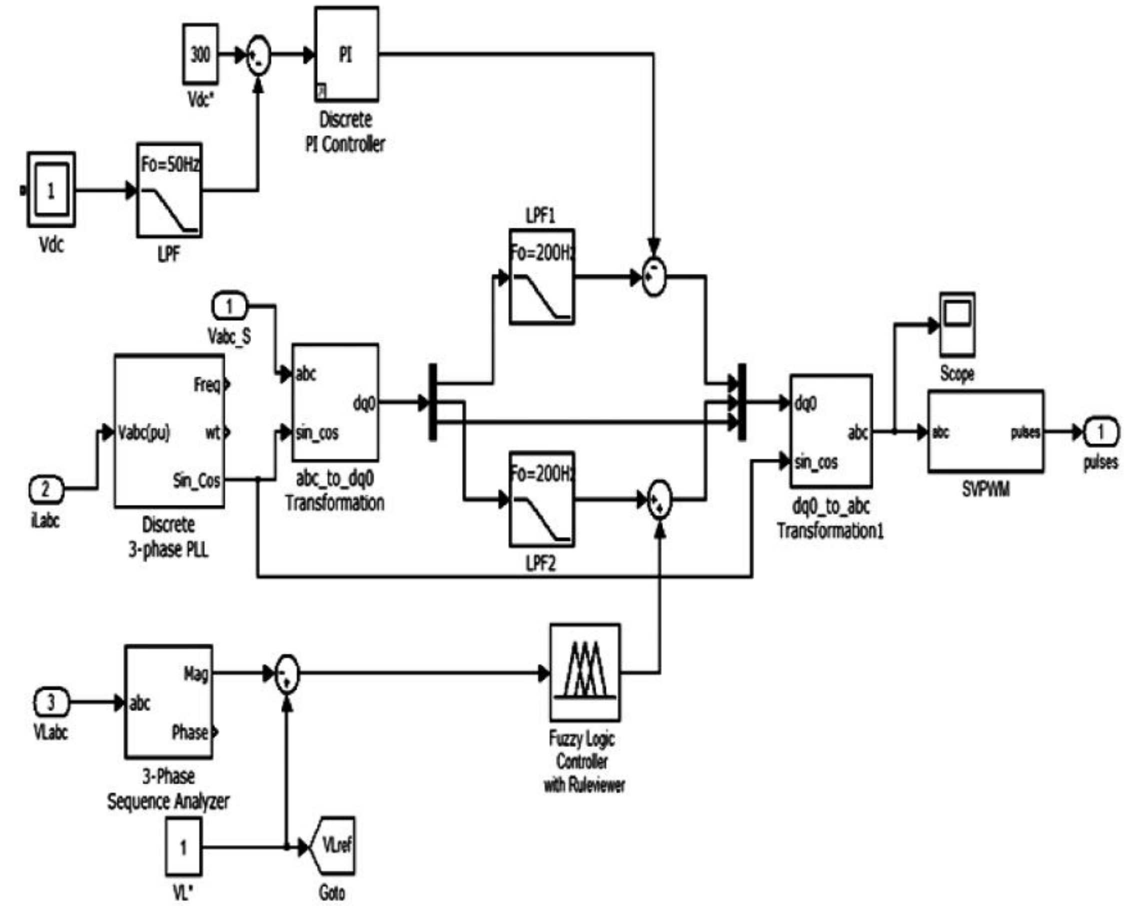


Figure 5: SRF Control for VSC by Using SVPWM and FUZZY Techniques



width modulation. Figure 5 shows a control model of the DVR in which the SRF theory is used for the control of DVR with SVPWM technique and fuzzy controller. In this paper we introduce a fuzzy logic controller in place of PI controller of Vdc error generator.

The fuzzy controller used in this voltage reference generator has '7' input membership functions and seven ouput membership function. The membership functions can be seen in Figure 7. By using the fuzzy logic tracking error and transient overshoots of SVPWM can be considerably reduced. Voltages at the PCC V_S are converted to the rotating reference frame using *abc–dqo*

Figure 6: SVPWM Gate Pulse Signals to the VSC

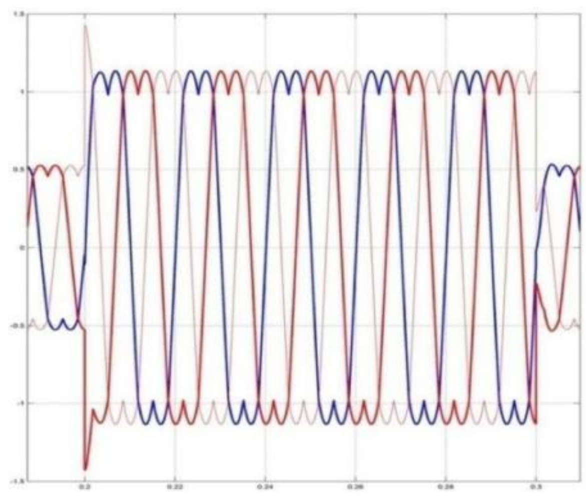
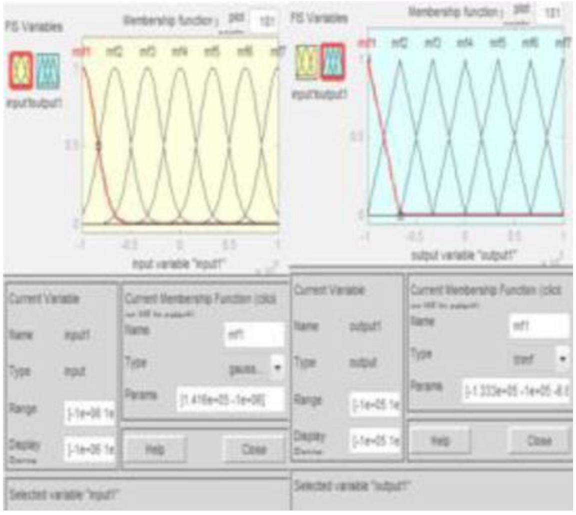


Figure 7: Fuzzy Input and Output Membership Functions



conversion using Park's transformation. The harmonics and the oscillatory components of the voltage are eliminated using lowpass filters (LPFs). The components of voltages in the *d*- and *q*-axes are

$$v_d = v_{ddc} + v_{dac} \quad ...(7)$$

$$v_q = v_{qdc} + v_{qac} \quad ...(8)$$

In this method the VSC is controlled by Space Vector PWM. Space Vector generated pulses to the VSC by the following equation.

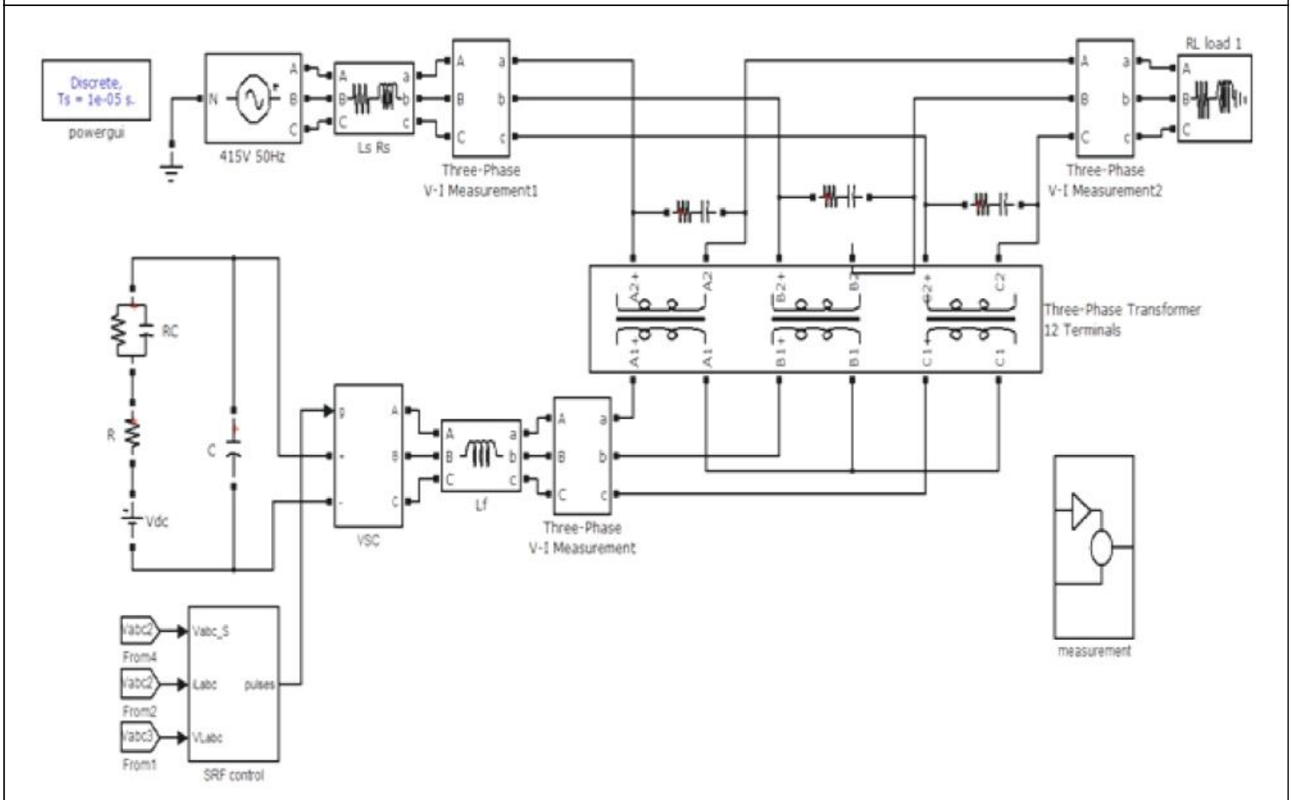
$$V_{SVPWM} = \frac{2}{\sqrt{3}}\left(V_{abc} - \frac{(V_{max}+V_{min})}{2}\right) \quad ...(9)$$

where $\frac{Vmax+Vmin}{2}$ is the offset voltage

Space Vector PWM can produce about 15% higher than Sinusoidal PWM in output voltage.

The compensating strategy for compensation of voltage quality problems consider that load terminal voltage should be of rated magnitude and undistorted.

Figure 8: MATLAB-Based Model of the BESS-Supported DVR-Connected System



MODELING AND SIMULATION

The DVR-connected system consisting of a three-phase supply, three-phase critical loads, and the series injection transformers shown in Figure 2 is modeled in MATLAB/Simulink environment along with a sim power system toolbox and is shown in Figure 8. An equivalent load considered is a 10-kVA 0.8-pf lag linear load. The parameters of the considered system for the simulation study are given in the Appendix. The performance of the PWM controlled and SVPWM controlled DVR is demonstrated for different supply voltage disturbances such as voltage sag and swell in Figures 10 and 11 respectively. Figures 10 and 11 shows the transient performance of the system under voltage sag and voltage swell conditions. At 0.2 s, a sag in supply voltage is created for five cycles, and at 0.4 s, a swell in the supply voltages is created for five cycles. It is observed that the load voltage is regulated to constant amplitude under both sag and

Figure 9: Fuzzy Rule Identification

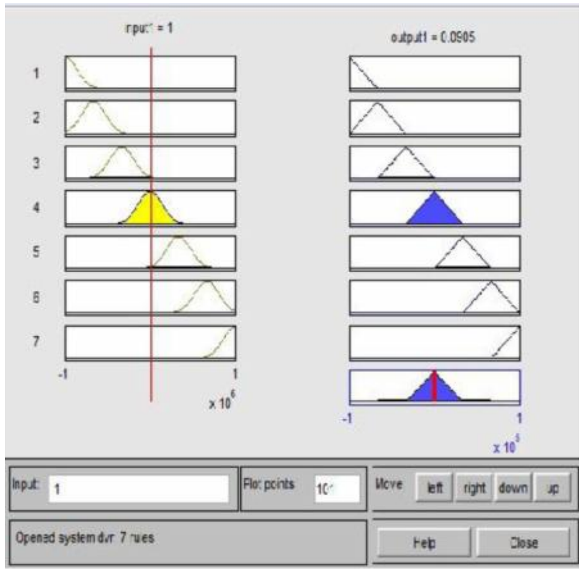


Figure 10: Dynamic Performance of PWM Controlled DVR with In-Phase Injection During Voltage Sag and Swell Applied to Critical Load

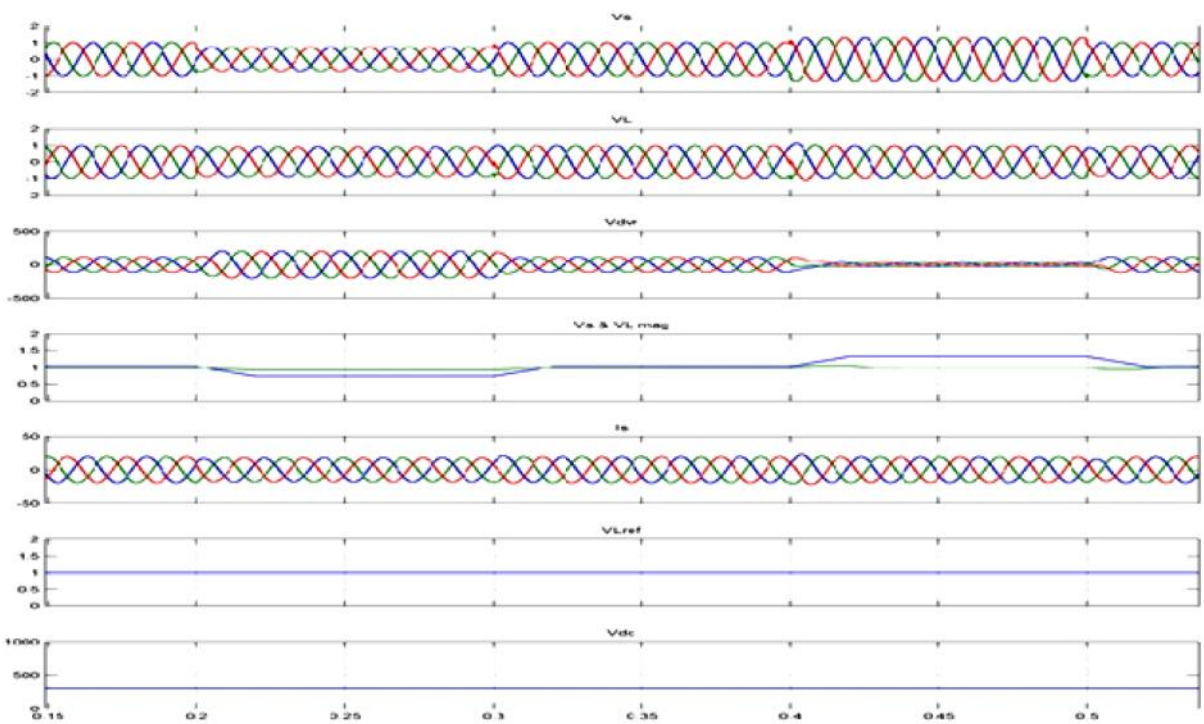


Figure 11: Dynamic Performance of SVPWM Controlled DVR with In-Phase Injection During Voltage Sag and Swell Applied to Critical Load

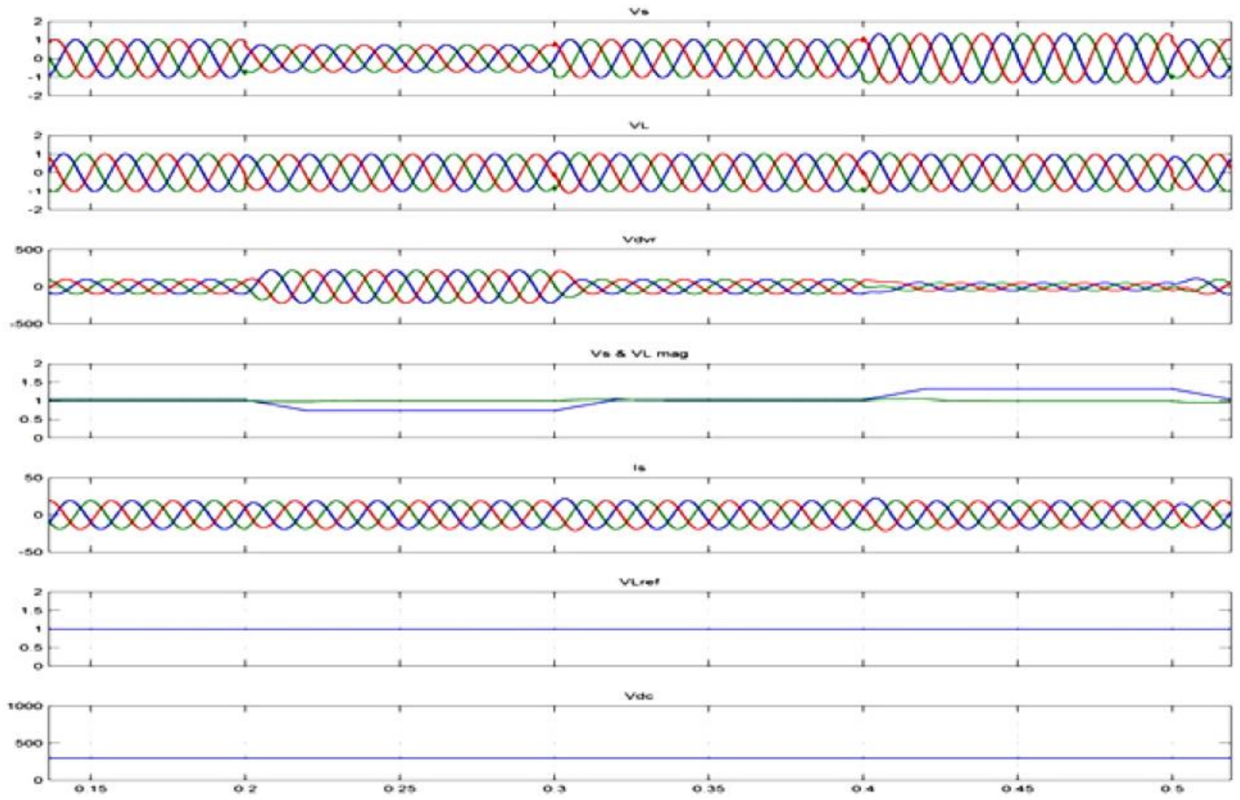
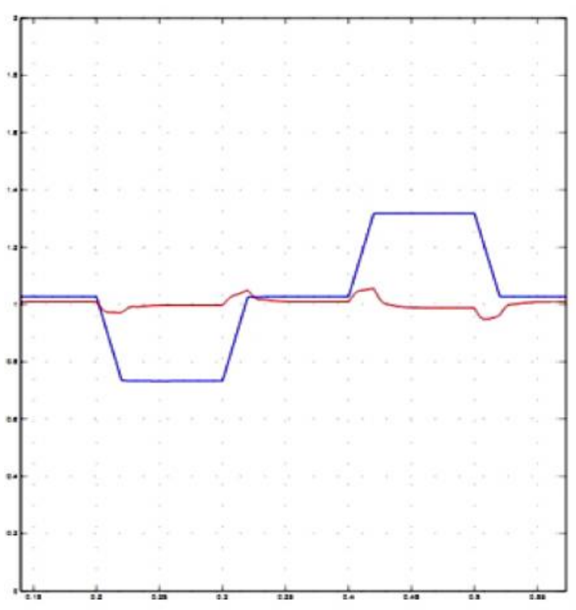


Figure 12: Voltage Magnitude at the PCC and Load During Sag and Swell



swell conditions PCC voltages V_S load voltages V_L DVR voltages V_C, amplitude of load voltage V_L and PCC voltage V_S source currents i_S reference load voltages V_{Lref}, and dc bus voltage V_{dc} are also depicted in Figure 11. The load and PCC voltages of phase A are shown in Figure 12, which shows the in-phase injection of voltage by the DVR.

The load voltage is maintained sinusoidal by injecting proper compensation voltage by the DVR. The Total Harmonics Distortions (THDs) of the voltage at the PCC, supply current, and load voltage are shown in Figures 14 and 15, respectively.

It is observed that the load voltage THD is the level of 0.60% for PWM controlled DVR and the load voltage THD is the level of 0.64%

Figure 13: Comparison of Output Compensation Voltages Between Sinusoidal PWM and SVPWM Techniques During Sag and Swell

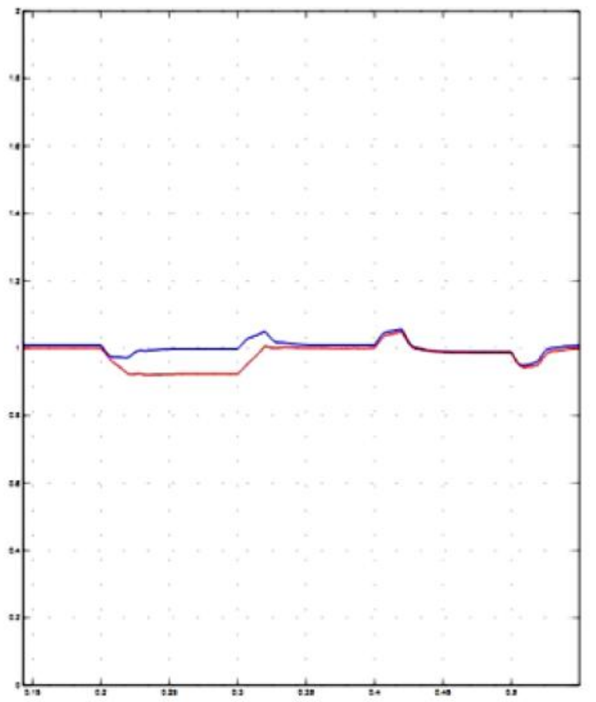


Figure 14: THD for PWM Controlled DVR

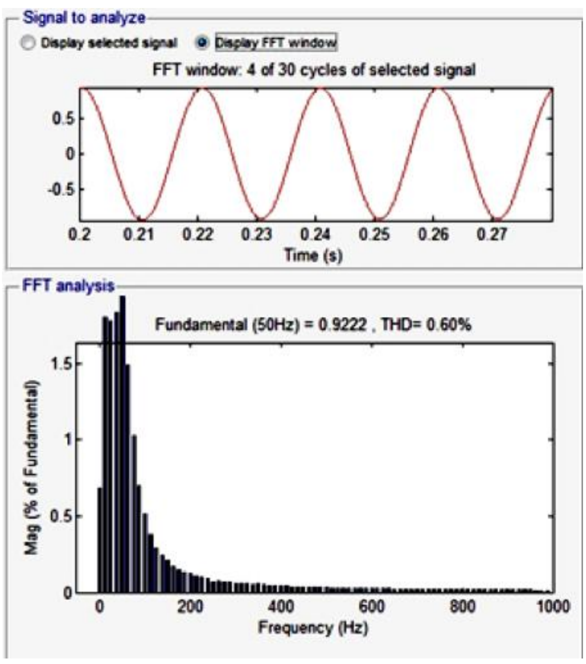


Figure 15: THD for SVPWM Controlled DVR

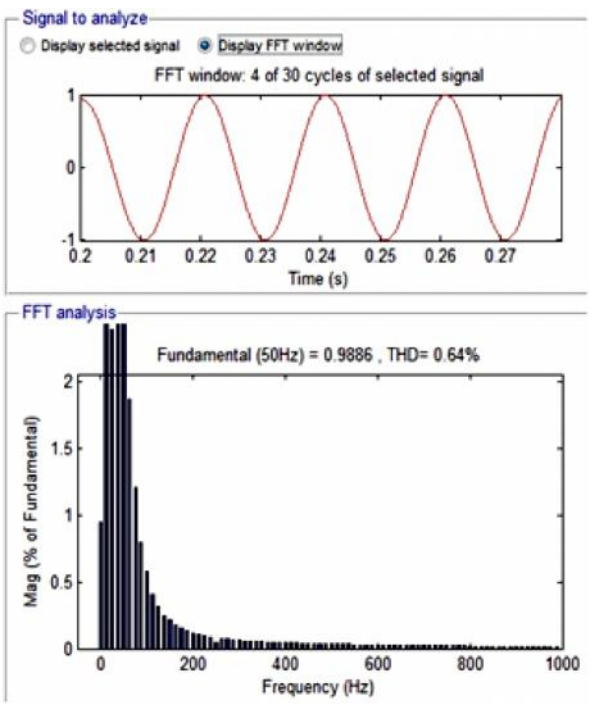


Table 1: Comparison of DVR Rating for Sag Mitigation

	Scheme-1	Scheme-2	Scheme-3	Scheme-4
Phase Voltage (V)	90	100	121	135
Phase Current (A)	13	13	13	13
VA per phase	1170	1300	1573	1755
KVA (% of Load)	37.5%	41.67%	50.42%	56.25%

for the SVPWM controlled DVR. The compensation of voltage by using SVPWM controlled DVR is much better than PWM controlled DVR but in point of THD the SVPWM controlled DVR is little lesser in the range of 0.04%. The magnitudes of the voltage injected by the DVR for mitigating the same kinds of sag in the supply with different angles of injection are observed. The injected voltage, series current, and kilovoltampere ratings of the DVR for the four injection schemes are given in Table 1. In Scheme-1 in Table 1, the in-phase injected voltage is V_{inj1} in the phasor diagram in Figure 1. In Scheme-2, a DVR voltage is injection at a small angle of 30%, and in Scheme-3, the DVR voltage is injected at an angle of 45°.

The injection of voltage in quadrature with the line current is in Scheme-4.

The required rating of compensation of the same using Scheme-1 is much less than that of Scheme-4. The injected voltage is higher compared with an inphase injected voltage (Scheme-1).

When a deep sag occurs in the line the PWM controlled DVR only compensate minimum level of voltage in the line where as SVPWM controlled DAR can compensate the voltage if the level of sag is more is shown in the Figure 13.

The fuzzy rule identification as follows in Figure 9.

SUMMARY

In this chapter we have seen simulink model designed and the corresponding results are obtained for the proposed system.

CONCLUSION

In this paper, study and performance of DVR for mitigating the voltage sags/swell in distribution power systems is presented. The various techniques show that the DVR is suitable for compensation of voltage sag and swell with the help of these different controlling techniques which are discuses in this paper. The controlling of DVR is simpler as compared to other customs power devices. A comparison of the performance of the DVR with different schemes has been performed with a PWM controlled VSC and SVPWM controlled VSC of DVR are illustrated. The reference load voltage has been estimated using the method of unit vectors, and the control of DVR has been achieved, which minimizes the error of voltage injection. The SRF theory has been used for estimating the reference DVR voltages. The controlling of DVR is simpler as compared to other customs power devices.

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APPENDIX

AC line voltage: 415 V, 50 Hz

Line impedance: Ls = 3.0 mH, Rs = 0.01 Ω

Linear loads: 10-kVA 0.80-pf lag

Ripple filter: Cf = 10 μF, Rf = 4.8 Ω

DVR with BESS

DC voltage of DVR: 300 V

AC inductor: 2.0 mH

Gains of the *d*-axis PI controller: $Kp1$ = 0.5, $Ki1$ = 0.35

Gains of the *q*-axis PI controller: $Kp2$ = 0.5, $Ki2$ = 0.35

PWM switching frequency: 10 kHz

DVR with dc bus capacitor supported

DC voltage of DVR: 300 V

AC inductor: 2.0 mH

PWM switching frequency: 10 kHz

Series transformer: three-phase transformer of rating 10 kVA, 200 V/300 V