CONVENTIONAL DYNAMIC VOLTAGE RESTORER (DVR) FOR MITIGATION OF VOLTAGE SAG IN POWER DISTRIBUTION SYSTEMS

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ABSTRACT

Voltage sag is a common and undesirable power quality phenomenon in the distribution systems which put sensitive loads under the risk. Dynamic voltage restorer (DVR) can provide the most commercial solution to mitigate voltage sag by injecting voltage as well as power into the system. This paper presents the application of dynamic voltage restorer (DVR) on power distribution systems for mitigation of voltage sags at critical loads. In this paper, an overview of the DVR, its functions, configurations, components, compensating strategies and control methods are reviewed along with the device capabilities and limitations. The proposed control scheme is very effective to detect any disturbance in power systems. Simulation results using MATLAB/Simulink software are presented to verify the effectiveness of the proposed scheme.

KEYWORDS: *Dynamic Voltage Restorer (DVR), Voltage Sag (dip), Control System, Custom power device, Power Electronics, Energy Storage.*

I. INTRODUCTION

Power distribution systems, should ideally provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of the power supply. As a result of these nonlinear loads, the purity of the supply waveform is lost in many places. This ends up producing many power quality problems [1], [2].

Voltage sags (dips) are one of the most occurring power quality problems. They occur more often and cause severe problems and economical losses. There are different ways to mitigate voltage dips in power systems. Among these, the distribution static compensator and the dynamic voltage restorer are the most effective devices; both of them based on the voltage source converter (VSC) principle [3].

Faults at either the transmission or distribution level may cause transient voltage sag in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Voltage sag (dip) is a short duration reduction in voltage magnitude between 10% to 90% compared to nominal voltage from half a cycle to a few seconds [4]. Voltage sag can case loss of production in automated process since voltage sag can trip a motor or cause its controller to malfunction. To compensate the voltage sag in a power distribution system, appropriate devices need to be installed at suitable location [5]. These devices are typically placed at the Point of Common Coupling (PCC) which is defined as the point of the network changes [6].

There are many different methods to compensate voltage sags, but the use of a custom Power device is considered to be the most efficient method. For example, Flexible AC Transmission Systems (FACTS) for transmission systems, the term custom power pertains to the use of power electronics controllers in a distribution system, specially, to deal with various power quality problems [7]. In this study, the applications of dynamic voltage restorer (DVR) on power distribution systems for mitigation of single-phase and three-phase voltage sags at critical loads are presented.

This paper is structured as follows: Section 2 describes briefly the Conventional of DVR model, Basic DVR configuration and the main components. Section 3 presents the principle of operation and modes of DVR. The compensation strategies or available voltage injection strategies are described in section 4. The proposed control system of the DVR output voltage is presented in section 5. Section 6 presents simulation results using MATLAB / Simulink for single-phase and three-phase load voltage compensation. At the end, discussions of the results and conclusion are given in section 7.

II. CONVENTIONAL DYNAMIC VOLTAGE RESTORER

Figure 1 depicts a typical connection of a sensitive load in the distribution system. The electrical system viewed from the Point of Common Coupling (PCC) has been modeled as a 3-phase voltage source with a short-circuit impedance. The connection includes a transformer and a conventional DVR that is composed of an inverter and a series connected transformer. The DVR can compensate voltage sags by means of the injection of the inverter voltage through the series connected transformer. The DVR works independent of the type of fault or any event that happens in the system. Its primary function is to rapidly boost up the load-side voltage in the event of voltage sag in order to avoid any power disruption to that load [8].

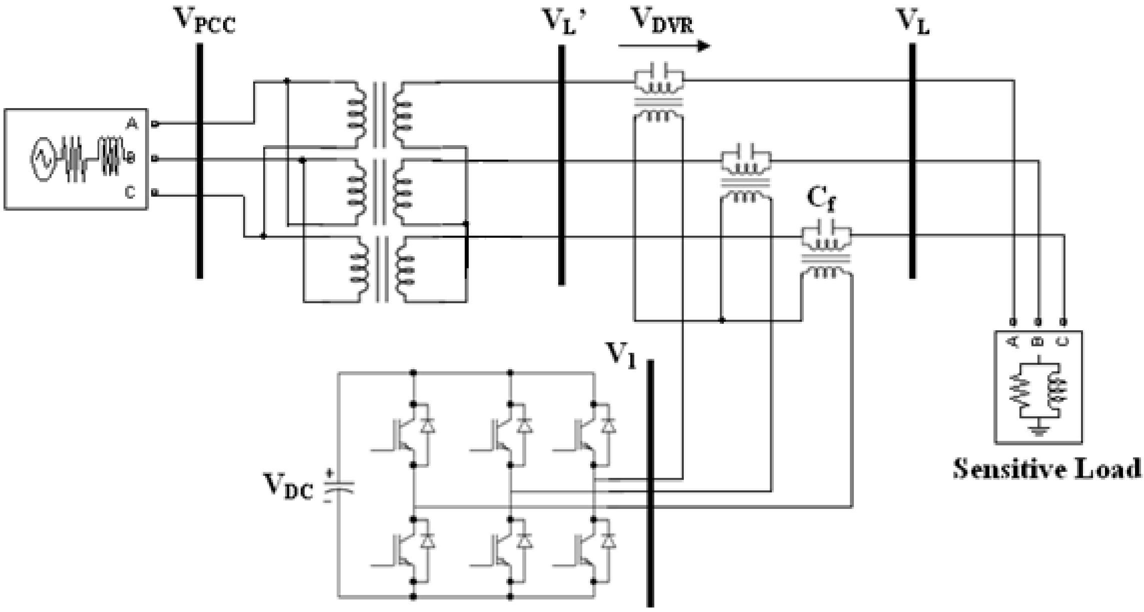


Fig. 1 Schematic diagram of Conventional dynamic voltage restorer

The main components of the DVR are shown in Figure 1 and are summarized hereafter:

2.1. Series Injection Transformer

The three single-phase injection transformers are used to inject missing voltage to the system at the load bus. To integrate the injection transformer correctly into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short–circuit impedance values of transformers are required.

2.2. Output Filter

The main task of the output filter is to keep the harmonic voltage content generated by the voltage source inverter to the permissible level.(i.e. eliminate high-frequency switching harmonics) [4]. These filters can be placed either in the inverter side or in the line side as shown in Figure 1.

2.3. Energy Storage Unit

The DC energy storage device provides the real-power requirements of the DVR during compensation. Various storage technologies have been proposed including flywheel energy storage, superconducting magnetic energy storage (SMES) and super capacitors. These have the advantage of fast response.[9], [10].

2.4. Voltage Source Converter (VSC)

Voltage source converters are widely used in Variable-speed drives (VSD), but can also be used to compensate voltage dips. The VSC is used to either completely replace the supply voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual one. Normally the VSC is not only used for voltage dip compensation, but also for other power quality issues, e.g. flicker and harmonics [11].

III. OPERATION MODES OF DVR

Generally, the DVR is categorized into three-operation mode which are: Protection mode, standby mode (during steady state) and boost mode (during sag). In Protection mode, the DVR is protected from the over current in the load side due to short circuit on the load or large inrush current. The bypass switches remove the DVR from system by supplying another path for current as shown in Figure 2. In standby mode, the DVR may either go into short circuit operation or inject small voltage to compensate the voltage drop on transformer reactance or losses as shown in Figure 3. Short circuit operation of DVR is generally preferred solution in steady state because the small voltage drops do not disturb the load requirements if the distribution circuit is not weak. In boost (Injection) mode, the DVR is injecting a compensation voltage through the voltage injection transformer due to a detection of a supply voltage disturbance.

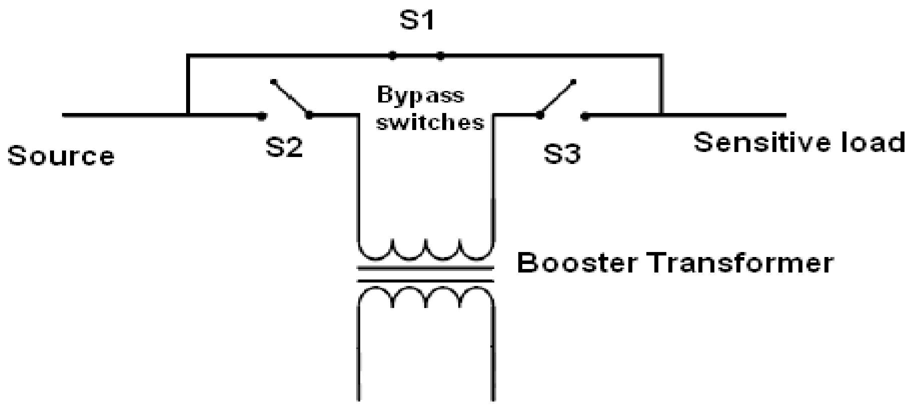


Fig. 2 Protection Mode (creating another path for the load current)

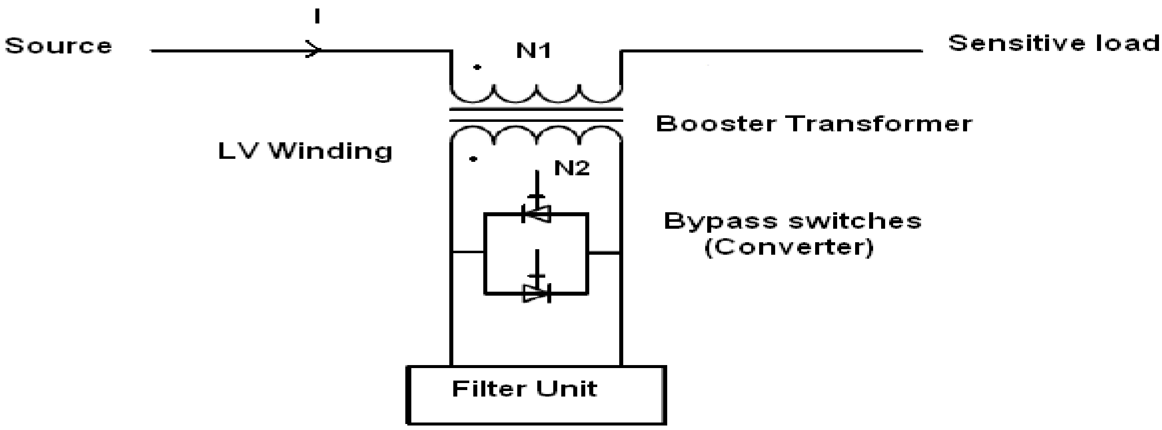


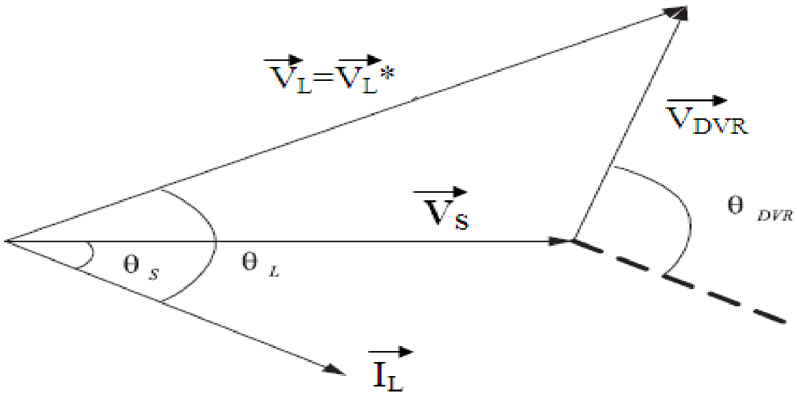
Fig. 3 The view of Standby Mode

IV. COMPENSATION STRATEGIES

The way in which the DVR is used during the voltage injection mode depends upon several limiting factors such as; DVR power rating, load conditions, and voltage-sag type [13, 14]. There are four different methods of DVR voltage injection which are:

4.1. Pre-sag/dip compensation method (PDC)

This method injects the difference (missing) voltage between sag and pre-fault voltages to the system. It is the best solution to obtain the same load voltage as the pre-fault voltage but there is no control on injected active power so high capacity energy storage is required. Figure 4 shows the single-phase vector diagram of this method [15].

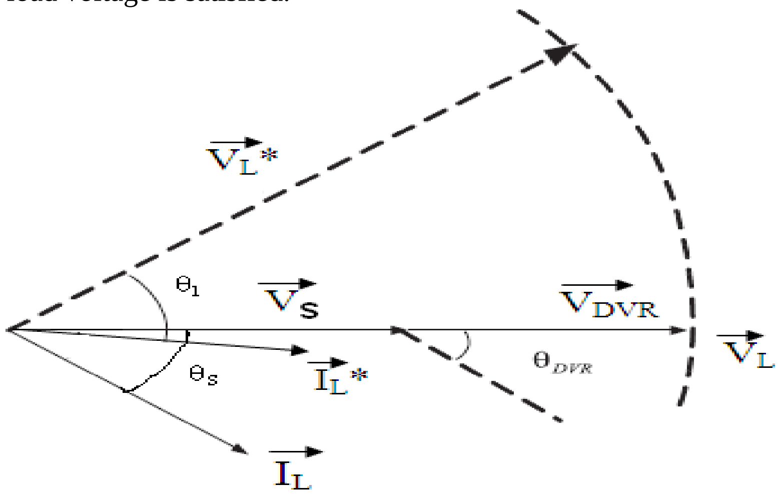


Where $\vec{V}_L^*$ ⟶ Pre-sag voltage

Fig. 4 Single-phase vector diagram of the PDC method

4.2. In-phase compensation method (IPC)

The injected voltage is in phase with the supply voltage. As shown in Figure 5.The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage is satisfied.



Where $\vec{V}_L^*$ ⟶ Pre-sag voltage, $\vec{I}_L^*$ ⟶ Pre-sag load current, $\theta_1 = \theta_S$

Fig. 5 Single-phase vector diagram of the IPC method

4.3. Phase advance method

The real power spent by the DVR is minimized by decreasing the power angle between the sag voltage and the load current. The values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage.

4.4. Voltage tolerance method with minimum energy injection

Generally the voltage magnitude between 90% -110% of the nominal voltage and phase angle variations between 5% -10% of the normal state will not disturb the operation characteristics of loads. This method can maintain the load voltage in the tolerance area with small change of voltage magnitude as shown in Figure 6 [13].

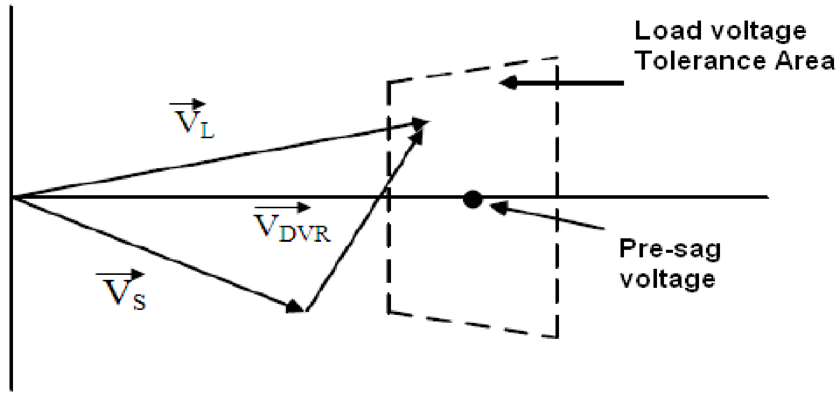


Fig. 6 Voltage tolerance method with minimum energy injection

V. CONTROL SYSTEM OF THE DVR OUTPUT VOLTAGE

The control system of a DVR plays an important role, with the requirements of fast response in the face of voltage sags and variations in the connected load. The main purpose of the control system is to maintain a constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. It will also look after the D.C. link voltage using the DC-charging unit [12]. The three main voltage controllers, which have been proposed in literature, are Feed-forward (open loop), Feedback (closed loop) and Multi-loop controller [17]. The Feed-forward voltage controller is the primary choice for the DVR, because of its simplicity and fastness. The drawback of the open loop controller is the high steady state error. The Feedback controller has the advantage of accurate response, but it is complex and time-delayed. Multi-loop control is used with an outer voltage loop to control the DVR voltage and inner loop to control the load current. Figure 7 depicts the d-axis and q-axis controllers that have been designed. The inputs of the controllers are the desired d and q load voltages and the outputs are the inverter voltages. Each controller is composed by a PI controller and selective controller. The PI controller tracks the reference signal at the positive sequence of the fundamental frequency and the selective controller its negative sequence. In that way, the DVR can compensate balanced and unbalanced voltage sags [18]. The q-axis controller is the same Figure, but replaces V_{Lq} and V_{Iq} instead of V_{Ld} (load voltage) and V_{Id} (inverter voltage). The control system used to control the DVR with a 9.9 kHz sampling frequency and 4.95 kHz switching frequency. Identical controllers for the d and q axes have been used. The parameters of the DVR test system are presented in Appendix (A).

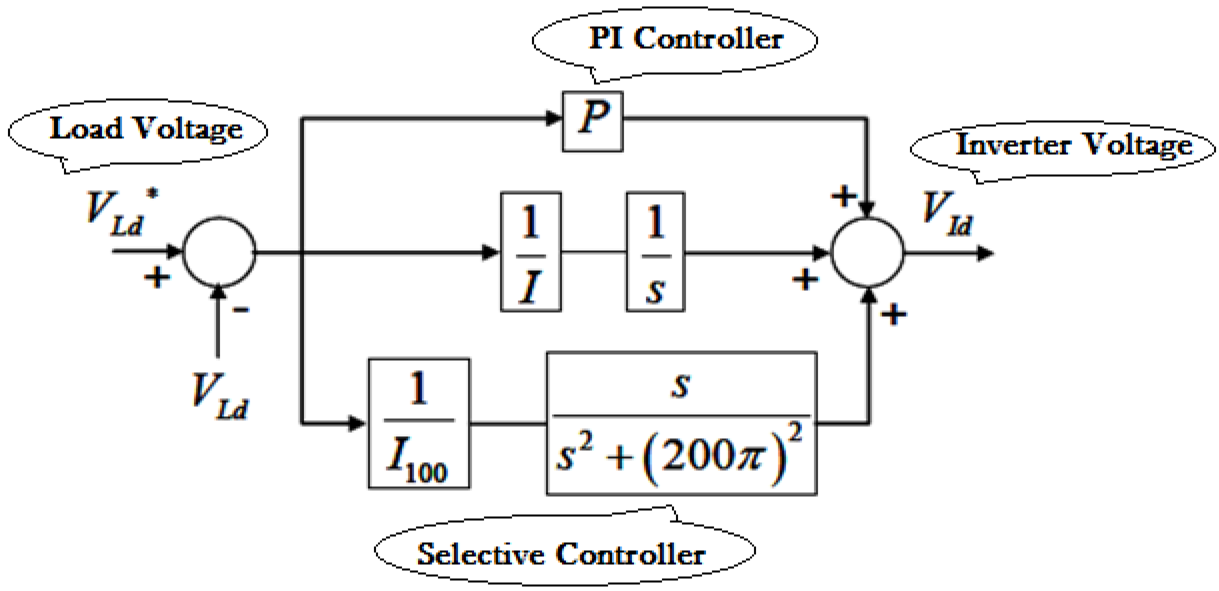


Fig. 7 Controllers for a DVR using a synchronously-rotating frame (d-axis Controller)

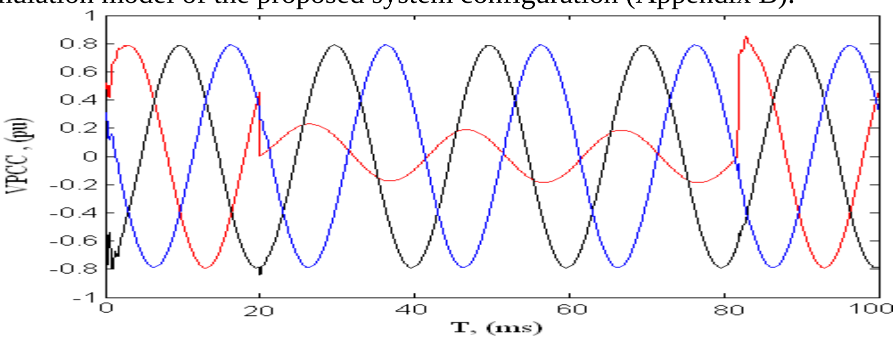
VI. Simulation Results and Discussions

In this Section representative simulation results are included to illustrate and understand the performance of DVR under single-phase and three-phase voltage sags conditions. The simulation studies have been carried out using MATLAB / Simulink SimPowerSystem Toolbox as shown in Appendix (B). The configuration of the studied test system is as shown in Figure 1. A strong voltage supply has been used (short circuit power = 20 pu). Since the fault detection mechanism is out of the scope of this paper, the DVR has been connected all the time in the simulation experiments reported in this paper. The test system is comprised of a three-phase voltage source of 11 kV at 50 Hz which feed a sensitive load. The sensitive load is made up of a resistance connected in parallel with an inductance. The inverters have been controlled using space-vector modulation with a switching frequency of 4.95 kHz and a 9.9 kHz sampling frequency. The load considered in the study is a 1 pu capacity with 0.93 power factor.

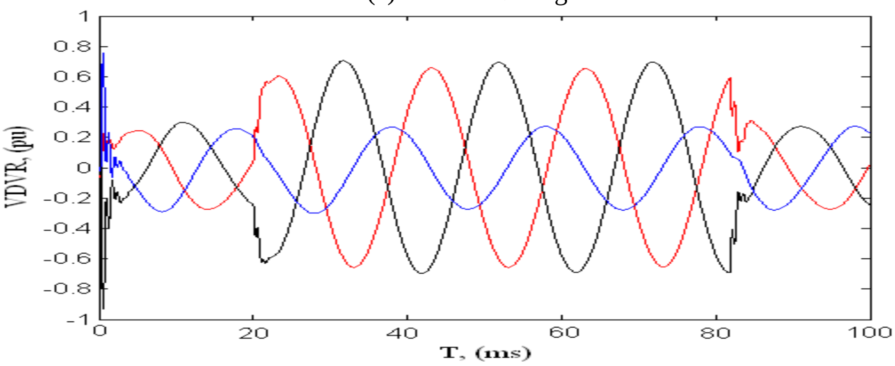
Figure 8 presents the results of simulation when a phase to ground resistive fault occurs, with a fault resistance equal to 0.0117 Ω. The fault is produced at the high-voltage (HV) side of the distribution transformer. It starts at 20 ms and last for three periods of the fundamental frequency. Observe that the DVR quickly injects the necessary voltage components to maintain the load voltage. The DVR injected voltage and the load voltage are shown in Figure 8 (b) and (c), respectively. It can be observed that during the fault the A-phase voltage at the PCC drops down to 20% of its nominal value, while phase to ground load voltages remain almost constant during the whole event, due to the compensating actions of the (DVR).

The same experiment has been carried out using a weak voltage supply of short-circuit power equal to 2 pu. Results are shown in Figure 9 for a conventional dynamic voltage restorer (DVR). As can be seen from the results, the DVR was able to produce the required voltage component rapidly and helped to maintain a balanced and constant load voltage at 1 pu. The voltage injected by the DVR and corresponding load voltage are shown in Figure 9 (b) and (c), respectively.

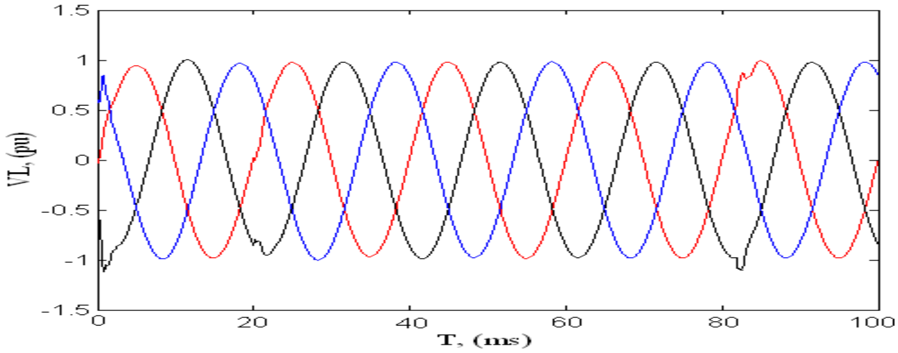
Figure 10 presents the simulation results for the system when there is a three-phase fault at the HV-side of the distribution transformer, with a fault resistance of 0.0117Ω. The source short-circuit power was made equal to 20 pu. The voltage sag starts at 20 ms and it is kept until 80 ms. Figure 10 (b) and (c) show the voltage generated by the DVR and the compensated load voltage, respectively. As a result of DVR, the load voltage is kept almost constant at 1pu throughout the simulation. Figure 11 shows the simulation model of the proposed system configuration (Appendix B).



(a) Source Voltage

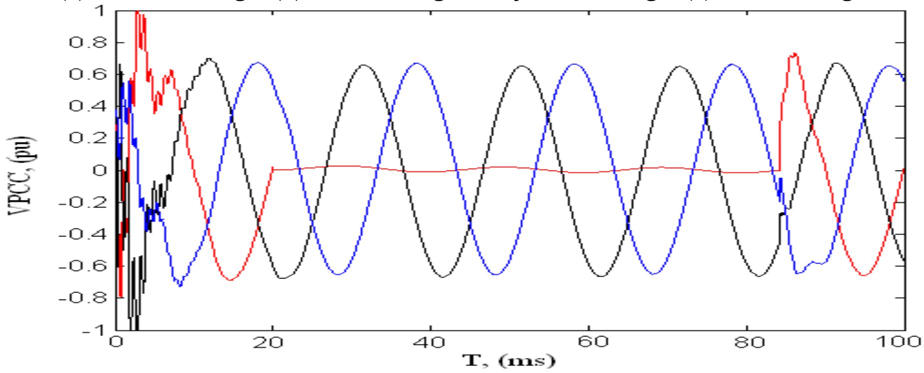


(b) Injected Voltage

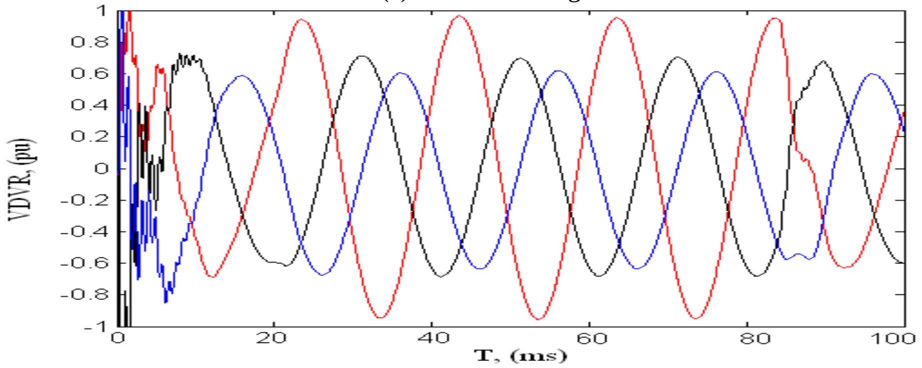


(c) Load Voltage

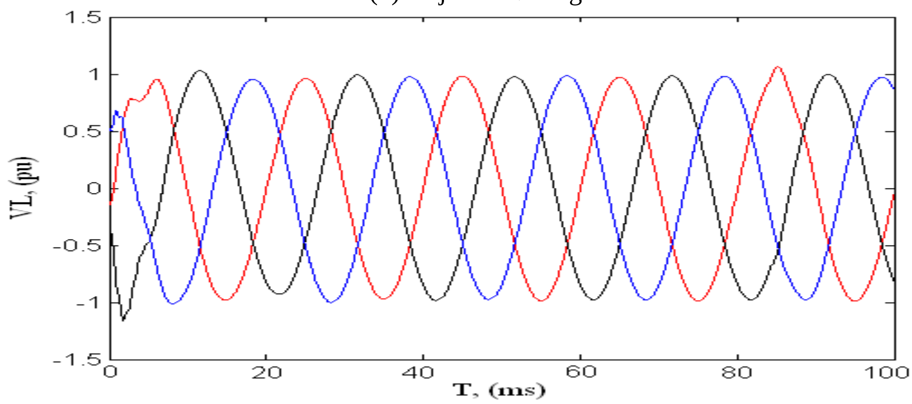
Fig.8 Compensation of load voltage for Conventioal DVR (single-phase fault and short circuit power = 20 pu). (a) Source Voltage; (b) DVR Voltage or Injected Voltage; (c) Load Voltage



(a) Source Voltage



(b) Injected Voltage



(c) Load Voltage

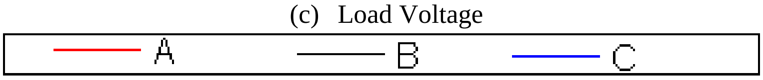
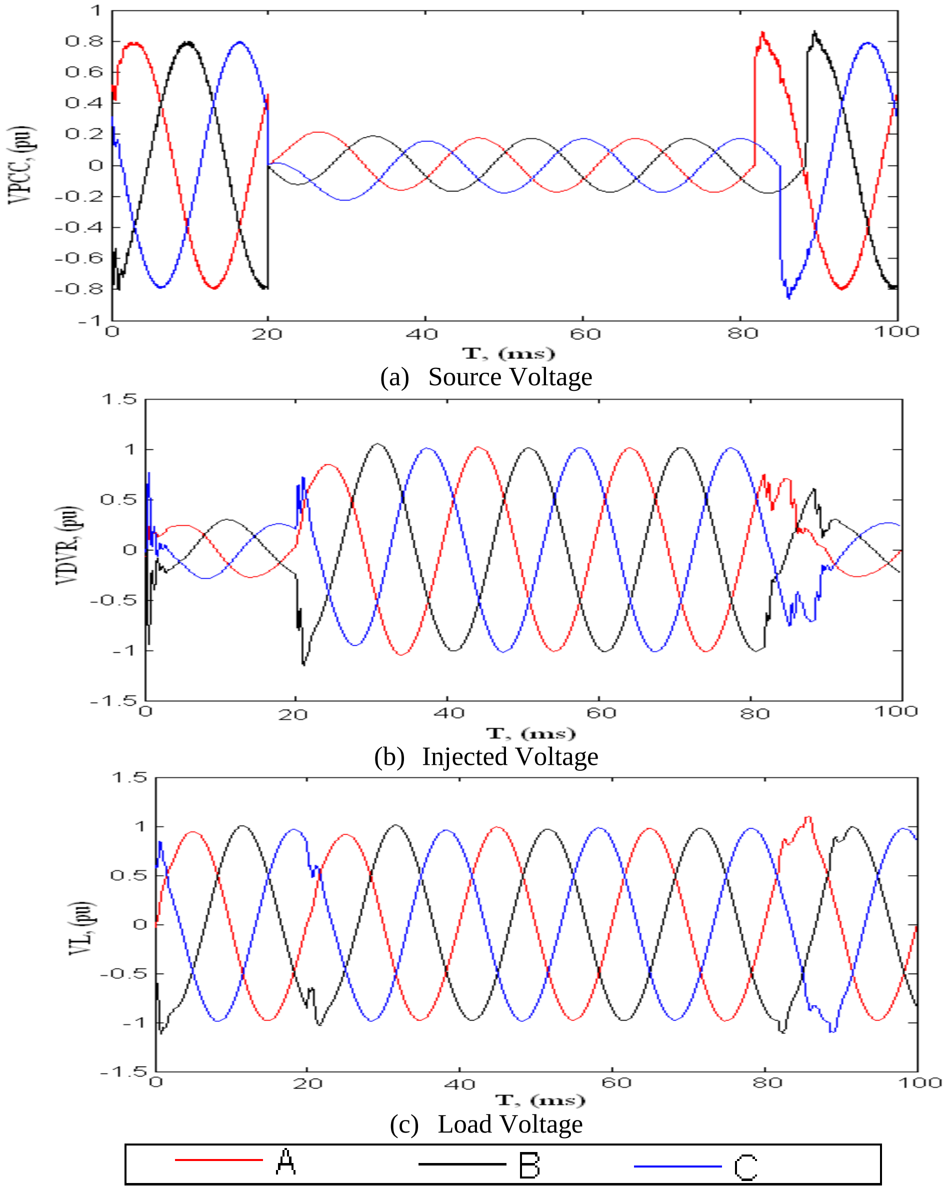


Fig.9 Compensation of load voltage for Conventioal DVR (single-phase fault and short circuit power = 2 pu). (a) Source Voltage; (b) DVR Voltage or Injected Voltage; (c) Load Voltage



(a) Source Voltage

(b) Injected Voltage

(c) Load Voltage

Fig.10 Compensation of load voltage for Conventioal DVR (Three-phase fault and short circuit power = 20 pu). (a) Source Voltage; (b) DVR Voltage or Injected Voltage; (c) Load Voltage

VII. CONCLUSION

Based on the simulation carried out, it is clear that a DVR can tackle voltage sags when protecting sensitive loads. The DVR handled both balanced and unbalanced situations without any difficulties and injected the appropriate voltage component to correct rapidly any disturbance in the supply voltage to keep the load voltage balanced and constant at the nominal value. This study has proposed the simulation of DVR using simulink in Matlab. The DVR is considered to be an efficient solution due to its relatively low cost and small size, also it has a fast dynamic response.

VIII. RECOMMENDATION OF FUTURE WORK

Voltage Sags due to connection of DVR are to be tested in actual simulation setup with MATLAB / Simulink SimPower System Toolbox. Lab Testing of DVR can be implemented as a part of future research work.

APPENDIX-A

1- Electrical System Viewed from the PCC

Short Circuit Power = 20 pu
System Frequency = 50 Hz
Equivalent inductance = 157 µs
Equivalent Resistance = 0.007 pu

2- Distribution Transformer and DVR Transformer

Short Circuit Power = 14 pu
Winding 1 Inductance = Winding 2 Inductance = 185 µs
Winding 1 Resistance = Winding 2 Resistance = 0.023 pu
Magnetizing Inductance = 63.66 s
Magnetizing Resistance = 1500 pu

3- Filter Unit

Filter Inductance = 369.5 µs
Filter Capacitance = 55.98 µs-1

4- Inverter Circuit

Switching Frequency = 4.95 kHz
Sampling Frequency = 9.9 kHz

5- Sensitive Load

Apparent Power = 1 pu
Power Factor = 0.93

6- Control System Parameters

P = 1.5, I = 6 x 10^{-4} and I_{100} = 5 x 10^{-4}

APPENDIX-B

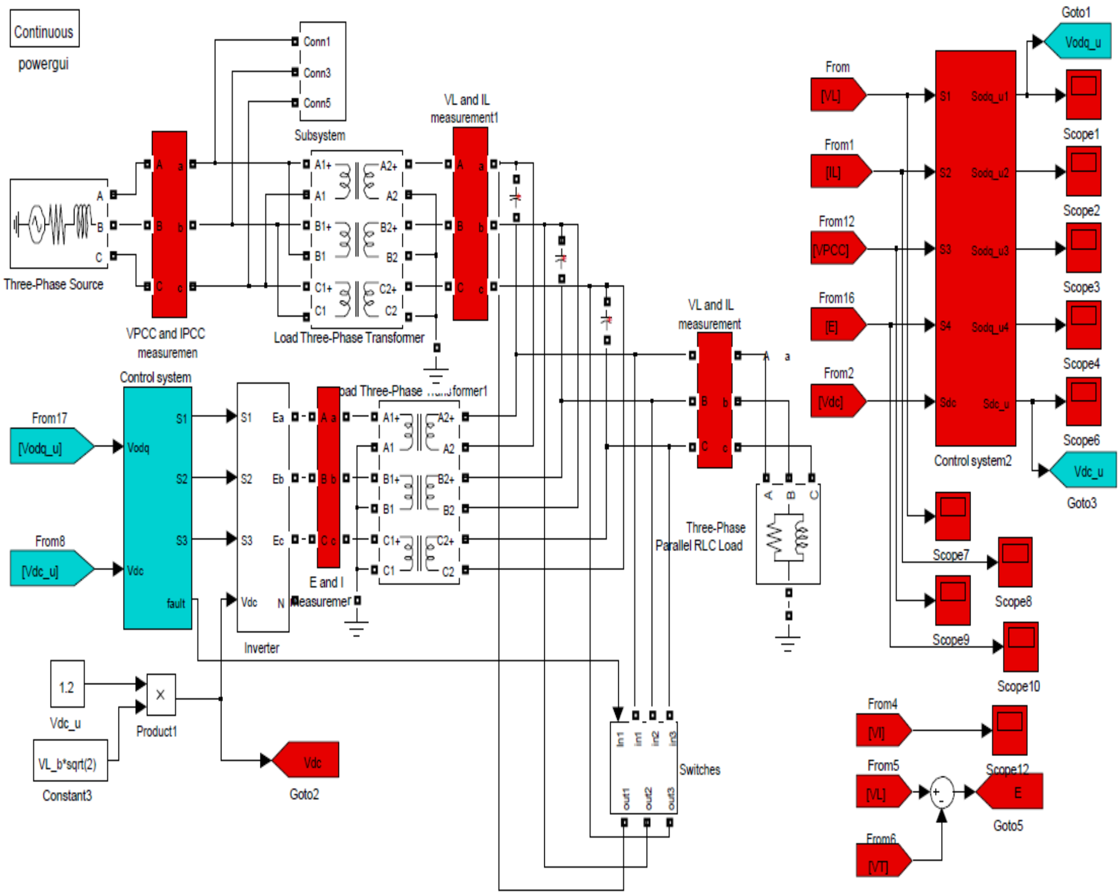


Fig. 11 Simulation model of the proposed system configuration

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BIOGRAPHIES

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Baraka Hasanin Received the PhD degree in Electrical Engineering Dept., Faculty of Engineering, from AL-azhar University, Egypt. Recently, he is the Dean of Faculty of Engineering, Al-azhar University in Qena. His recent research interests include electrical power systems, power quality, control systems, voltage stability, electrical machines and drive.