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Performance Analysis of Dynamic Voltage Restorer (DVR) Against Voltage Sag

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Abstract

Power quality is major concern in industries today because of enormous losses in energy and money. With the advent of sophisticated electrical and electronic equipment's which are very sensitive to disturbances and non-linear loads at distribution systems, produces many power quality problems like voltage sags, swells and harmonics and the purity of sine waveform is lost. Voltage sags are considered to be one of the most severe disturbances to the industrial equipment's. Dynamic voltage restorer has been considered the very effective solution for the mitigation of voltage sags. In this paper the effectiveness of dynamic voltage restorer for voltage balancing is presented.The dqo based control algorithm is considered for mitigating voltage sag. The MATLAB/Simulink demonstrates the validity and superiority of proposed control strategy during various fault conditions on distribution system.

Keywords: Power Quality, Voltage Sag, DVR, Custom power device, dqo algorithm.

Introduction

Power quality issues are divided into two categories voltage quality and frequency quality. Voltage quality issues are related with voltage sag, voltage swell, under voltage and over voltage while frequency quality issues are related with harmonics and transients. One of the most imperative power quality issues is voltage sag which occurs due to the usage of voltage sensitive devices. It has made industrials processes more susceptible to supply voltage sags [1]. Voltage sag and swell can be defined as given in the following Table.1.

Table-1: Voltage Disturbances

Type of Disturbance	Voltage	Duration
Voltage Sag	0.1-0.9 p.u.	0.5-30 cycles
Voltage Swell	1.1-1.8 p.u	0.5-30 cycles

Voltage swells are not as important as voltage sags because they are less common in distribution systems. There are many methods to mitigate voltage sags and swells, but the use of custom power devices is considered to be most efficient method. Switching off a large inductive load or energizing a large capacitor bank is typical system event that causes swells [1].

The paper is organized in different sections. First section gives introduction about power quality issues. The second section describes Dynamic Voltage Restorer and its operating principle. The third section deals with a simple control scheme based on dqo algorithm to compensate voltage sags. Fourth section includes MATLAB/SIMULINK model based simulated results.

Dynamic Voltage Restorer (DVR)

Configuration of DVR

Dynamic voltage restorer is a series connected power-electronic converter-based device with the distribution feeder to protect critical loads from all supply-side disturbances other than outages. It can provide the most cost effective solution to mitigate voltage imbalance by establishing the proper voltage quality level that is required by customer. When a fault happens in a distribution network, sudden voltage sag will appear on adjacent loads. DVR installed on a sensitive load, restores the line voltage to its nominal value within the response time of a few milliseconds thus avoiding any power disruption to the load. The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid [2].

The DVR consists of:
a. Injection transformer/Series transformer
b. Harmonic filter
c. Voltage source converter (VSC)
d. Energy storage
e. Control system

As shown in Fig.1. injection transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side [7]. Its main tasks are: connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage [3].

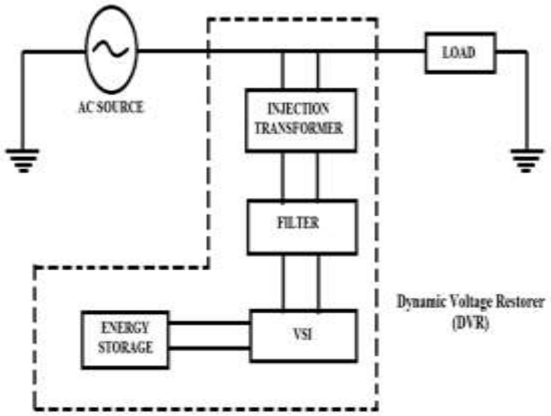

Figure-1: Schematic diagram of DVR

The purpose of energy storage devices is to supply necessary energy to the VSC via a dc link for the generation of injected voltage . The voltage source converter (VSC) is a power electronic device which consists of switching devices which can generate sinusoidal voltage at any required frequency, magnitude and phase angle. VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The nonlinear characteristics of semiconductor devices cause distorted waveforms associated with high frequency harmonics at the inverter output. To overcome this problem and provide high quality energy supply, a harmonic filtering unit is used. The control of compensation voltages in DVR is based on dqo transformation along with Phase Locked Loop (PLL) [4][5].

Equivalent Circuit

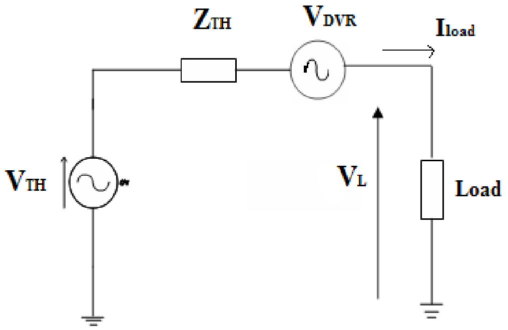

Figure-2: Equivalent circuit of DVR

Fig.2. Shows the Thevenin equivalent circuit of the DVR. During Voltage sag/ swell, the DVR injects a series voltage V_{DVR} through the injection transformer so as to maintain the desired load Voltage V_L .The series voltage injected by the DVR (V_{DVR}) can be obtained as

$$V_{DVR} = V_L + Z_{TH}I_L - V_{TH} \qquad (1)$$

Where,
V_L = Desired load voltage
Z_{TH} = Thevenin equivalent impedance
I_L = Load current
V_{TH} = System voltage during fault

The load voltage is given by,

$$I_L=[P + jQ_L]/V_L \qquad (2)$$

The load power factor angle θ is given by

$$\theta = \tan^{-1}(Q_L/P_L) \qquad (3)$$

The complex power injected by DVR is,

$$S_{DVR} = V_{DVR}I^* \qquad (4)$$

From the above equation, it is clear that when the injected voltage V_{DVR} is in quadrature with I_L, DVR requires only reactive power and the DVR itself generate the reactive power[3][9]. Other phase relationship between $V_{DVR}$and I_L requires active power injection which must be provided by the energy storage of the DVR system.

Operating modes

The DVR has three modes of operation which are Protection mode, Standby mode, Injection mode [3].

Protection Mode

If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed).

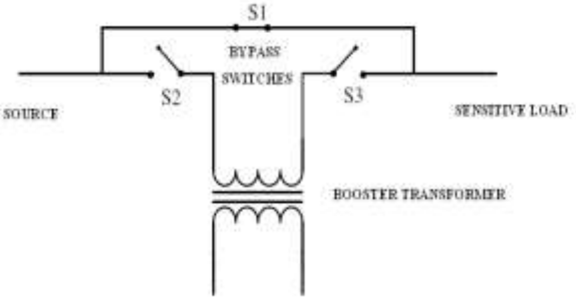

Figure-3: Protection Mode

Standby Mode ($V_{DVR} > 0$)

In the standby mode the booster transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the primary.

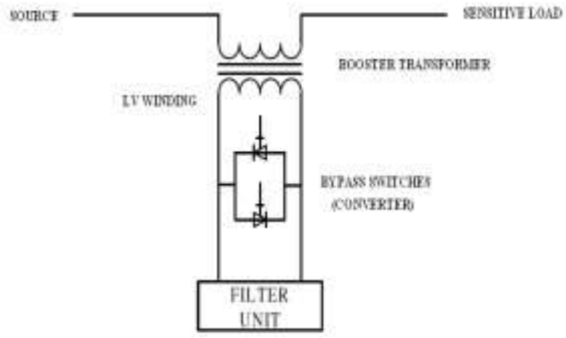

Figure-4: Standby Mode

Injection Mode ($V_{DVR} > 0$)

Injection mode is also called as boost mode. In the Injection mode the DVR is injecting a compensating voltage through the booster transformer due to the detection of a disturbance in the supply voltage.

Compensation methods

Presently, there are three known restoration methods for sag compensation, they are in-phase compensation, pre-fault compensation and phase advance compensation. The most significant difference in these methods is the selection of reference voltage for the control system of the compensator during the restoration process.

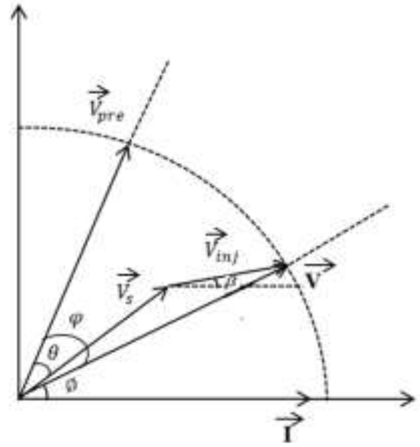

Figure-5: General phasor diagram showing compensation of voltage sag

Fig. 5 is a phasor diagram describing the electrical condition of Fig. 2 where it is clear that $\vec{V} = \vec{V}_s + \vec{V}_{inj}$. The phasor diagram can be used to explain the three compensation schemes analytically, assuming that the voltage sag/swell is balanced. In Fig. 5, the compensated load-current phasor $\vec{I}$ is used as the reference, $\vec{V}$ is the compensated load voltage, $\emptyset$ is the load power factor angle, and $\vec{V}_{\mathrm{pre}}$ is the prefault phasor of $\vec{V}_s$.θ is the phase shift between $\vec{V}_{\mathrm{pre}}$ and $\vec{V}_s$. It is defined such that if $\vec{V}_s$ lags $\vec{V}_{\mathrm{pre}}$, θ is positive. As $\vec{V}_s$ is the consequence of an upstream fault or disturbance, its magnitude and phase are not controllable. Note that, the compensated load-side voltage magnitude $|\vec{V}|$ is restored to its pre disturbance value $|\vec{V}_{pre}|$.φ is the phase difference between $\vec{V}_{\mathrm{pre}}$ and $\vec{V}$. It is also defined thus: if $\vec{V}$ lags $\vec{V}_{\mathrm{pre}}$, then φ is positive. Based on Fig. 5, therefore, it can be seen that the total injected active power from the Series Compensator (SC) under such a balanced condition is

$$P_{inj} = 3\left|\vec{V}_{inj}\right|\left|\vec{I}\right| \cos\beta$$

$$P_{inj} = 3\left[\left|\vec{V}\right| cos\,\emptyset - \left|\vec{V}_s\right| cos(\emptyset + \varphi - \theta)\right]\left|\vec{I}\right| \qquad (5)$$

Where β is the phase difference between $\vec{I}$ and $\vec{V}_{inj}$. Eq.(5) will be applicable for any of the three compensation methods.

In-phase Compensation Method

In this method the injected DVR voltage $\vec{V}$ is in phase with the supply side voltage $\vec{V}_s$ regardless of the load current $\vec{I}$ and the pre-fault voltage $\vec{V}_{\text{pre}}$ as shown in Fig.6. This method is suitable for minimum voltage or minimum energy operation strategies. In other word, this approach requires large amounts of real power to mitigate the voltage sag, which means a large energy storage device. Since this method requires the compensated load voltage to be in phase with $\vec{V}_s$, then φ would be equal to θ. Using this method, the corresponding phasor diagrams for voltage sag is shown in Figure.6. From Fig. 6, it is noticed that the injected active power from the SC is

$$P_{inj} = 3\left[\left|\vec{V}\right| cos\,\emptyset - \left|\vec{V}_s\right| cos(\emptyset)\right]\left|\vec{I}\right| \qquad (6)$$

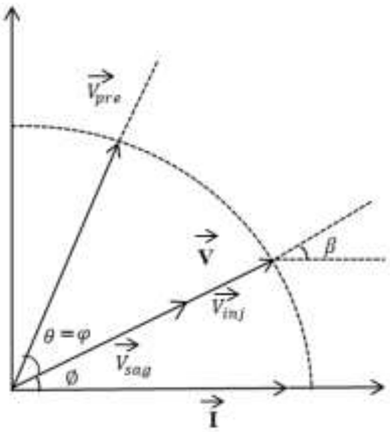

Figure-6: Phasor diagram of In-phase Compensation method

During a voltage sag, (i.e.$|\vec{V}| > |\vec{V}_s|$), Eq.(6) indicates that this compensation method will cause a net injection of active power from the SC into the external interconnected system.

Pre-fault Compensation Method

This method tracks the supply voltage continuously and compensates load voltage during fault to pre-fault condition. In this method, the load voltage can be restored ideally, but the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions [8][10]. This method is achieved by using a fault detector to freeze the output from the Phase Locked Loop (PLL) circuit, when the fault occurs. Then, the frozen angle is used to restore the previous balanced load voltages by using the Park transform. The lack of the negative sequence detection in this method leads to the phase-oscillation in the case of single-line faults. Fig.7. shows the phasor diagram of this method.

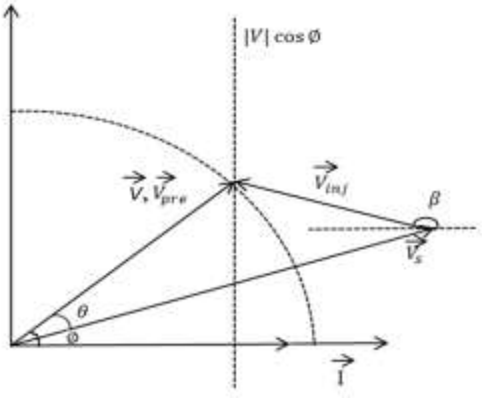

Figure-7: Phasor diagram of the Pre-sag compensation method

Pre-fault compensation has often been adopted in practice since it would result in an almost undisturbed load voltage. By continuously tracking $\vec{V}_s$, $\vec{V}_{inj}$ is introduced in such a way that $\vec{V}$ is compensated to its pre-fault condition $\vec{V}_{\text{pre}}$, . Therefore, φ would be zero and the injected active power is

$$\mathrm{P_{inj}} = 3\left[\left|\vec{\mathrm{V}}\right| \cos\emptyset - \left|\vec{\mathrm{V}}_{\mathrm{s}}\right| \cos(\emptyset - \theta)\right]\left|\vec{I}\right| \qquad (7)$$

From this equation, one observes that if the magnitude of is such that

$$|\vec{\mathrm{V}}_{\mathrm{s}}| > \frac{|\vec{\mathrm{V}}|\cos\emptyset}{\cos(\emptyset - \theta)}$$

Then $P_{inj} < 0$ .Under such a voltage disturbance condition, the SC absorbs active power from the external system. On the other hand, if

$$|\vec{\mathrm{V}}_{\mathrm{s}}| < \frac{|\vec{\mathrm{V}}|\cos\emptyset}{\cos(\emptyset - \theta)}$$

this leads to $P_{inj} > 0$. The SC will inject active power to the external system and would decrease.

Phase Advance Compensation Method

Pre-sag and in-phase compensation method must inject active power to loads to correct voltage disturbance. However, the amount of possible injection active power is confined to the stored energy in DC link, which is one of the most expensive components in DVR. Due to the limit of energy storage capacity of DC link, the DVR

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restoration time and performance are confined in these methods. In short, this method uses only reactive power and unfortunately, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags [4].

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Control Scheme for DVR

The dqo transformation or Park's transformation is used to control of DVR. The dqo method expresses the voltage error and phase shift information as instantaneous space vectors with start and end times. The voltage is converted from abc reference frame to d-q-o reference. For simplicity, zero phase sequence components is ignored [6]. The detection of error in voltage is carried out in each of the three phases. The control scheme for the proposed system is based on the comparison of a reference voltage and the measured terminal voltage (Va, Vb, Vc). The error signal allows generation of a commutation pattern by means of the pulse width modulation technique (PWM).The injection voltage is generated by difference between the reference load voltage and supply voltage and is applied to the VSC to produce the preferred voltage, with the help of pulse width modulation (PWM).Fig.7.shows the basic control scheme and parameters that are measured for control purposes [7]. The control algorithm produces a three phase reference voltage to the series converter that tries to maintain the load voltage at its reference value.

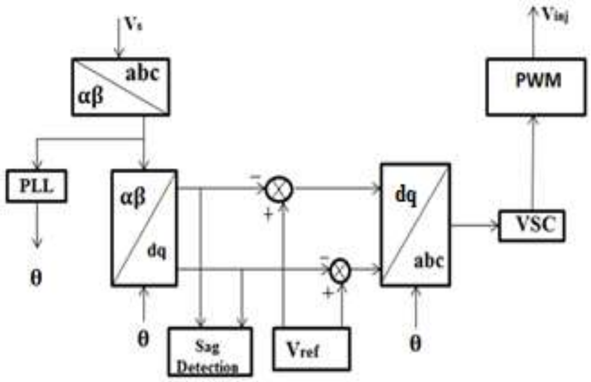


Figure-8: Control Scheme of DVR

The d-reference component is set to a rated voltage and the q-reference components are set to zero .In the control scheme, the actual voltage is measured and also the desired voltage .These voltages are converted in dqo with the Parks transformation.

$$f_{dqo} = K_f f_{abc} \qquad (8)$$

Where,

$$\left(f_{dqo}\right)^T = \left(f_d f_q f_o\right) \qquad (9)$$

$$\left(f_{abc}\right)^T = \left(f_a f_b f_c\right) \qquad (10)$$

$$K_f = \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (11)$$

Equation (8) defines abc to dqo transformation. In this transformation, phase A is aligned to the d-axis that is in quadrature with the q-axis.

Results and discussion

Case.1.

The scale down model of three phase Transmission line is developed in simulation. This model is scaled down from 173 MVA to 8.66 KVA and 289KV to 400V.Here 8 pi sections of transmission line are designed. These pi sections are connected in series; each section has 50 km length. The total length of line is 400km. The performance analysis on 400 km Transmission line is carryout with and without Dynamic Voltage Restorer using MATLAB/Simulink Following parameters are considered for simulation

Table-2 : System parameters for 400km Transmission Line

Main voltage	400v
Injection transformer ratio	1:1
Filter inductance	10mH
Filter Capacitance	30μF
Load resistance	30.67 Ω
Load inductance	96.73mH
Line Frequency	50 Hz

It is observed that before placing the DVR device the load voltage was found to be 0.8pu. After placing the DVR device the load voltage was improved to 0.92pu.

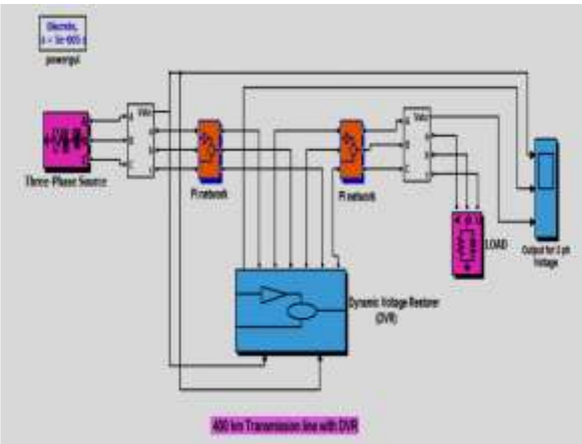
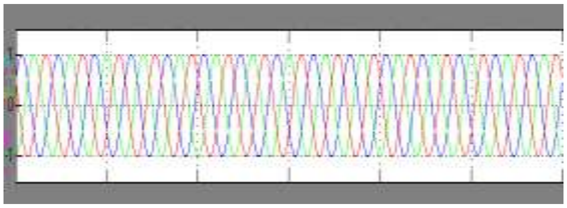
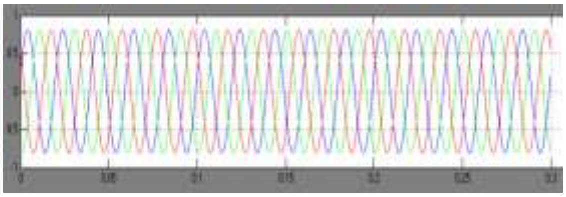


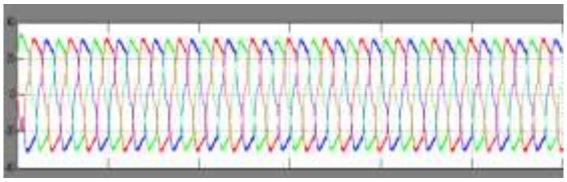
Figure-9: Simulation diagram of 400km Transmission Line with DVR



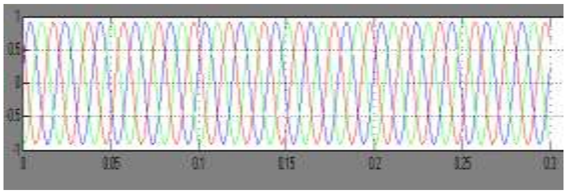
(a) Supply Voltage



(b) Load voltage without DVR



(c) DVR injected Voltage



(d) Load Voltage with DVR

Figure-10:(a),(b),(c),(d) Simulation results for 400 km Transmission line during Voltage sag

Case.2.

A three phase Transmission line is considered for simulation. The performance analysis of DVR for various fault conditions is carried out. Following parameters are considered for simulation

Table-3: System Parameters for 3ph Transmission Line

Main Supply voltage per phase	200v
Injection transformer ratio	1:1
Filter inductance	1mH
Filter Capacitance	20µF
Load resistance	40 Ω
Load inductance	60mH
Line Frequency	50 Hz

Single line to ground fault

In this case a single line to ground is created. Here fault resistance is 0.50 ohms and ground resistance is 1 ohm. The fault time is o.1s to 0.2s.The result of load voltage for this condition is shown below.

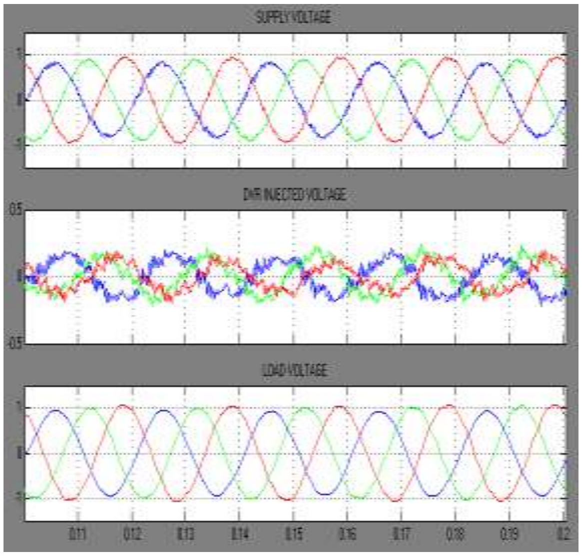


Figure-11: Simulation result for single line to ground fault

Double line to ground fault

In this case a double line to ground is created. Here fault resistance is 0.75 ohms and ground resistance is 1 ohm. The fault time is o.1s to 0.2s.The result of load voltage for this condition is shown below.

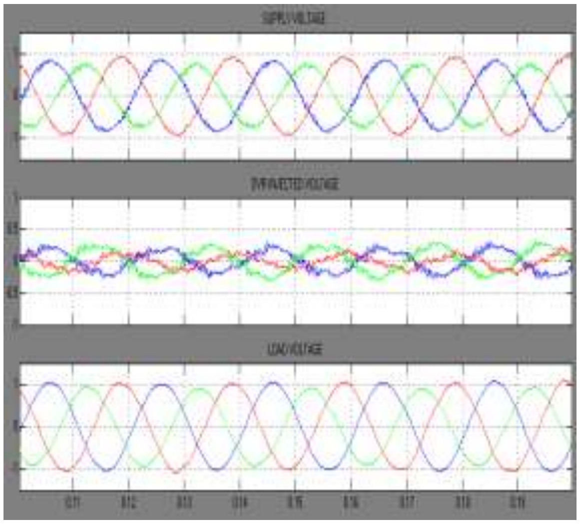


Figure-12: Simulation result for double line to ground fault

Three phase to ground fault

In this case a three phase to ground fault is created. Here fault resistance is 0.75 ohms and ground resistance is 1 ohm. The fault time is o.1s to 0.2s.The result of load voltage for this condition is shown below.

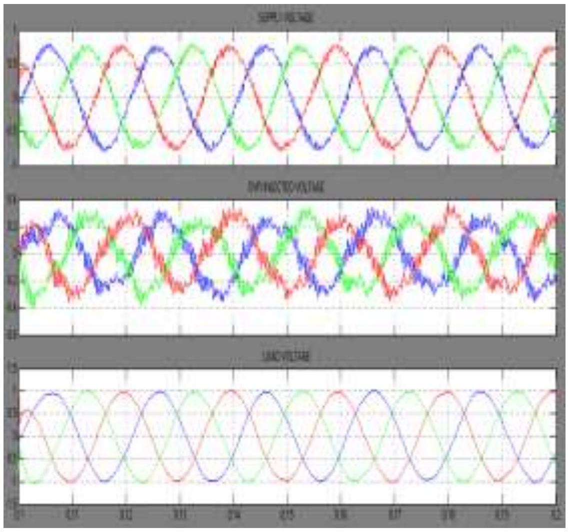


Figure-13: Simulation result for three phase to ground fault

Conclusion

This paper deals with the performance analysis of Dynamic Voltage Restorer (DVR) against voltage sag. The impact of voltage sags on sensitive equipment is severe. Therefore, DVR is considered to be an efficient solution due to its relatively low cost and small size, also it has a fast dynamic response. The simulation results clearly show the performance of a DVR in mitigating voltage sags during various fault conditions. The DVR handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to keep the load voltage balanced and constant at the nominal value.

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