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Dynamic Voltage Restorer Based on Load Condition

H.P. Tiwari, Sunil Kumar Gupta

***Abstract*—Dynamic voltage restorers (DVR) can provide the most commercial solution to mitigation voltage sag by injecting voltage as well as power into the system. The mitigation capability of these devices is mainly influenced by the maximum load; power factor and maximum voltage dip to be compensated. Maximum load on a feeder is an important task for DVR system operation and appropriate desired voltage sag compensation. This paper is intended to assimilate the amount of DC energy storage depends on the installed load. It is available in a convenient manner for DVR power circuit.**

***Index Terms*—Capacitor Rating, DC Energy Storage, Dynamic Voltage Restorer, Voltage Sag.**

I. Introduction

Power quality means maintaining nearly sinusoidal voltage at frequency 50/60 Hz. Voltage sag is broadly considered as a short duration voltage variation and method of characterization involves both magnitude and duration. The duration of voltage sag varies between five cycles to a minute. To prevent sensitive load from sag interruption in the source side, a series connected custom power device is used. SSSC (static synchronous series compensator) and DVR both are presently used for series voltage sag compensation. Operating principle and functioning of these devices differ significantly as the SSSC injects a balance voltage in series whereas the DVR compensates the unbalance in supply voltage of different phases. The DVR supplies the active power with help of DC energy storage and required reactive power is generated internally without any means dc storage. DVR can compensate voltage at both transmission and distribution sides. Usually a DVR is installed on a critical load feeder. During the normal operating condition (without sag condition) DVR operates in a low loss standby mode [1]. During this condition the DVR is said to be in steady state. When a disturbance occurs (abnormal condition) and supply voltage deviates from nominal value, DVR supplies voltage for compensation of sag and is said to be in transient state. The DVR is connected in series between the load and the supply voltage [2].

It basically supplies the voltage difference (difference between the pre sag and sag voltage) to transmission line and maintains the pre sag values condition in the load sides [3]. Use of DVR is proposed in low and medium voltage distribution network to protect sensitive load from sudden voltage dips/sag [4]. Pulse width modulated inverter is used to vary the amplitude and the phase angle of the injected voltages, thus allowing the control of both real and reactive power exchange between the distribution system and the load [5]. For proper voltage sag compensation, it is necessary to derive suitable and fast control scheme for inverter switching. The general requirement of a control scheme is to obtain an ac waveform with minimum total harmonic distortion (THD) and best dynamic response against supply and load disturbance when the DVR is operated for voltage sag compensation [6].

Section II discusses the PI controller strategy employed for inverter switching in the DVR. The simulation model is developed using MATLAB SIMULINK in section III. Section IV presents and discusses simulation results with different load conditions. Overall DC storage performance is discussed with different load condition in section V.

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II. Control Philosophy

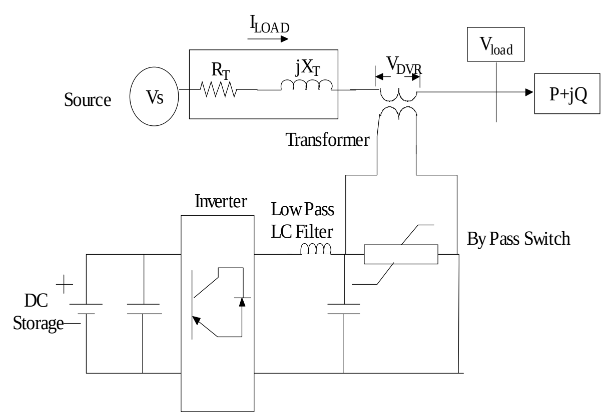

Figure 1. Basic Structureof Dynamic Voltage Restorer.

The basic structure of a DVR is shown in Fig.1. It is divided into six categories: (i) *Energy Storage Unit:* It is responsible for energy storage in DC form. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used as energy storage devices. It is supplies the real power requirements of the system when DVR is used for compensation [3]. (ii) *Capacitor:* DVR has a large DC capacitor to ensure stiff DC voltage input to inverter. (iii) *Inverter:* An Inverter system is used to convert dc storage into ac form [7]. Voltage source inverter (VSI) of low voltage and high current with step up injection transformer is used for this purpose in the DVR

Compensation technique [3]. (iv) *Passive Filters:* Filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This is achieved by eliminating the unwanted harmonic components generated VSI action. Higher orders harmonic components distort the compensated output voltage [8]. (v) *By-Pass Switch:* It is used to protect the inverter from high currents in the presence of faulty conditions. In the event of a fault or a short circuit on downstream, the DVR changes into the bypass condition where the VSI inverter is protected against over current flowing through the power semiconductor switches. The rating of the DVR inverters becomes a limiting factor for normal load current seen in the primary winding and reflected to the secondary winding of the series insertion transformer. For line currents exceeding the rating, a bypass scheme is incorporated to protect the power electronics devices [9]. (vi) *Voltage Injection Transformers:* In a three-phase system, either three single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose [8].

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.3. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A proportional-integral (PI) controller (shown in Fig. 2) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is

$$V_{ref} - V_{in}. \quad (1)$$

V_{ref} equal to 1 p.u. voltage
V_{in} voltage in p.u. at the load terminals.

The controller output when compared at PWM signal generator results in the desired firing sequence.

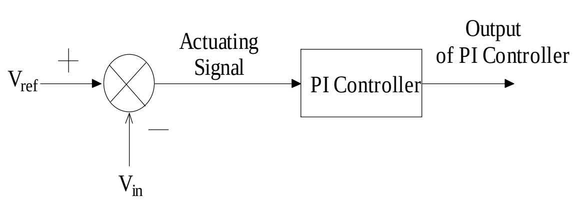

Figure 2. Schematic of a typical PI Controller.

The modulated angle is applied to the PWM generators in phase A as shown in (2). The angles for phases B and C are shifted by 120° and 240°, respectively as shown in (3) and (4). In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme [7].

The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle and the modulated three-phase voltages are given by

$$V_a = \sin(\omega t + \delta) \quad (2)$$
$$V_b = \sin(\omega t + \delta + 2\pi/3) \quad (3)$$
$$V_c = \sin(\omega t + \delta + 4\pi/3) \quad (4)$$

III. Parameters Of DVR Test System

Electrical circuit model of DVR test system is shown in Fig.3. System parameters are listed in Table 1. Voltage sag is created at load terminals via a three-phase fault as shown in Fig.3. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}).

TABLE 1. System Parameters

S.No.	System Quantities	Standards
1	Inverter Specifications	IGBT based,3 arms , 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 μs
2	Transmission Line Parameter	R=0.001 ohms ,L=0.005 H
3	PI Controller	K_P=0.5 K_i=50 Sample time=50 μs

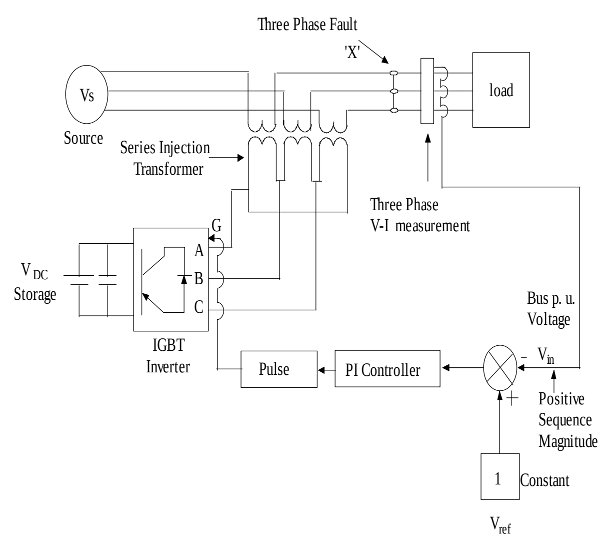

Figure 3. Circuit Model of DVR Test System

MATLAB Simulation diagram of the test system is shown in Fig.4. System comprises of 13 kV, 50 Hz generator, feeding transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/ 11 kV.

IV. Simulation Results

Detailed simulations are performed on the DVR test system using MATLAB SIMULINK. System performance is analyzed for compensating voltage sag with different DC storage capacity so as to achieve rated voltage at a given load. Various cases of different load condition are considered to study the impact DC storage on sag compensation. These various cases are discussed below:

Case I: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 16.75%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 5.

TABLE 2. Variable System Parameters

S.No.	System Quantities	Standards
1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 10 Kw Inductive Reactive Power =400 Var
3	Load-2	Active power = 10 Kw Inductive Reactive Power =400 Var

The simulation results without DVR compensation technique are shown in Fig. 6 on p.u basis. Fig. 7 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 3.1kV.

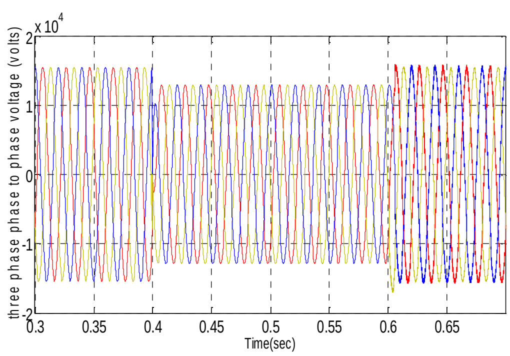

Figure 5. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

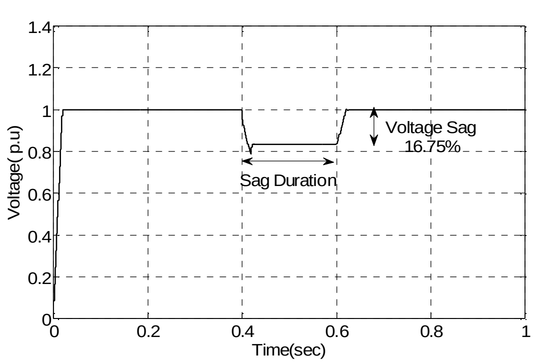

Figure 6. Voltage p.u. at the Load Point without DVR System

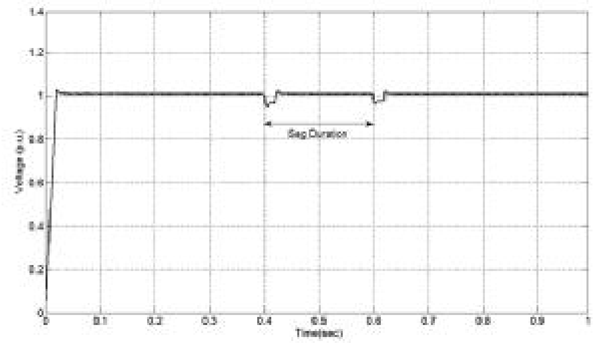

Figure 7. Voltage p.u. at the Load Point with DC storage of 3.1 kV.

Case II: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 16.87%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 8.

TABLE 3. Variable System Parameters

S.No.	System Quantities	Standards
1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 100 Kw Inductive Reactive Power =400 Var
3	Load-2	Active power = 100 Kw Inductive Reactive Power =400 Var

The simulation results without DVR compensation technique are shown in Fig. 9 on p.u basis. Fig. 10 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 3.4kV.

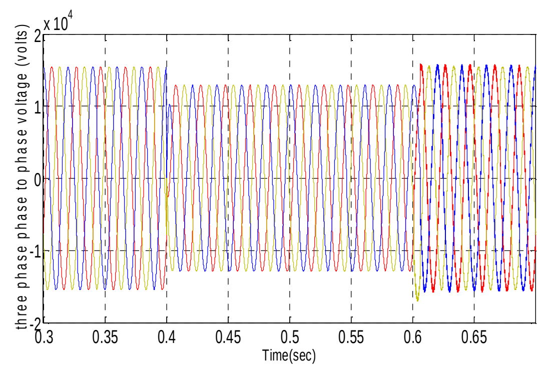

Figure 8. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

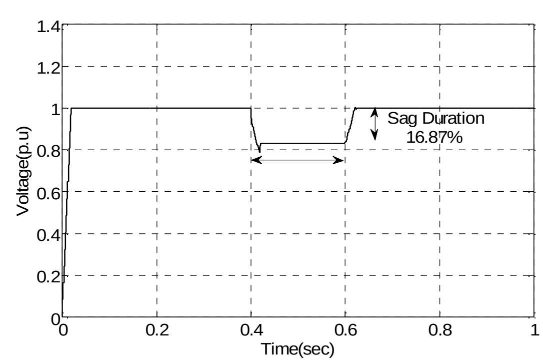

Figure 9. Voltage p.u. at the Load Point without DVR System.

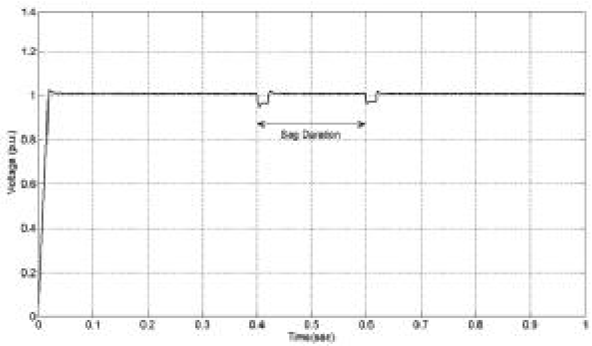

Figure 10. Voltage p.u. at the Load Point with DC storage of 3.4 kV.

Case III: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 16.95 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 11.

TABLE 4. Variable System Parameters

S.No.	System Quantities	Standards
1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 1000 Kw Inductive Reactive Power =400 Var
3	Load-2	Active power = 1000 Kw Inductive Reactive Power =400 Var

The simulation results without DVR compensation technique are shown in Fig. 12on p.u basis. Fig. 13 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 5.9kV.

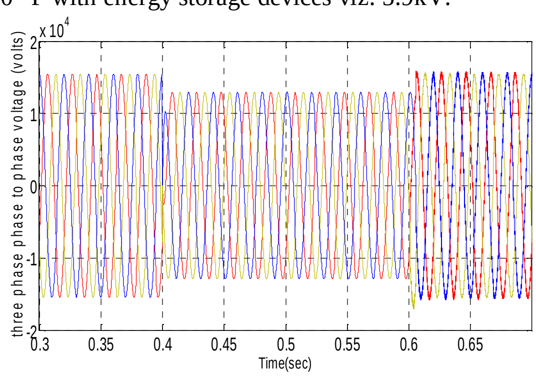

Figure 11. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

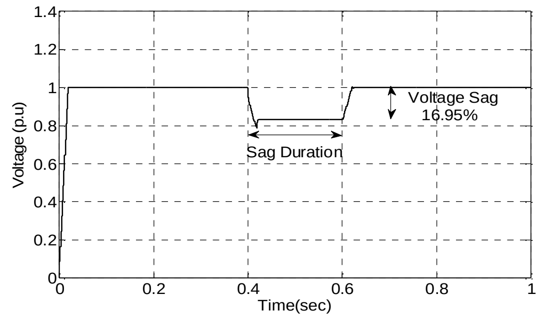

Figure 12. Voltage p.u. at the Load Point without DVR System.

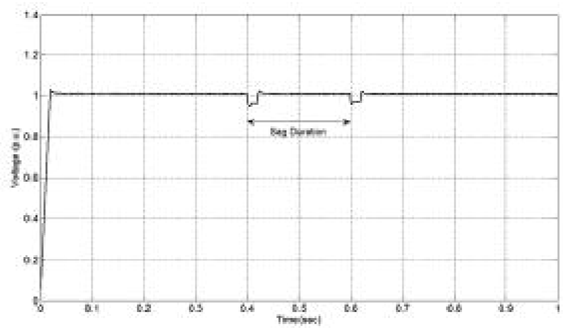

Figure 13. Voltage p.u. at the Load Point with DC storage of 5. 9 kV.

Case IV: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.16%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 14.

TABLE 5. Variable System Parameters

S.No.	System Quantities	Standards
1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 2 Mw Inductive Reactive Power =400 Var
3	Load-2	Active power = 2 Mw Inductive Reactive Power =400 Var

The simulation results without DVR compensation technique are shown in Fig. 15 on p.u basis. Fig. 16 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 8.5kV.

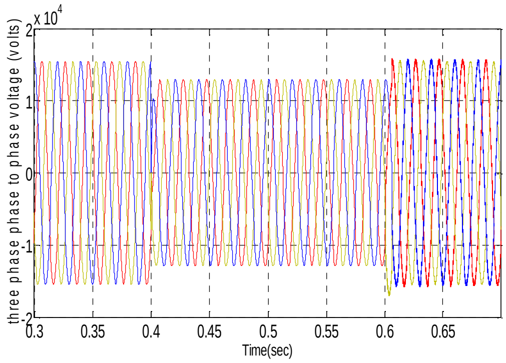

Figure 14. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

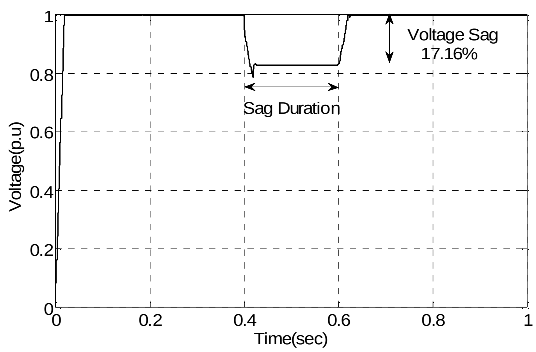

Figure 15. Voltage p.u. at the Load Point without DVR System.

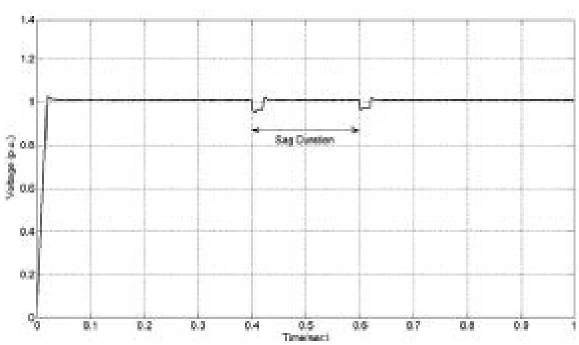

Figure 16. Voltage p.u. at the Load Point with DC storage of 8.5 kV.

Case V: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.56%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 17.

TABLE 6. Variable System Parameters

S.No.	System Quantities	Standards
1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 4 Mw Inductive Reactive Power =400 var
3	Load-2	Active power = 4 Mw Inductive Reactive Power =400 var

The simulation results without DVR compensation technique are shown in Fig. 18 on p.u basis. Fig. 19 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with different energy storage devices viz. above 3kV.

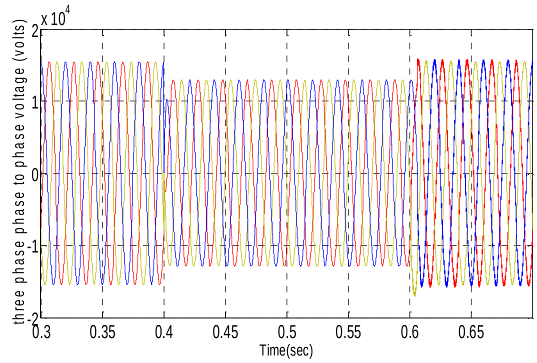

Figure 17. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

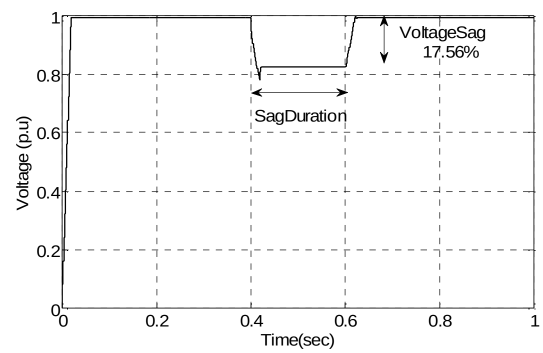

Figure 18. Voltage p.u. at the Load Point without DVR System.

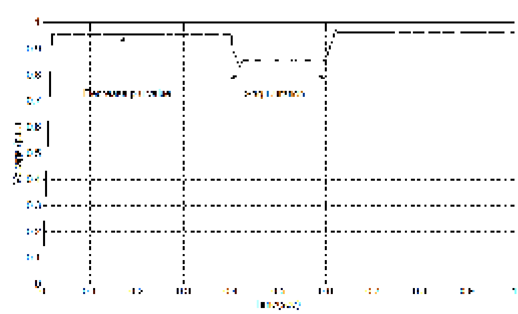

Figure 19. Voltage p.u. at the Load Point with DC storage of some kV.

Case VI: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 18.26 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 20.

TABLE 7. Variable System Parameters

S.No.	System Quantities	Standards

1	Fault Resistance	R= 0.66 ohms
2	Load-1	Active power = 10 Mw Inductive Reactive Power =400 var
3	Load-2	Active power = 10 Mw Inductive Reactive Power =400 var

The simulation results without DVR compensation technique are shown in Fig. 21 on p.u basis. Fig. 22 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with different energy storage devices above 3kV.

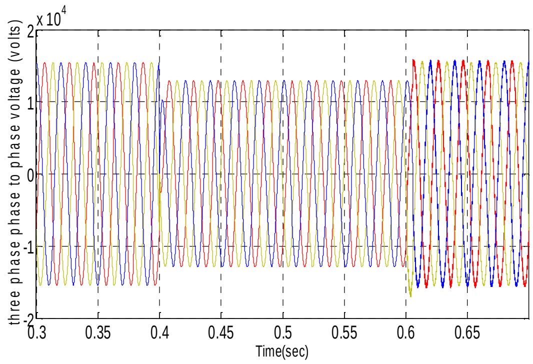

Figure 20. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

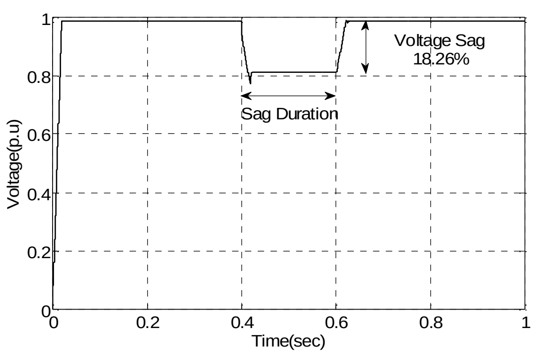

Figure 21. Voltage p.u. at the Load Point without DVR System.

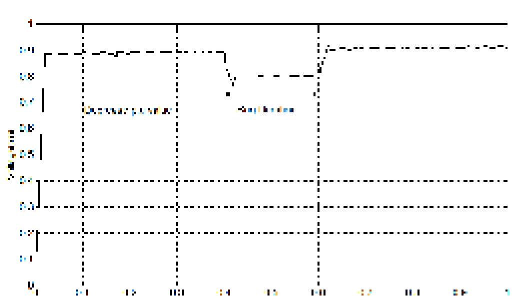

Figure 22. Voltage p.u. at the Load Point with DC storage of some kV.

V. Overall Dc Storage Performance

Voltage sag compensation is done through DVR power circuit by using DC storage units. It is used for maintaining the load terminal voltage at 11kV transmission level as shown above from *Case I* to Case *VI*. Comparison results show in tabular form in Table 8.

TABLE 8. Desired Voltage sag Compensation Comparison.

S.No.	Load-1	Load-2	Remark
1	10 Kw,400 Var	10 Kw,400 Var	DC voltage = 3.1KV
2	100 Kw,400 Var	100 Kw,400 Var	DC voltage = 3.4KV
3	1Mw,400 Var	1Mw,400 Var	DC voltage = 5.9KV
4	2Mw,400 Var	2Mw,400 Var	DC voltage = 8.5KV
5	4Mw,400 Var	4Mw,400 Var	Above 3kV
6	10 Mw, 400 Var	10 Mw, 400 Var	Above 3kV

Above results shows that DC storage values are different for different loads. Simulation result shows that when the load increases on the 11 KV feeders, the DC storage value also increase with increasing the load as shown in above case from I to IV. In the case V and VI are observed that when increase load above from 4 Mw, the per unit voltage value fall below 1 per unit and continuously decreases with increase the loads above 4Mw on the 11 kV feeder.

VI. Conclusion

Based on the analysis of test system, it is suggested that load amount are major factors in estimating the DC storage value. Investigations were carried out for various cases of load at 11kV feeder. The effectiveness of a DVR system mainly depends upon the rating of DC storage rating and the loads. In the test system it is observed that after a particular amount of load increases on 11 kV feeders, the voltage levels at the load terminal decreases.

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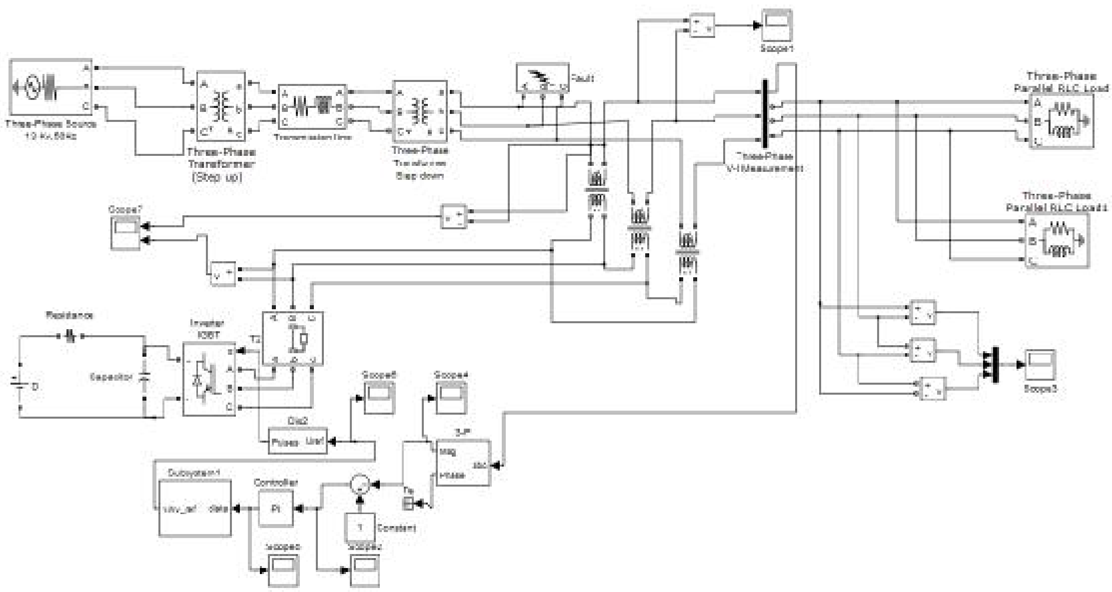

Figure 4. Simulation Model of DVR Test System