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Voltage Correction Methods in Distribution System Using DVR

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Abstract: *Voltage crash analysis is a multifaceted stochastic issue in these days, which involves many random factors. Some of the factors are mentioned here like type of short-circuits in the power system, protective system, fault locations, and atmospheric discharges. They have severe impact on connected loads. The impact varies from load disruptions to considerable economic losses up to millions of dollars. Out of all categories of electrical conflicts, the voltage crash (sag) and continues disturbances are the nemeses of the automated industrial process. Many solutions have been identified to protect sensitive loads against such kind of disturbances but the DVR is considered to be the most efficient and reliable solution. In comparison to other techniques it has lower cost, smaller size and active response to the disturbance. In this paper Dynamic Voltage Restorer (DVR) and its operating principle introduced. Analyses of the voltage correction methods in distribution system and simulation results to understand the performances of DVR also presented in this paper.*

Keywords: *Custom Power, Dynamic Voltage Restorer (DVR), Power Quality, Static Series Compensator (SSC), Voltage Sags.*

1. INTRODUCTION

The electric power system is consisting of three functional blocks generation, transmission and distribution. For the stability of the power system, the generation unit must produce sufficient power to meet consumer demand, transmission systems must transport adequate power over long distances without overloading and distribution systems must deliver continues electric power to each customer's premises from transmission systems. The distribution system is located at the end part of power system and is connected to the customer directly, so the power quality mainly depends on distribution system. In the Recent days, modern power system specially the distribution system is now based on electronic devices and mostly the electronic devices are very sensitive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics **[1]**.

Problems related to power quality can be classified as:

- WAVEFORM DISTORTION

  Harmonics

  Inter harmonics

  Notching

  Noise

- TRANSIENTS

  Impulsive transients

  Oscillatory transients

- SHORT DURATION VARIATION

  Voltage sag or dip

Voltage swell

Interruption

- LONG DURATION VARIATION

Under voltage

Overvoltage

Interruption

Significant voltage drop may occur in the system under heavy load conditions. In power system voltage sag can occur at any instant of time, with amplitudes ranging from 10 – 90% and a duration lasting for half a cycle to one minute **[2].** But on the other side voltage swells are not so much important as voltage sag because it is less common in distribution systems. Voltage sag and swell can create large disturbances in the field. Sensitive equipment can be fail or shut down (such as found in semiconductor or chemical plants). Also it can create a maximum current unbalance that could blow fuses or trip breakers but these effects make a customer in an odd situation, ranging from minor quality variations to production downtime and equipment damage **[3].**

1.1. Voltage Sag

According to IEEE standard **[4]**, sag (or dip) is an rms reduction in the ac voltage at the power frequency for durations from a half a cycle to a few seconds which can be caused by a short circuit, overload or starting of electric motors. Magnitude and duration are two essential and important sag characteristics that determine the equipment behaviour **[5]**. There are different types of faults which increases the severity of the balanced and the unbalanced sag. During the sag if the phase voltages have unequal magnitudes or phase relationship other than 120, the sag is considered to be unbalanced **[5]**. The fault type, transformer connection and equipment influence the characteristics of voltage sag for the every phase of a 3-phase system. The classification of voltage sag is being done in to seven types mentioned as A, B, C, D, E, F and G.

- Sag of type A generally occurs on the end user devices. It is generally occurred in the transmission system. The power requirement is the same for each of the three- phase devices.
- The sags of type B and type D are occurs due to the single-line faults and they are generally occurs in the distribution systems, it has 70% occurrence among all sags. In Type B sag, to make the non-faulted phases healthy the system is solidly grounded. In Type D sag, the system is grounded through the impedance. The non- faulted phases experience voltage change because the zero sequence differs from positive and negative impedance of the system.
- Double-line faults are the main cause of type C and E type sag. These voltage sags have 20% occurrence among all types of sags. Both of the sags have common properties except for the angle between the sagged phases.
- Due to double line ground faults occurrence of F and G type sags take place. The worst situation for such kind of sag occurred when system is grounded through impedance. For that case, the zero sequence voltage drops is increased drastically, so it is expected to have voltage change in non-faulted phases. The voltage changes in non-faulted phases occur because the zero sequence voltage drop increases effectively.

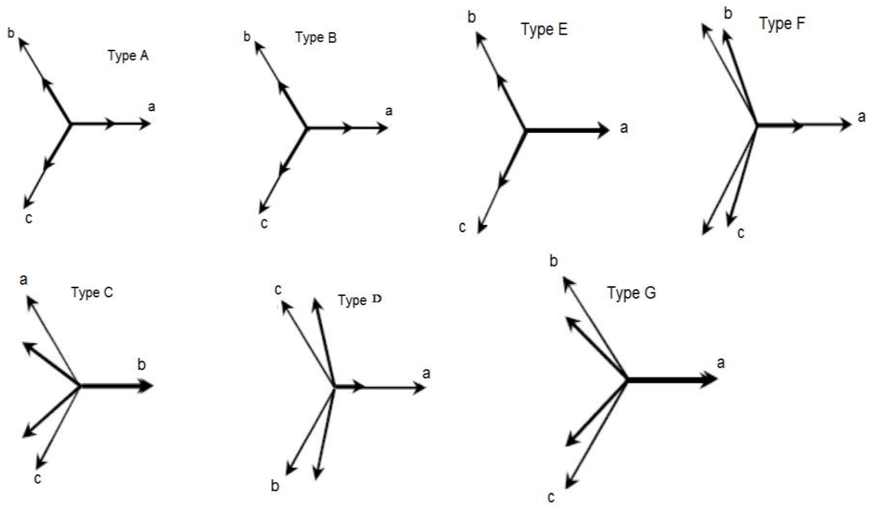

Fig1. *Types of Voltage Sag (Phasor diagram)*

Table1. *Type of voltage sags and causes*

Type	**Cause**
A	Three phase fault
B	Single phase fault in solidly grounded system
C	Double line fault with phase angle shift in sagged phase
D	Single line fault in impedance grounded system
E	Double line fault
F	Double line to ground fault
G	Double line to ground fault

2. Solutions to Power Quality Problems

To improve power quality there are two approaches. The solution of the power quality problems can be achieved by either from customer side or from utility side. Solution from the customer side is known as load conditioning according to which the equipment is less sensitive to power disturbances, and it allows the operation even under some significant voltage distortion and the solution from the utility side is to suppress the power system disturbances by installing the line conditioning equipment's . In this solution the compensating device is connected to low and medium voltage distribution system in either shunt or in series. The difference in Shunt active power filters and series active power filters is controllable current source and controllable voltage source but both schemes are based on the PWM inverters with a DC source also containing the capacitor as a reactive power element. For compensate load current harmonics the series active filter must operate in conjunction with shunt passive filters **[6]**. Even we have many alternate methods to illuminate voltage sags and swells, but the use of a custom Power device is considered to be the most efficient and reliable method. It makes sure customers get pre-specified quality and reliability of supply like FACTS improves the power transfer capabilities and stability margins **[7]**. To getting this stability or quality and reliability we uses the number of custom power devices. Some are classified as Active Power Filters (APF), Battery Energy Storage Systems (BESS), Surge Arresters (SA), Dynamic Voltage Restorer (DVR), Distribution static synchronous compensators (DSTATCOM), Super conducting Static Electronic Tap Changers (SETC), Solid State Fault Current Limiter (SSFCL), Magnetic Energy Systems (SMES), Solid-State Transfer Switches (SSTS), and unified power quality conditioner (UPQC).

The most important custom power devices which are being used in distribution system for power quality improvement are:

- Shunt connected Distribution STATCOM (DSTATCOM)
- Series connected Dynamic Voltage Restorer (DVR)
- Combined shunt and series, Unified Power Quality Conditioner (UPQC)
- Active Power Filter (APF)
- Solid State Current Limiter (SSCL)
- Solid State Transfer Switch (SSTS)

The power electronic static controllers are acting as custom power devices which are being used in the recent days for power quality improvement on distribution systems rated 1 through 38 kV. The interest in the usage of power quality devices (PQDs) arises from the need of mounting power quality levels to meet the everyday growing sensitivity of consumer needs and expectations **[8].** But if the level of Power quality is not achieved then it can cause costly downtimes and customer dissatisfaction. The main cause of downtime is the power fluctuations according to contingency planning research company's annual study. In order to face these new needs, advanced power electronic devices have developed over the last years. Their performance has been demonstrated at medium distribution levels, and most are available as commercial products **[9], [10].**

A DVR (Dynamic Voltage Restorer) is a static VAR device that has seen applications in a variety of transmission and distribution systems. It is a series compensation device, which protects sensitive electric load from power quality problems such as voltage sags, swells, unbalance and distortion through power electronic controllers that use voltage source converters (VSC). It contains one Switch either GTO or IGBT, a capacitor bank as energy storage device and injection transformers. We can see that DVR is connected in between the distribution system and the load as shown in figure 2. Through an injecting transformer a control voltage is generated by a forced commuted convertor which is in series to the bus voltage. In the figure 2 DC capacitor bank provides regulated DC voltage.

The DVR is capable of generating or absorbing independently controllable real and reactive power at its ac output terminal but the reactive power injection of the device must be provided by an external energy source or energy storage system. **[11]**. And the amplitude and phase angle of the injected voltages are variable which allowing control of the real and reactive power exchange between the DVR and the distribution system. The dc input terminal of a DVR is connected to an energy storage device of appropriate capacity. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components. The real power exchanged at the DVR output ac terminals is provided by the DVR input dc terminal by an external energy source or energy storage system. The series compensator can restore the load side voltage to the desired amplitude and waveform by inserting a voltage of required magnitude and frequency, even when the source voltage is unbalanced or distorted.

When there is no voltage sags in the distribution system under normal operating conditions, DVR provides very less magnitude of voltage to compensate for the voltage drop of transformer and device losses. But when there is a voltage sag in distribution system, a required controlled voltage of high magnitude and desired phase angle is generated which ensures that load voltage is uninterrupted and is maintained properly. In the whole process the capacitor will be discharged to keep the load supply constant **[12]**. Generally response time of DVR is very short and it can further limited by the power electronics devices and the voltage sag detection time. The expected response time is about 25 milliseconds, and which is very less than some of the traditional methods of voltage correction such as tap-changing transformers.

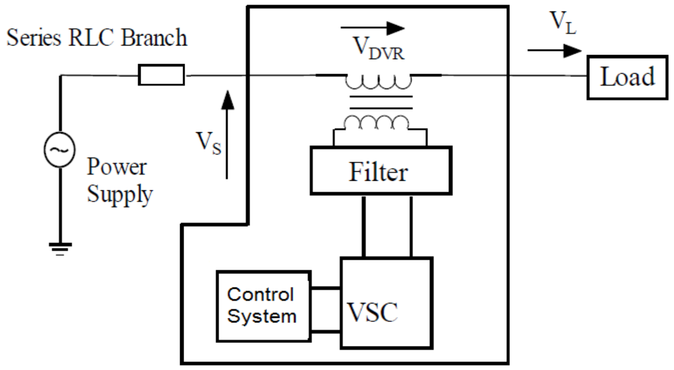

Fig2. *Schematic diagram of DVR*

There are three modes of operation of the DVR which are:

- Protection Mode
- Standby Mode
- Injection/Boost Mode.

2.1. Protection Mode

During the short circuit or fault condition the by-pass switch is activated to give an alternate path for the fault current. The DVR will be cut off from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed).

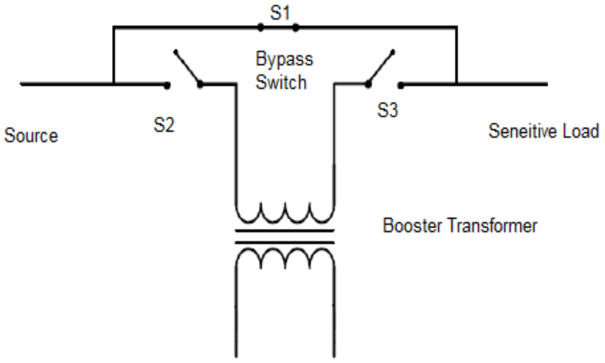

Fig3. *DVR Protection mode*

2.2. Standby Mode

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.

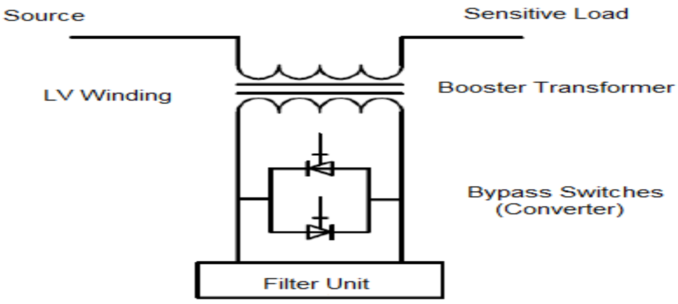

Fig4. *DVR Standby mode of DVR*

2.3. Injection/Boost Mode

When the voltage dip is occurred in the distribution network then DVR starts working as injection or boost mode in which it injects the voltage difference between the pre-sag and the main sag voltage, by supplying the real power requirement from the energy storage device together with the reactive power. By varying the rating of DC energy storage and the voltage injection transformer ratio the maximum injection capability of the DVR can be limited.

3. Discrete PWM- Based Control Scheme

For the smooth operation of the DVR a PI controller is an essential part required to control DVR during the fault conditions only. During the faulty condition first step is to sense the load voltage and then it passed through a sequence analyzer and the second step is to compare the magnitude of the actual voltage with reference voltage (Vref). Pulse width modulated (PWM) control system is applied for inverter switching so as to generate a three phase 50 Hz sinusoidal voltage at the load terminal. In the DVR control system a voltage angle control is as follows: an error signal is obtained by comparing the reference voltage with the RMS voltage measured at the load point. The PI controller processes the error signal and generates the required angle δ to drive the error to zero, for example; the load RMS voltage is brought back to the reference voltage.

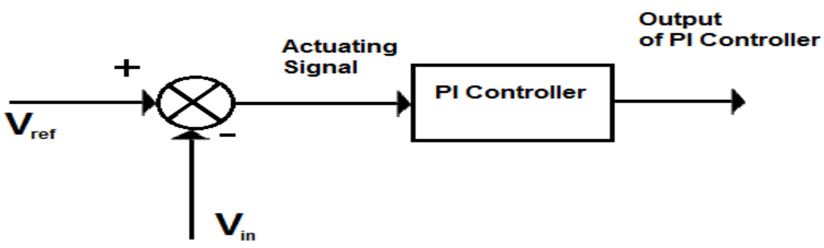

Fig5. *Error Signal Generation*

It should be noted that, an assumption of balanced network and operating conditions are made. The modulating angle ä or delta is applied to the PWM generators in phase A, whereas the angles for phase B and C are shifted by 240° or -120° and 120° respectively i.e.

$$V_A = \sin(wt + \delta) \quad (1)$$

$$V_B = \sin(wt + \delta - 2\pi/3) \quad (2)$$

$$V_C = \sin(wt + \delta + 2\pi/3) \quad (3)$$

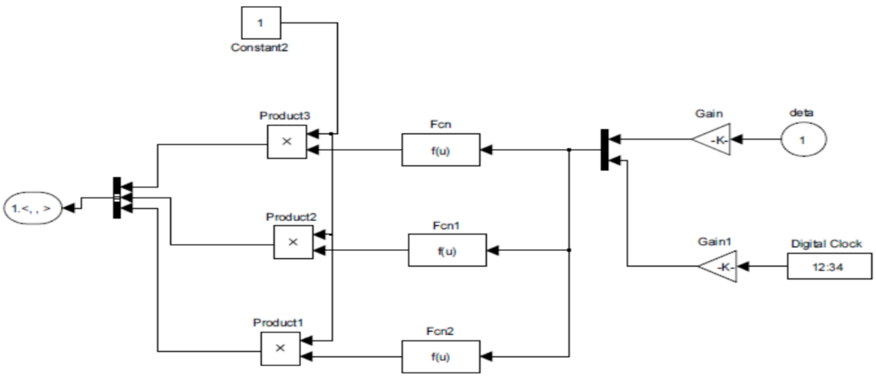

Fig6. *Phase Modulation of Control Angle*

and the modulated signal $V_{control}$ is compared with the triangular signal to generate the switching signals for the VSC. The important parameters of the sinusoidal PWM are the amplitude modulation index of the signal, and the frequency modulation index of the triangular signal which will be used to generate the 3- phase waveform as shown in the Figure below

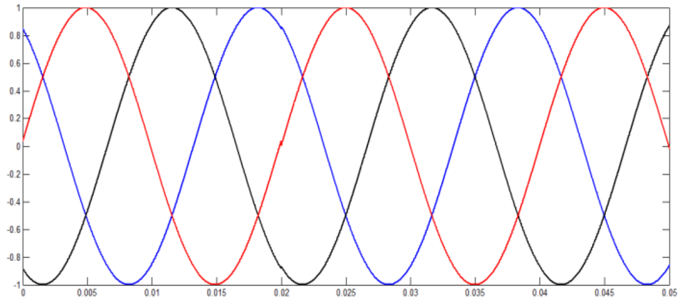

Fig7. *Three Phase Waveform Generated by Dvr controller*

It is observed that the control implementation is very simple by using only the voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the simulation results and the pulses by discrete PWM generators are shown in the figure as shown.

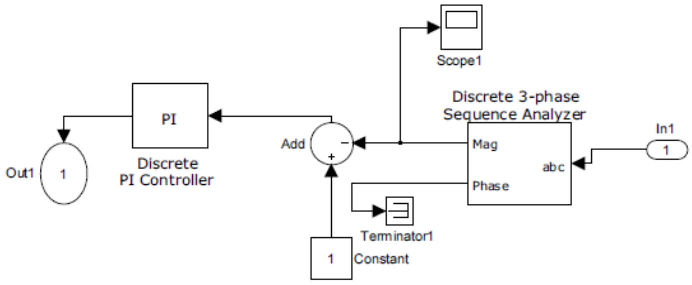

Fig8. *Simulink model of the DVR controller*

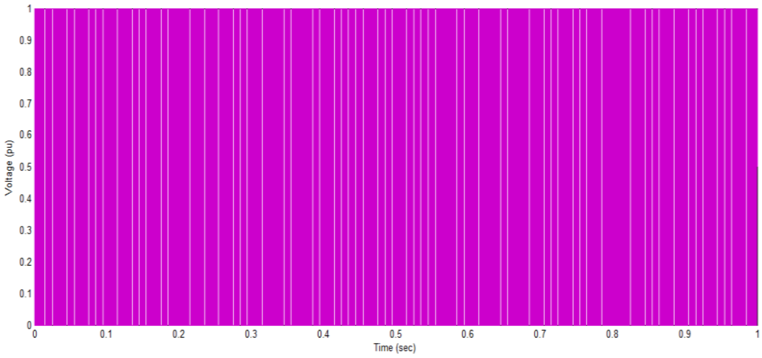

Fig9. *Waveform of Pulses generated by PWM generator*

4. Parameters and Simulation Results of Dvr Test System

The test system employed in the proposed system is to take out the simulation regarding the DVR actuation. Single line diagram of the proposed model of DVR is composed by a 11kV, 50 Hz generation system, having two transmission lines through a transformer connected in Y/Δ, 11/115KV. These transmission lines feed two distribution networks through two transformers connected in Δ/Y, 115/11 kV. To check the working of DVR for voltage compensation a fault is applied at point X of resistance 0.6pu for time duration of 0.4 to 0.6 seconds.

Table2. *Parameters of DVR Test Model*

S.No	System Quantities	Parameters
1	Source	3- Phase, 11 KV, 50 HZ
2	Inverter parameters	IGBT/Diode, 3 arms, 6 pulse, universal bridge
3	PWM generator parameters	Carrier frequency 1080 HZ, sample time 5 us
4	RLC series load	Active power 110 KV, inductive & capacitive reactive power 110 VAR
5	Step up transformer	Y-Δ 11/115 KV
6	Step down transf.	Δ- Y 115/11 KV

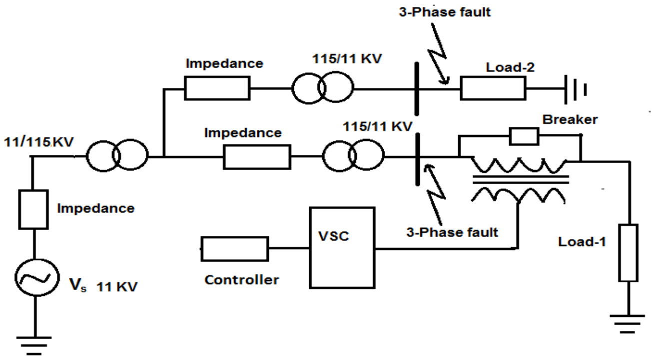

Fig10. *Single Line Diagram of DVR Test Model*

4.1. Case 1: Single Phase Ground Fault Condition

In this model a single phase line to ground fault is created in the both the feeders. The fault resistance is 0.60 ohms and the ground resistance is 0.01 ohms the time taken for the fault is 0.5s to 0.7s. The results of the load voltages and currents are given below in Fig 11 & 12.

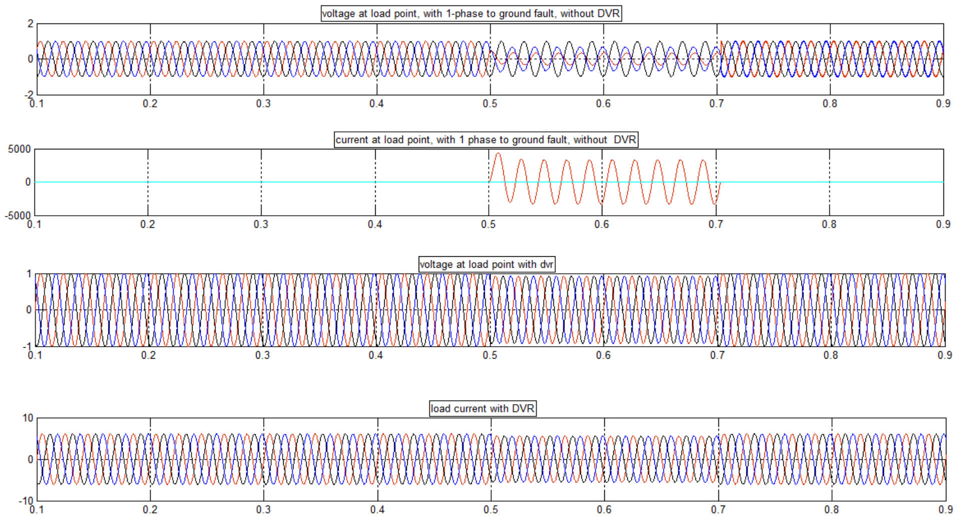

Fig11. *Voltage and Current waveform for single line to ground fault at load point without and with DVR*

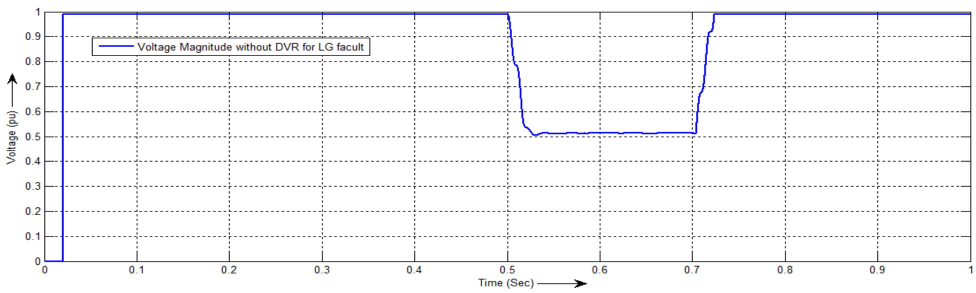

Fig12. *Waveform of Voltage magnitude without DVR for SLG fault*

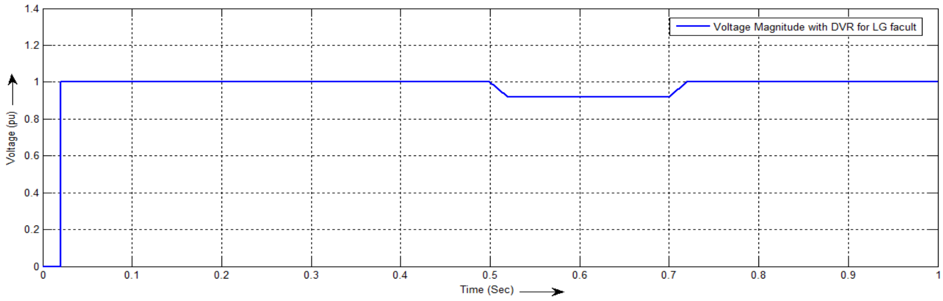

Fig13. *Waveform of Voltage magnitude with DVR for SLG fault*

4.2. Case 2: Double Line to Ground Fault

In this model a double line to ground fault is created in the both the feeders. The fault resistance is 0.60 ohms and the ground resistance is 0.01 ohms the time taken for the fault is 0.5s to 0.7s.The results of the load voltages and currents are shown in fig 14, 15 & 16. Form the results wave shape it is clear that the DVR is also effective in the case of the double line to ground fault conditions also.

4.3. Case 3: Three Phase Fault

The result for the three phases to ground faults is shown in fig 17, 18 & 19. In the proposed system the three phase fault is created on both the feeders. The three phase fault with the fault resistance work as the source of voltage sag. From the voltage magnitude curves it is clear that the voltage compensation is decreases in some one extent.

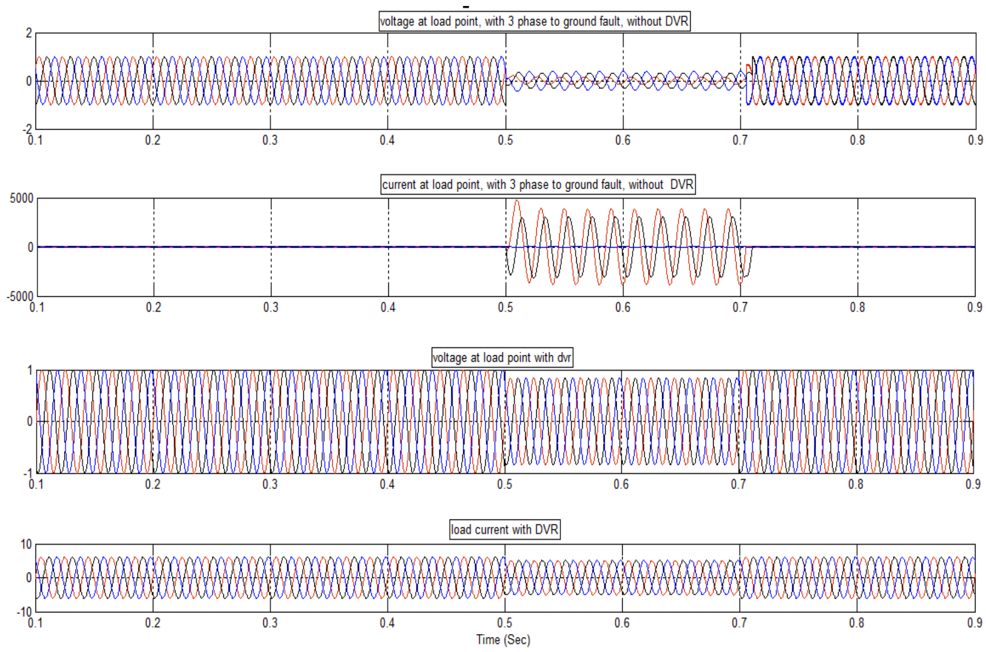

Fig14. *Voltage and Current waveform for double line to ground fault at load point without and with DVR*

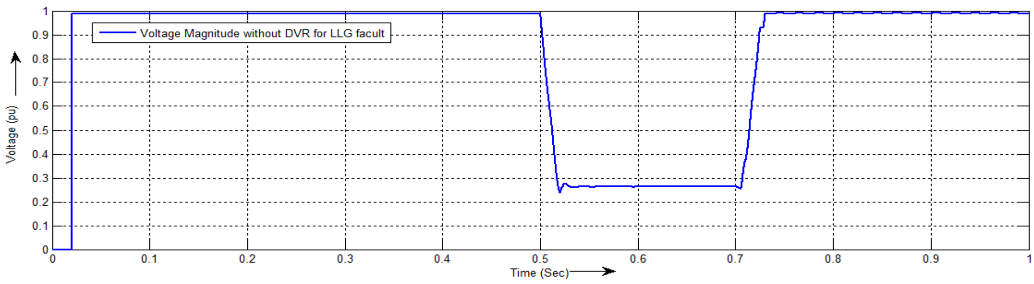

Fig15. *Waveform of Voltage magnitude without DVR for L-L-G fault*

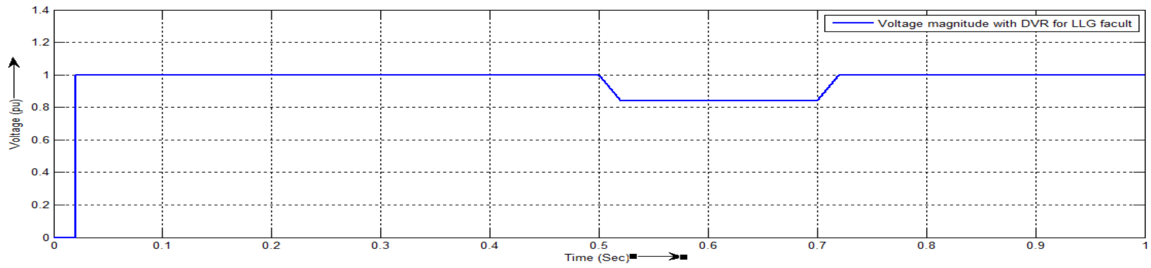

Fig16. *Waveform of Voltage magnitude with DVR for L-L-G fault*

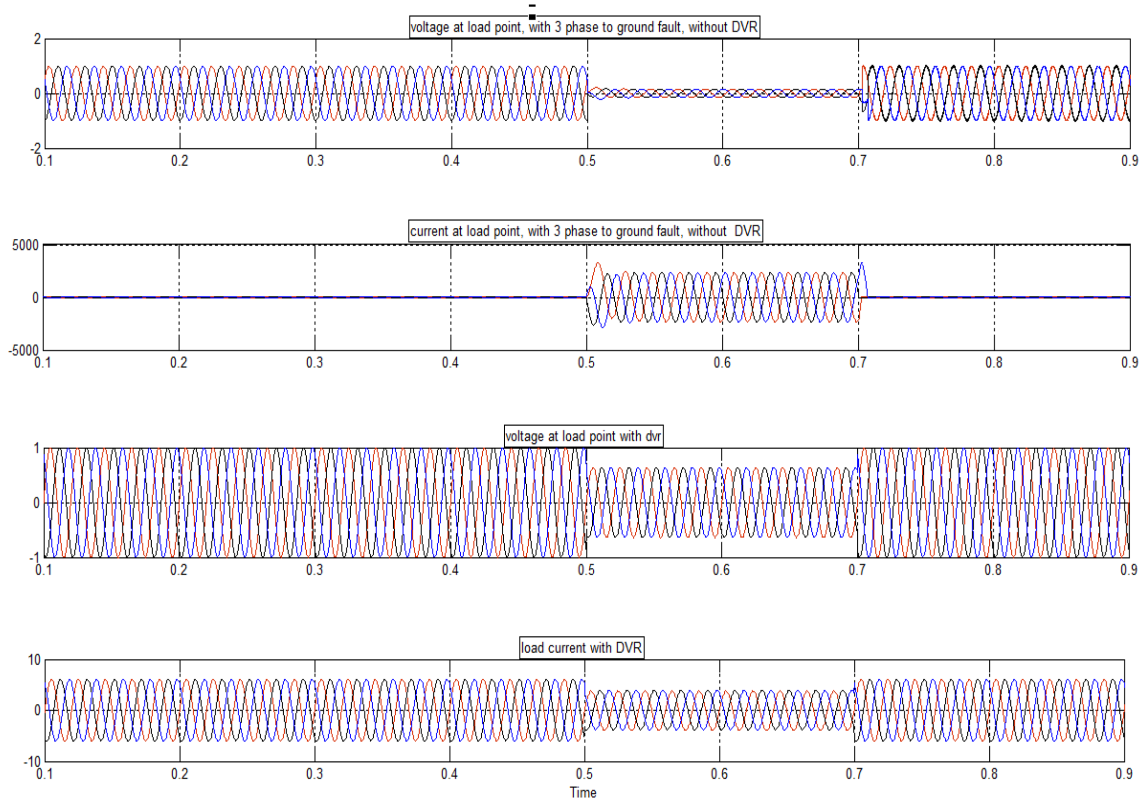

Fig17. *Voltage and Current waveform for 3-Phase line to ground fault at load point without and with DVR*

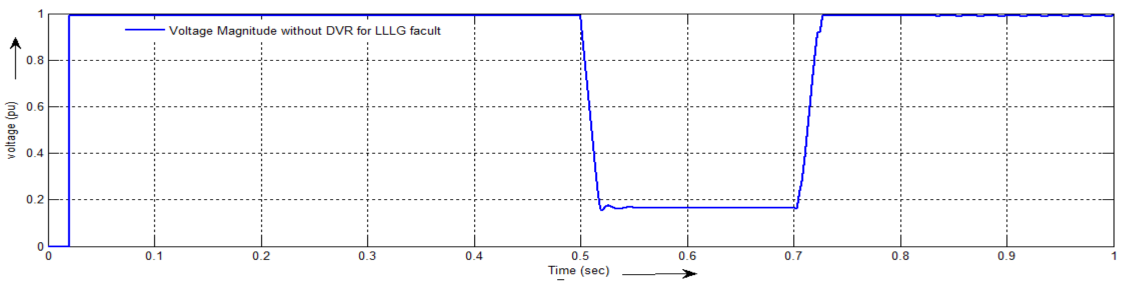

Fig18. *Waveform of Voltage magnitude without DVR for L-L-L-G fault*

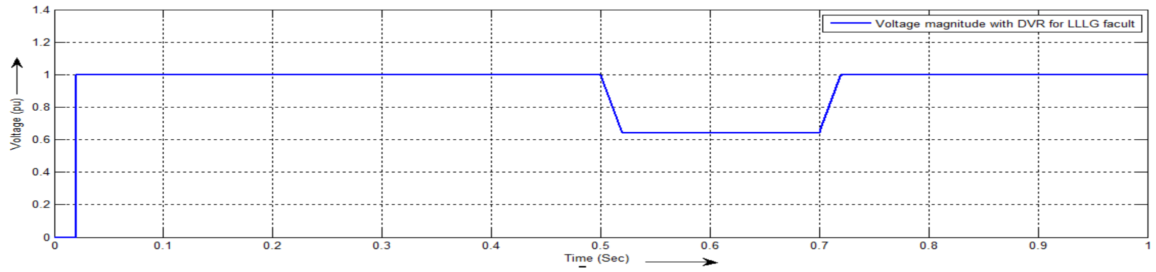

Fig19. *Waveform of Voltage magnitude with DVR for L-L-L-G fault*

The compensating power of the DVR in increasing order is in case of various faults conditions are given below LLLG<LLG<SLG.

5. Conclusion

In this proposed work the cost effective dynamic voltage restorer (DVR) is proposed for the mitigation of the problems, voltage sag during various faults conditions. The extent of compensation for various faults is given below.

- The DVR compensates up to 0.55 pu voltage during the single line to ground fault condition.
- DVR compensates up to 0.45 pu voltage during the double line to ground fault condition.
- DVR compensates up to 0.4 pu voltage during the three phase to ground fault condition.

It is clear from above that the compensation capability is decreases as the severity of the fault increases. The speed and response of the working of the DVR is very fast. The effectiveness of DVR using PI controller is established during various faults conditions. The PI control strategy also puts THD in permissible value.

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