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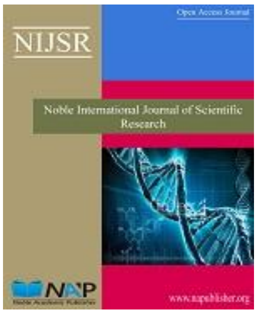

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Voltage Sag Matigation in Distribution Network by Dynamic Voltage Restorer

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Abstract: Presently, most power quality issues in distribution networks are identified by voltage sags. Therefore, various solutions have been attempted to mitigate these voltage sags in the distribution network in order to avoid economic losses. Dynamic voltage restorers (DVRs) are being more recognized in distribution networks in reducing the effect of voltage sags to critical loads. The DVR, which is arranged in series with a critical load, must have capability to generate and absorb the active and reactive power from the system. In this paper, a dynamic voltage restorer is modelled based on Cascaded double-loop vector control method for voltage sag mitigation. The proposed approach is to illustrate these by an example of a real Pakistani distribution system. A feeder of Gulzar colony Hyderabad is modelled in Matlab/Simulink software for power quality analysis and simulations are carried out to verify the results.

Keywords: Power Quality, Voltage Sag, Custom Power Devices, Dynamic Voltage Restorer (DVR), Vector Control Method.

1. Introduction

Power quality is of significant importance in the electricity supply system due to its impacts on both industrial and commercial consumers as well as on domestic electrical consumers. In many ways, electricity consumers are gravely affected by problems of poor power quality. It results in malfunction or damage of electrical appliances, increased power losses, loss of production and interference with communication circuits, etc. [1, 2]. IEEE defines the power quality problem as "Any power disturbance that may appear as a change in the current, voltage or frequency waveform that results in malfunction or failure of sensitive equipment." Many power quality problems are currently being addressed to the distribution network, such as voltage spikes, surges, drops, momentary interruptions and harmonic distortions in which the most dangerous and frequent problem of power quality is the collapse of the voltage [3]. The voltage drop is a very serious disturbance that produces a sudden and unexpected reduction of the voltage but not a complete disruption of a power, it is a momentary drop of the nominal voltage value below 90%, plus most of the depths of the sag vary from 50% to 90% of the normal voltage value and for a duration of 10 ms to a few seconds or from 50 to 170 milliseconds [4]. Short circuits, sudden change of load, activation of the transformer and the starting of a larger motor are the main sources that cause the voltage sag. Towards voltage change, electrical and electronic equipment such as microprocessor based controllers, variable speed drives and computers are very sensitive [3].

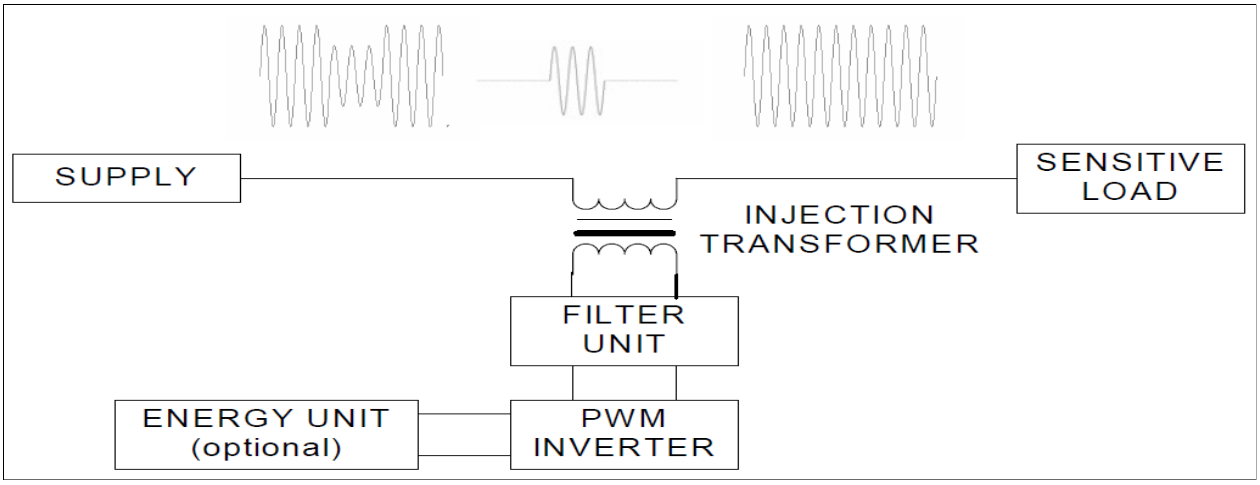
Power electronic technology based custom power devices are found to be the most effective and economical as compared to other conventional devices. Hingorani was the first to propose the custom power concept in 1995. Custom power devices of different types are used to improve power quality issues such as Dynamic Voltage Restorer (DVR), Uninterruptible Power Supplies (UPS), Distribution Static Compensators (DSTATCOM), Static Var Compensator (SVC) and Unified Power Quality Capacitor (UPQC) are some of them [1, 5]. Each of them has its own advantages and limitations. Among them DVR is considered as the most effective and efficient, economical, results oriented, technically forward and advanced device to mitigate voltage sag. DVR has the ability to inject voltage at the coupling point (PPC) in order to maintain the nominal value of the voltage across the load. It is also equipped with additional functions such as reactive power compensation and mitigation of harmonic distortions.

In Pakistan, even in major urban communities such as Hyderabad and Karachi day-to-day power outages, some of them last for a few hours, voltage drops, transients over voltages and momentary distortions are persistently present. In this paper DVR is used to improve the power quality of any particular feeder in the Pakistani distribution system, i.e. Gulzar Colony, Hyderabad. DVR operating characteristics and its structural diagram are explained in section II while in section III; different DVR voltage compensation techniques are explained. Section IV details on the proposed control technique for DVR. Finally, the MATLAB / Simulink software is used to perform the simulations in order to verify the effectiveness of the control strategy used in DVR.

2. DVR Configuration and Its Operation

A DVR is power electronic based series compensator that has been designed to safeguard the sensitive and critical electrical loads from almost all supply-side disturbances such as voltage immersion, flicker and swell in the system voltages, harmonics distortion, etc. DVR operation is divided into three modes [3] which are standby mode, pulse mode and protection mode. Under normal operating conditions, the supply side and load side voltage will remain the same so that the DVR does not insert any voltage into the system and operate in standby mode. In protection mode, bypass switches are used to protect the DVR from overcurrent due to the occurrence of a fault or a short circuit in the load. In the boost or injection mode, the DVR will go into operation and inject the voltage necessary for the system to return it to its normal state. DVR will absorb the reactive power of the supply in case of swell of the voltage, while for the sag voltage will supply reactive power to the load [6, 7]. DVR is generally linked between the primary distribution feeder and the sensitive electrical load as shown in figure 1.

Figure 1. Systematic Diagram of DVR.



DVR circuit mainly consists of two parts

a) Power circuit
b) Control circuit

Control unit is the essential part of the DVR. It used to detect the sag voltage in the distribution system and to vary the parameters such as phase shift, magnitude and frequency of compensating voltage to be injected by the DVR while the Power circuit consists DVR main components of DVR such as Voltage Source Converter (VSC), energy storage unit, harmonic filter and injection transformer.

2.1. Voltage Source Converter (VSC)

Power electronic based voltage source converter consists of switching and storage devices i.e. battery. At the input, the low impedance stiff DC power supply is used to energize the VSI. It is used to produce missing voltage at any required magnitude, frequency and phase angle. VSI output variation can be minimized using capacitor. For three-phase DVR two common inverter connections are Graetz bridge inverter and neutral point clamp inverter while for single-phase DVR H-bridge inverter is common method.

2.2. Energy Storage Unit

During the heavy fault condition, energy storage devices are needed to deliver active energy to the load so that the system voltage can be restored. Flywheel or Super-capacitors, SMES and lead-acid batteries are examples of energy storage devices. Several methods are used to charge the Dc link such as the use of an external power supply or to maintain the DC voltage; the DC side of the DVR must be connected to the controlled or uncontrolled rectifier. The capacity of the energy storage unit required for DVR depends on the depth and duration of the sag voltage.

2.3. Filter Circuit

Since semiconductor devices have non-linear characteristics, the output of the inverter is distorted and contains many unwanted harmonic components. Therefore, at the output of the DVR inverter, the LC filter circuits are used to filter the harmonics generated by VSI. The depths of sag voltage to be compensated and the load voltage are the main aspects to design the filter parameters. The basic types of filtering scheme used in DVR circuits are side filtration and inverter side filtration.

2.4. Injection Transformer

The three single phase injection transformer is always connected in series with the distribution system. When the fault occurs in the system, the system voltage will drop below the nominal value, and then the DVR will insert the necessary voltage required through the injection transformer. It is also used to isolate and link the DVR to the distribution network. To ensure maximum efficiency and reliability of the injection transformer, it is necessary to select the correct transformer electrical parameters. In order to properly connect the injection transformer to the DVR system, the values of current ratings, MVA ratings, the turn ratio, short-circuit impedance and primary voltage winding are required

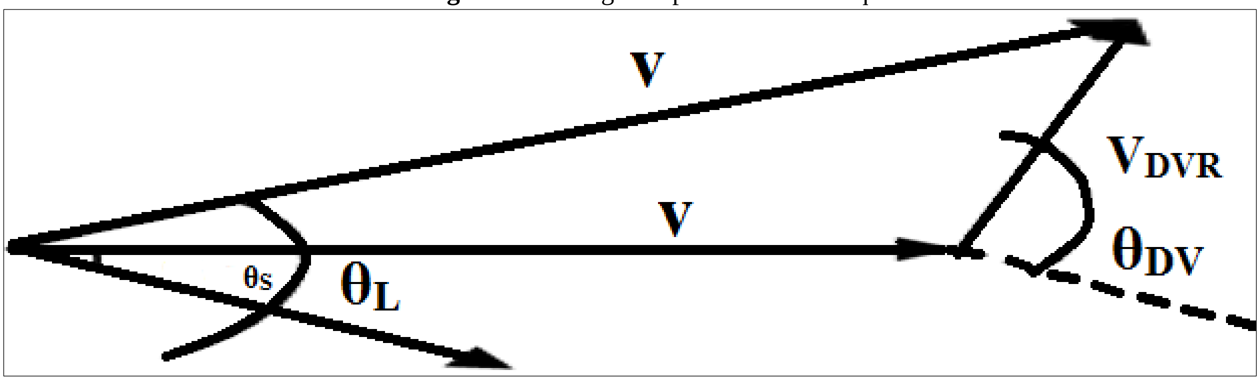
3. Voltage Sag Compensation Techniques in DVR

Different types of voltage drops, various load conditions and power rating of DVR are the factors on which DVR compensation methods depends. Some of the loads are delicate to fluctuations of magnitude while some are delicate towards the phase jump and others are unaffected by these. Therefore, the compensation methods will vary as the load characteristics change. Compensation techniques are divided into four types depending on the load requirement and its characteristics. Generally the change in magnitude and phase angle of the system voltage states as sag voltage. Therefore, the voltage compensation technique must be selected such that it satisfies both the magnitude and the phase angle of the voltage.

3.1. Pre-Sag Compensation Method

In this method, the supply voltage is monitored continuously whenever there is a disturbance in the supply voltage the DVR makes up for the loss voltage, so that the system voltage can be reset to its nominal value again. In this method, both the phase angle and the magnitude of the sag voltage can be compensated. In addition, it is difficult to regulate the injected active power which is determined by external characteristics such as load conditions and types of fault.

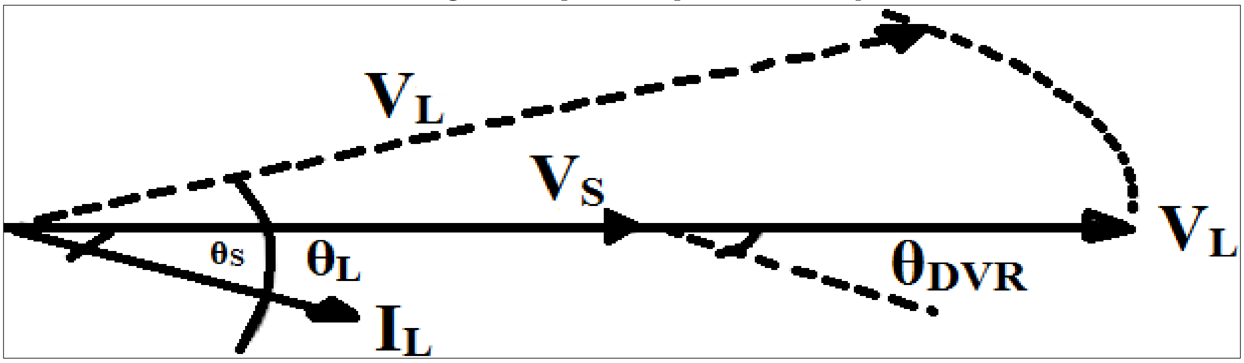
Figure 2. Pre Sag Compensation Technique.



3.2. In Phase Voltage Compensation Method

This method is only used to compensate for the magnitude of the sag voltage. As phase angle compensation is not required so this method is only used in linear loads. It is more efficient than the pre-sag compensation method because any type of voltage drop can be offset by it. In this method, the supply voltage and the compensation voltage are in the same phase regardless of the load current and the pre-fault voltage. Compared to other types it is relatively better because the magnitude of the compensation voltage is lower.

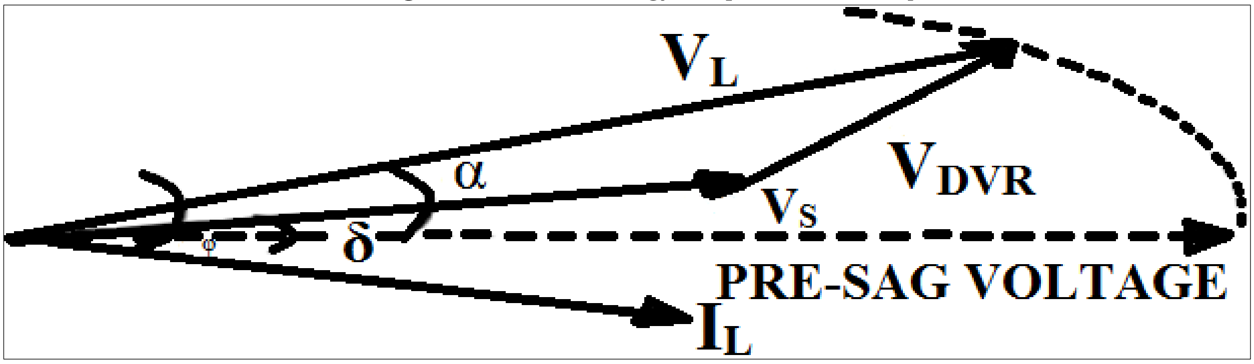
Figure 3. In phase compensation technique.



3.3. Minimum Energy Compensation Method

In this method, real power spent by DVR can be lowered to the maximum level by decreasing the angle between the load current and the sag voltage. In the system, the values of the load current and the load voltage always remain the same, therefore only the phase angle of the sag voltage can be modified. The main disadvantage of this method is that it only uses reactive power for sag compensation since not all voltage sags are offset without using active power so that it is only used to mitigate specific types of sags.

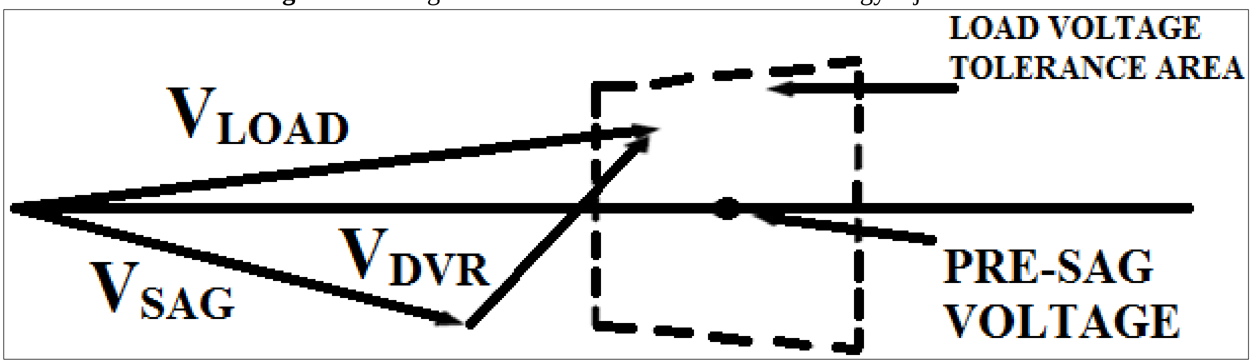
Figure 4. Minimum energy compensation technique.



3.4. Voltage Tolerance Method with Minimum Energy Injection

The load itself can tolerate small changes in magnitude as well as in phase angle of the system voltage. Generally the phase angle between 5%-10% of nominal state and the voltage magnitude between 90%- 110% of normal voltage does not affect the operational characteristics of load. With small change in magnitude, this method can maintain the voltage across the load within the tolerance area.

Figure 5. Voltage tolerance method with minimum energy injection.

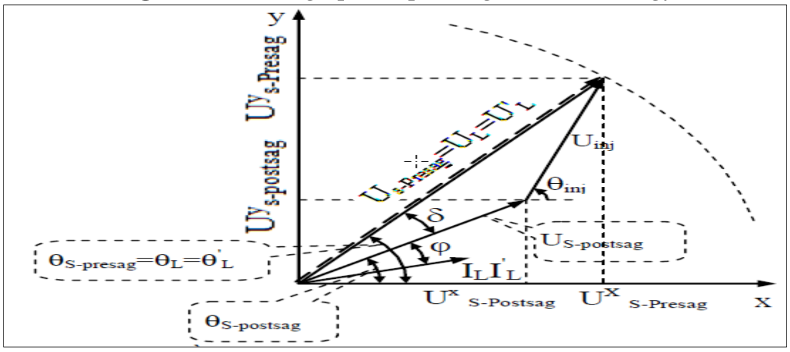


4. Proposed Control Strategy

4.1. "Pre-sag" Control Method

The load-side voltage U'_L after restoration is assumed to be in-phase with this pre-sag voltage $U_{S\text{-}Presag}$. Figure 6 shows the principle of the control method.

Figure 6. Vector graph of 'pre- sag' control strategy



In figure 6, the vector graph shows the principle of the "pre-sag" approach. When the system is operating under normal conditions, the magnitude of the supply voltage U_s is defined as the pre-set voltage and is denoted by the $U_{S\text{-}presag}$ symbol. In this case, the DVR does not insert any voltage into the grid, the U_L load voltage and the supply voltage will be considered equal. When a recessed voltage event occurs, the magnitude and phase angle of the supply voltage can be varied and referred to as the voltage while the concave is denoted as $|U_{spost,\ sag}|$, as the DVR operates and creates a voltage $|U_{inj}|$ to insert into the grid, this voltage is called the input voltage and is denoted U_{inj}. If the concave voltage is compensated by the DVR, the load voltage will be equal to the voltage before the $U_{S\text{-}presag}$.

In figure 6, the vector is denoted as follows: $U_{s\text{-}Postsag}$ is the source voltage vector while the sag, $U_{S\text{-}Presag}$ is the source voltage vector before sag, U_{inj} is the voltage vector inserted by DVR, U_L is the electrical vector rated load, U_L "is the voltage vector after the load is restored, I_L is the load current; I_L "load current after recovery, $\theta_{S\text{-}postsag}$ is phase angle while concave, $\theta_{S\text{-}Presag}$ is phase angle before concave, θ_{inj} angle of input voltage of DVR, δ phase jump angle while concave ($\delta = \theta_{S\text{-}postsag} - \theta_{S\text{-}Presag}$).

The "pre sag" method is capable of compensating for both voltage and phase angle. In this technique, the U_{inj} voltage generated by the DVR is calculated in two cases:

- In case of voltage sag there is no phase angle shift $\delta = 0$ voltage amplitude U_{inj} equals sign Between magnitude of source voltage before concave $U_{S\text{-}presag}$ and source voltage while concave $U_{S\text{-}postsag}$

$$|U_{inj}| = |U_{s\text{-}presag}| - |U_{s\text{-}postsag}| \qquad (1)$$

- Where the voltage sag has a phase angle shift $\delta \neq 0$, the magnitude of the voltage U_{inj} increases when the angle decreases δ and can be calculated from the formula:

$$|\mathrm{Uinj}| = \sqrt{U_{s-presag}^2 + U_{s-postsag}^2 - 2U_{s-presag}^2 U_{s-postsag}^2 \cos\left(\theta_{S-postsag} - \theta_{S-Presag}\right)} \qquad (2)$$

Phase angle is calculated to generate the voltage vector to ensure the objective of the strategy is determined by the expression:

$$\theta_{inj} = \tan^{-1}\frac{U_{s-presag}.\sin(\theta_{s-presag})}{U_{s-presag}.cos(\theta_{s-presag}) - U_{s-postsag}.cos(\theta_{s-postsag})} \qquad (3)$$

The required power to pump into the grid when using this method is determined by the expression:

$$P_{inj} = \sqrt{3}|U_{inj}||I_L|\cos(\theta_L+\theta_{inj}) \qquad (4)$$

From the power quality point of view, this method is considered to be the best compensation method, which results in low voltage waveform distortion, due to the compensated load voltages not changing both magnitude and phase angle compared to the voltage before the sag occurred. However, this control method has a relatively large insertion voltage, which results in a relatively large amount of active p_{inj} being used for pumping into the grid, which in turn affects the capacity of the reservoir or energy storage to be obtained from the supply grid while a sag voltage occurs. In this method high rated series transformer is required. The "pre-sag" strategy is best applied in cases where the load is particularly sensitive to changes in phase angle and voltage magnitude (e.g. frequency inverters, industrial information systems, programmed by PLC).

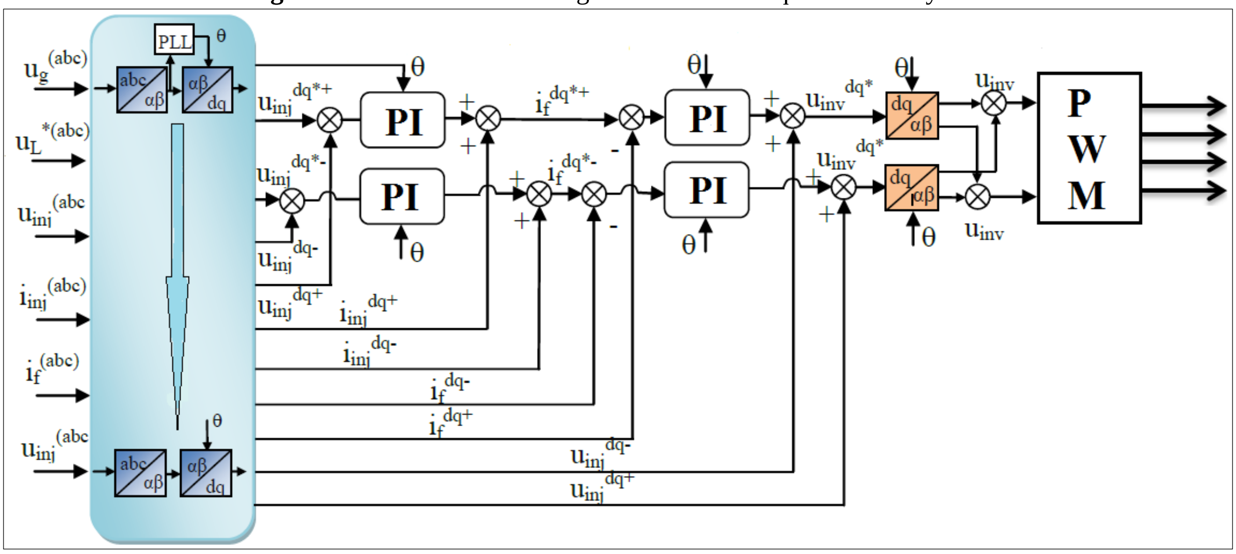
4.2. Vector Control Method

The control scheme for the proposed system was developed based on the vector control method implemented in the dq coordinate system and on the static αβ coordinate system with two control loops. This control scheme was given in [8, 9] and depicts an outstanding performance for compensating the sag voltages. When designing the control mechanism concept for DVR, attach the LC filter to the VSI output, as it affects the DVR's dynamic characteristics. In addition, the filter elements produce an additional voltage drop and a loss of power in the inductance branch and also cause variation in the phase angle of the voltage. To terminate the problem of voltage drop due to the connection of the LC filter and to update the DVR attributes cascade double-loop vector control is illustrated in figure 7. Constant charge voltage can be maintained through the function of controller, so

$$u^{dq}_{inj} = u^{dq}_{L} - u^{dq}_{S} \tag{5}$$

Where *uL dq* is load voltage in dq system, *uinj dq** is the injected voltage by the DVR in *dq* system.

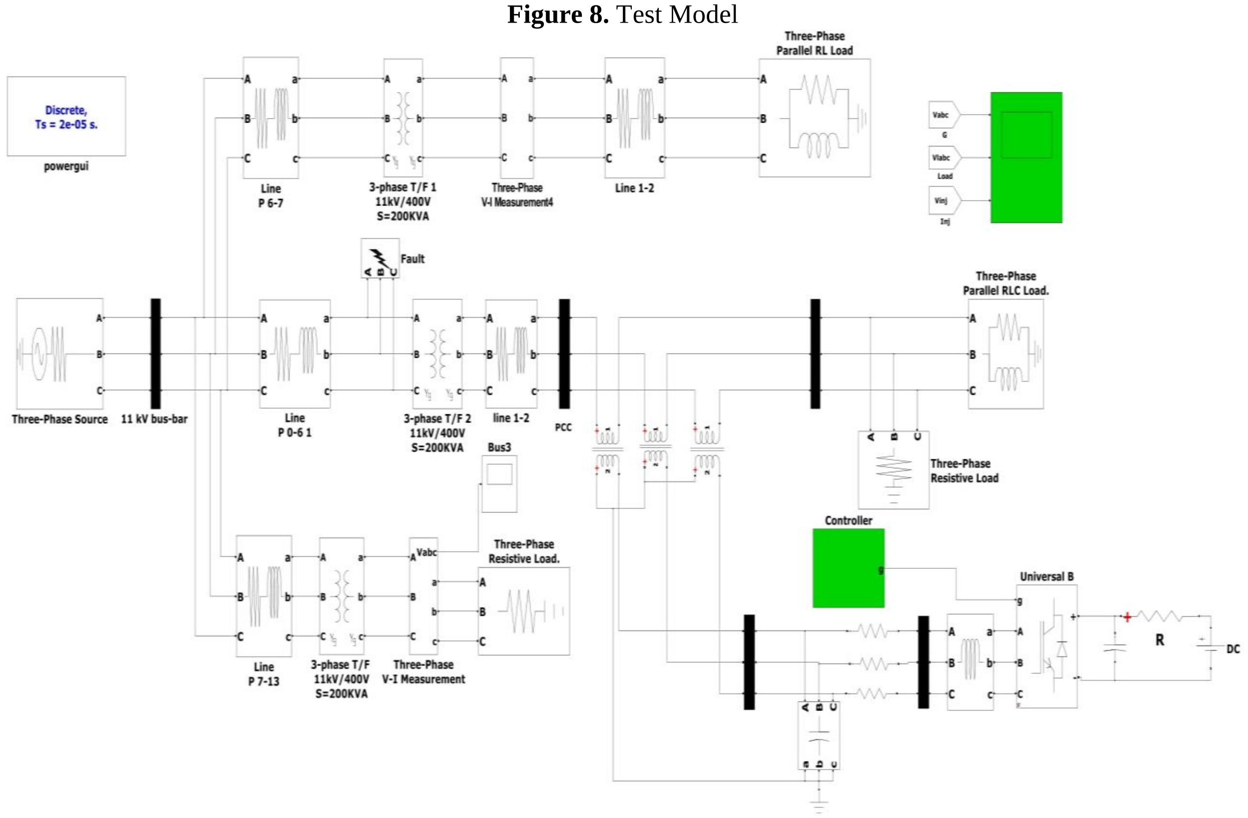
Figure 7. Control structure diagram of DVR on dq coordinate system



4.3. Test System Description

In order to show the performance of the DVR in voltage sag mitigation, a simple radial distribution system is simulated using MATLAB/SIMULINK and shown in figure 8. The parameters of main component are listed in table 1.

Figure 8. Test Model



A three-phase 11kV, 50Hz voltage source with source resistance of 0.1Ω is connected to feeder of 10 km and it step down to 400V, 50Hz through 11kV/400V transformer at point of common coupling (PCC). A three phase parallel RL load and series R load is connected to PCC.

Table 1. System Parameters

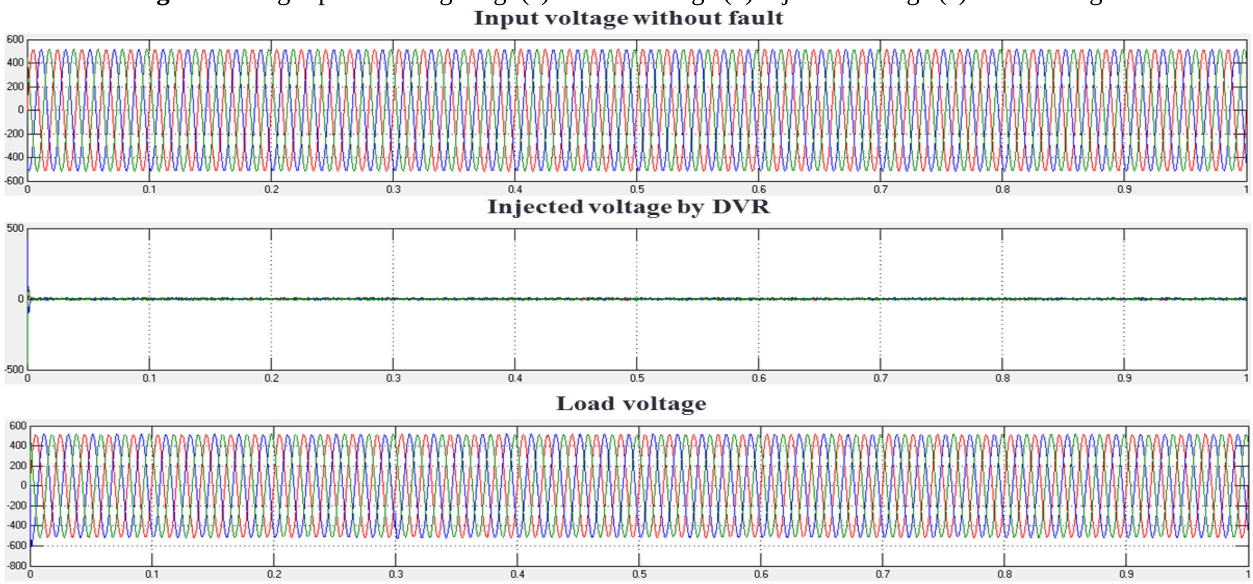
Sr. No.	System Quantities	Standards
1.	Three phase source	11KV, 50HZ
2.	Set- down transformer	Δ-Y, 11kV/400V
3.	Transmission line parameter	R= 0.*001 ohms* *L= 16.58e*-6 H
4.	Three-phase Resistive Load	100KW
5.	Three-Phase Parallel RL Load	100kW, 100VA
6.	VSC, switching frequency	IGBT based, 3 arms 6 pulses, 1080Hz
7.	DC battery (DVR)	600V
8.	DVR capacitor	26 mF
9.	Filter inductance	7.1mH
10.	Filter capacitance	7μF
11.	Feeder length	10 km

5. Simulations and Results

In this section we have examined and discussed different results obtained after performing various simulations. This test system consists of an 11 kV distribution feeder. This distribution system has been investigated under different conditions of the system faults, such as single-phase ground fault, double line fault and three-phase fault. MATLAB Simulink / power system block will be used in this work to perform the simulation.

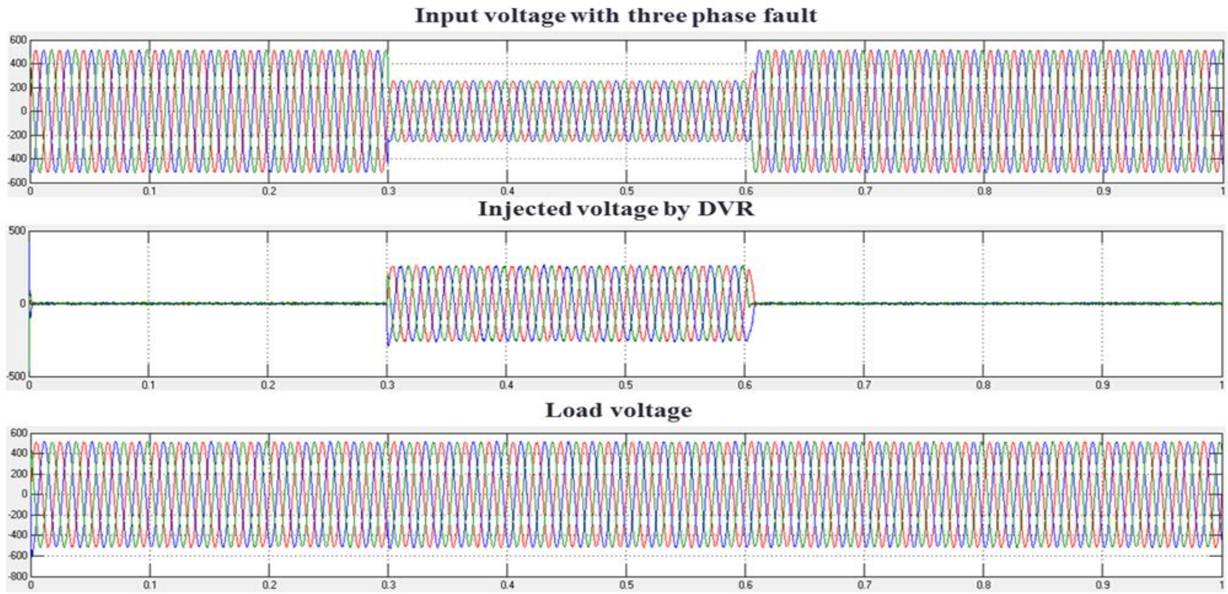
Case 1: The first simulation was performed without producing any failure in the system. Under normal conditions DVR will not inject any voltage into the system and will remain in standby mode. Figure 9 Shows the source waveforms and the load voltage when there is no fault in the system. Therefore it is observed that the input voltage magnitude is approximately similar to the load voltage. The time for the simulation for the test system is taken as 1 second.

Figure 9. Single-phase voltage sag: (a) Source voltage (b) Injected voltage (c) Load voltage.



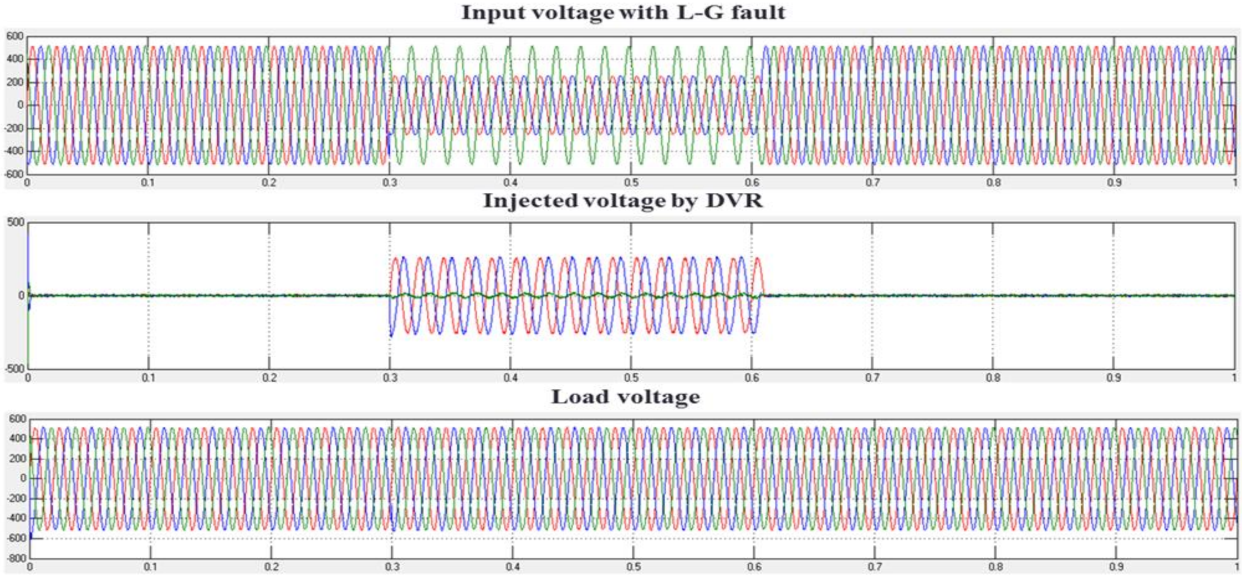
Case 2: The second simulation is performed by injecting a three-phase fault for time duration of 300 milliseconds i.e. from 0.3 second to 0.6 second whereas simulation time is taken as 1 second. The fault resistance and ground resistance are taken as 0.1Ω and 0.001Ω respectively. The waveform shows that when a three-phase fault occurs in the system, DVR will insert the necessary voltage to bring the voltage across the load back to its nominal value.

Figure 10. Three phase voltage sag: (a) Input voltage (b) Injected voltage (c) Load voltage



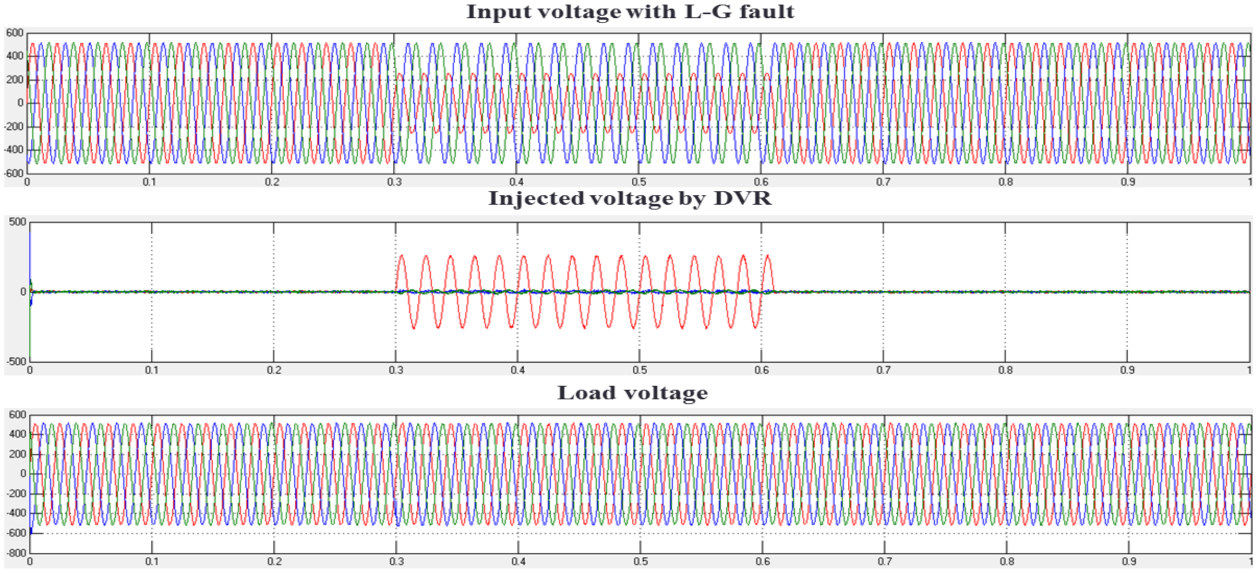
Case 3: The third simulation is performed by injecting a double line fault for time duration of 300 milliseconds i.e. from 0.3 second to 0.6 second whereas simulation time is taken as 1 second. The fault resistance is taken as 0.1Ω. The fault is in phase A and B, so a voltage drop is observed in the red and blue phase of the system, while phase C i.e. the voltage of the green phase remains unchanged.

Figure 11. Double phase voltage sag: (a) Source voltage (b) Injected voltage (c) Load voltage



Case 4: The fourth simulation is performed by injecting a line to ground fault for time duration of 300 milliseconds i.e. from 0.3 second to 0.6 second whereas simulation time is taken as 1 second. The fault resistance and ground resistance are taken as 0.1Ω and 0.001Ω respectively. The fault is in phase A, so the voltage drop is only observed in the red phase of the system, while phase B and C i.e. the voltage of the green and blue phase remain unchanged.

Figure 12. Single-phase voltage sag: (a) Source voltage (b) Injected voltage (c) Load voltage



From the above simulations it is observed that when a fault occurs on the system, it will reduce the load voltage magnitude to a very low value. In this condition DVR will enter in injection mode and inject required voltage to restore any change in the supply voltage thus to keep the constant voltage across the load at the rated value during fault condition.

6. Conclusion

In this paper MATLAB / Simulink software is used to present modeling and simulation of a DVR. A control technique based on vector control method with two control loops was developed and applied to mitigate the voltage sag in electrical distribution system. In this paper, DVR simulations have been performed under different fault conditions such as three-phase fault, line to ground fault and double line fault. The result of the simulations clearly shows that the DVR is effective and efficient device to mitigate the voltage sags in both balanced and unbalanced conditions. Furthermore this research work can be extended to mitigate the other power quality issues of distribution networks. Besides Cascaded double-loop vector control technique, other control techniques such as sliding mode controllers, fuzzy logic controllers, and adaptive PI or PID fuzzy controllers may also be used in the DVR compensation technique. In this research work, a voltage source converter is used to control the voltage sags. This problem can be minimized by developing DVR through the implementation of Matrix converter.

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