Dynamic Voltage Restorer against Voltage Sag

H.P. Tiwari and Sunil Kumar Gupta

***Abstract*—A dynamic voltage restorer (DVR) is a custom power device used to correct the voltage sag by injecting voltage as well power into the system. The mitigation capability of these devices is mainly influence by the maximum load; power factor and maximum voltage dip to be compensated. Voltage Dips 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 voltage dip. It is available in a convenient manner for DVR power circuit.**

***Index Terms*—DC Energy Storage, Dynamic Voltage Restorer, Power Quality, Voltage Sag.**

I. Introduction

One of the major concerns in electricity industry today is power quality problems to sensitive loads. Presently, the majority of power quality problems are due to different fault conditions. These conditions cause voltage sag [1]. Voltage sag may cause the apparatus tripping, shutdown commercial, domestic and industrial equipment, and miss process of drive system. Dynamic voltage restorer (DVR) can provide the cost effective solution to mitigate voltage sag by establishing the appropriate voltage quality level, required by the customer [2, 3]. It is recently being used as the active solution for voltage sag mitigation.

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 [4]. 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 [1].

(v) *By-Pass Switch:* It isused 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 [5]. (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. [1].

Basic principal of DVR is to transfer the voltage sag compensation value from DC side of the inverter to the injected transformer after filter. The compensation capacity of a particular DVR depends on the maximum voltage injection capability and the active power that can be supplied by the DVR. When DVR's voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system [6]. A DC system, which is connected to the inverter input, contains a large capacitor for storage energy. It provides reactive power to the load during faulty conditions. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage decrease. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the require voltage thus, size and rating of capacitor is very important for DVR power circuit [7]. The DC capacitor value for a three phase system can be derived [8]. The most important advantage of these capacitors is the capability to supply high current pulses repeatedly for hundreds of thousands of cycles. Selection of capacitor rating is discussed on the basis of RMS value of a capacitor current, rated voltage of a capacitor and VA rating of the capacitor [9].

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 sag conditions. Overall DC storage performance is discussed with different sag condition in section V.

II. Control Philosophy

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

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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

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

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.

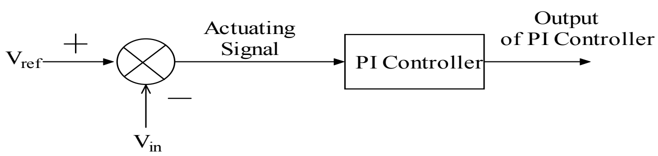

Fig.1. Schematic of a typical PI Controller

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 [4].

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

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

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
4	Load-1	Active power = 1 Kw Inductive Reactive Power =400 Var
5	Load-2	Active power = 1 Kw Inductive Reactive Power =400 Var

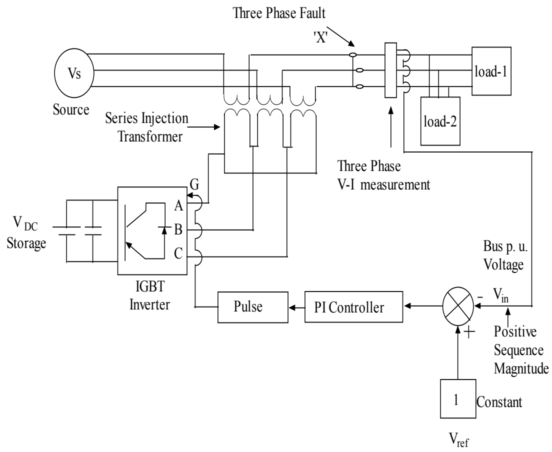

Fig.2. Circuit Model of DVR Test System

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 17.02 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 5.

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.

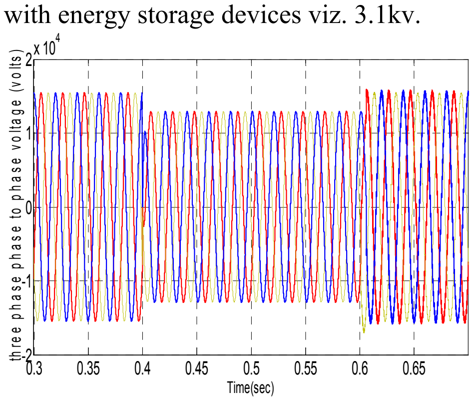

Fig.4. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

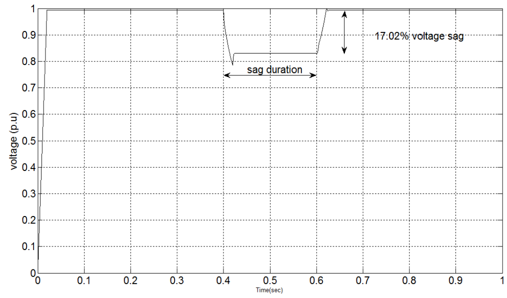

Fig.5. Voltage p.u. at the Load Point without DVR System

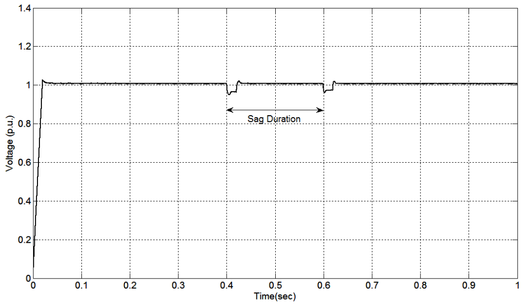

Fig.6. Voltage p.u. at the Load Point with DC storage of 3.1 kV

Case II: A three-phase fault is created at point X via a resistance of 0.60 Ω which results in a voltage sag of 19 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 8.

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. 3.3 kV.

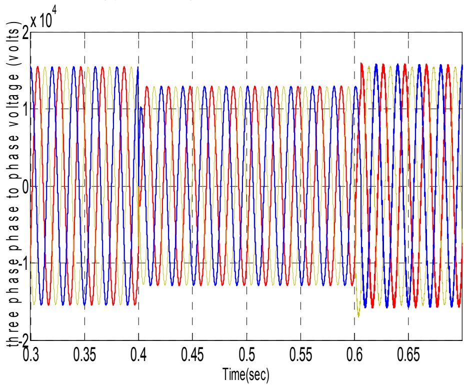

Fig.7. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

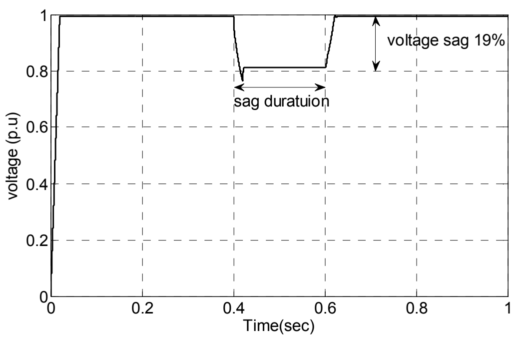

Fig.8. Voltage p.u. at the Load Point without DVR System

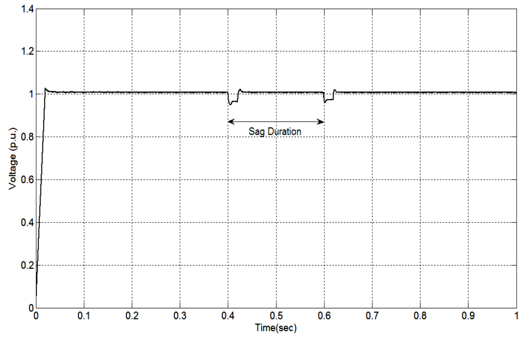

Fig.9. Voltage p.u. at the Load Point with DC storage of 3.3 kV

Case III: A three-phase fault is created at point X via a resistance of 0.50 Ω which results in a voltage sag of 23 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 11.

The simulation results without DVR compensation technique are shown in Fig. 12 on p.u basis. Fig. 13 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 3.5 kV.

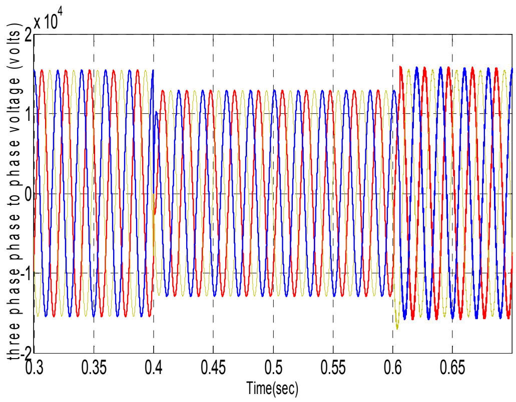

Fig.10. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

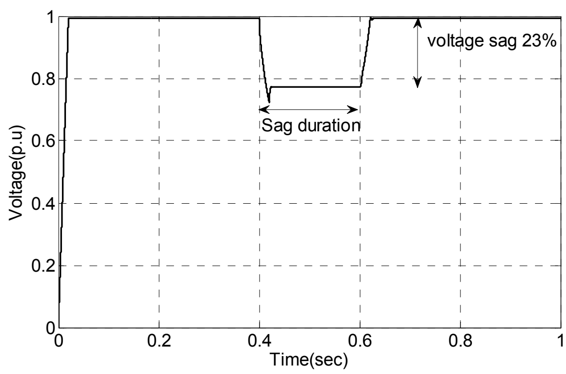

Fig.11. Voltage p.u. at the Load Point without DVR System

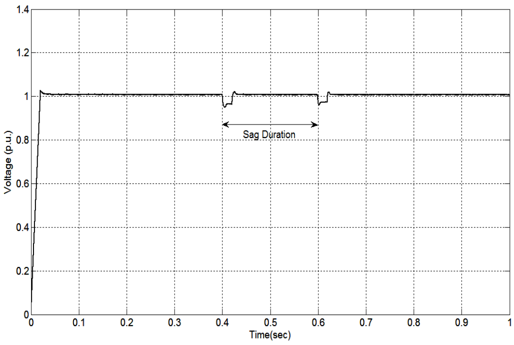

Fig.12. Voltage p.u. at the Load Point with DC storage of 3.5 kV

Case IV: A three-phase fault is created at point X via a resistance of 0.45 Ω which results in a voltage sag of 26 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 14.

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 different energy storage devices viz. 3.7kV.

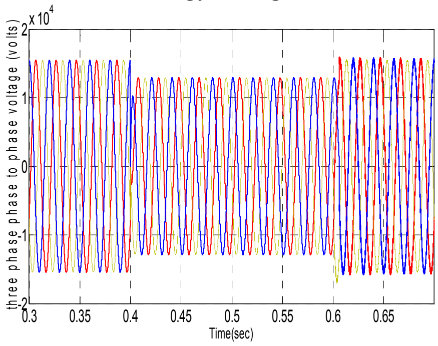

Fig.13. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

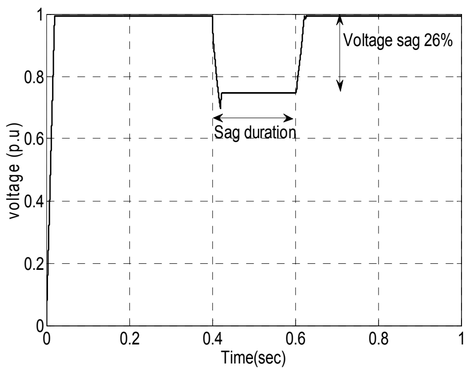

Fig.14. Voltage p.u. at the Load Point without DVR System

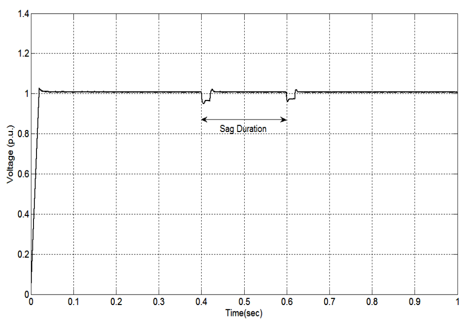

Fig.15. Voltage p.u. at the Load Point with DC storage of 8.5 kV

Case V: A three-phase fault is created at point X via a resistance of 0.40 Ω which results in a voltage sag of 29 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 17.

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 3.7kv.

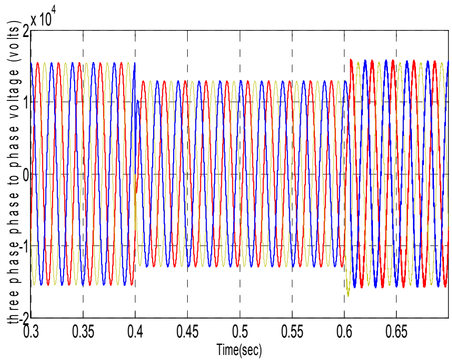

Fig.16. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

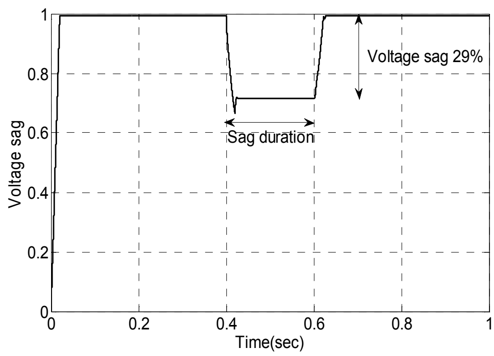

Fig.17. Voltage p.u. at the Load Point without DVR System

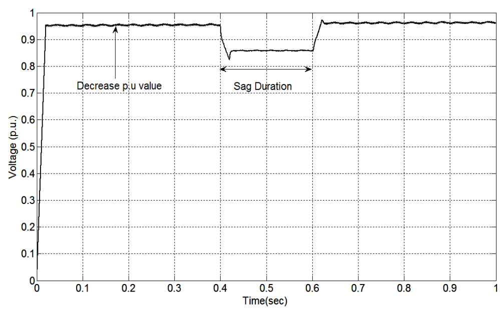

Fig.18. Voltage p.u. at the Load Point with DC storage of 4.3 kV.

V. Overall DC Storage Rating Performance with Voltage Dip

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 *IV*.

TABLE.2 DESIRED VOLTAGE SAG COMPENSATION COMPARISON.

S.No.	Percentage Voltage Sag	Required DC Voltage
1	17.02%	3.1
2	19%	3.3

3	23%	3.5
4	26%	3.7
5	29%	Above 3.7 kV

In the above table it is shown that required DC storage values are not same for different voltage sag conditions, when the load is fixed on 11 kV feeders. The amount of DC energy storage is increased with increase in the percentage voltage sag as shown above from case I to IV. In case V, it is observed that when percentage voltage sag is increased above 28% (approximate). The per unit voltage fall below 1 per unit value and it is continuously decreases with increase in percentage voltage sag for 11 kV feeder.

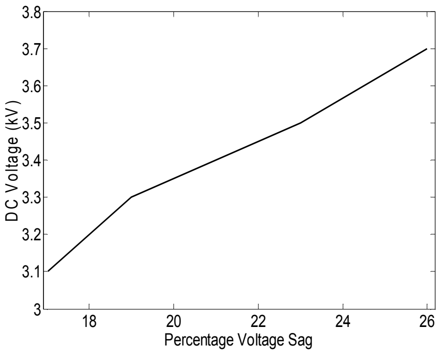

Fig.19. Percentage Voltage Sag Verses DC Storage (kV)

Fig .20 shows the variation of DC storage voltage with the increase percentage voltage sag. DC storage value can be estimated from the following Equation (1)

$$Y = 0.0012 X^3 - 0.008X^2 + 1.8X - 10 \quad (1)$$

Where Y= DC Voltage (kV) and

X= Percentage Voltage sag

Equation (1) has one limitation that it is valid up to 26% voltage dip mitigation. Above this value it is not valid. The voltage sags values continuously decrease with increase in percentage voltage sag at 11 kV feeders as shown in case V.

VI. CONCLUSION

Based on the analysis of test system, it is suggested that voltage sag values 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 percentage voltage sag. In the test system it is observed that after a particular amount of voltage sag, the voltage level at the load terminal decreases.

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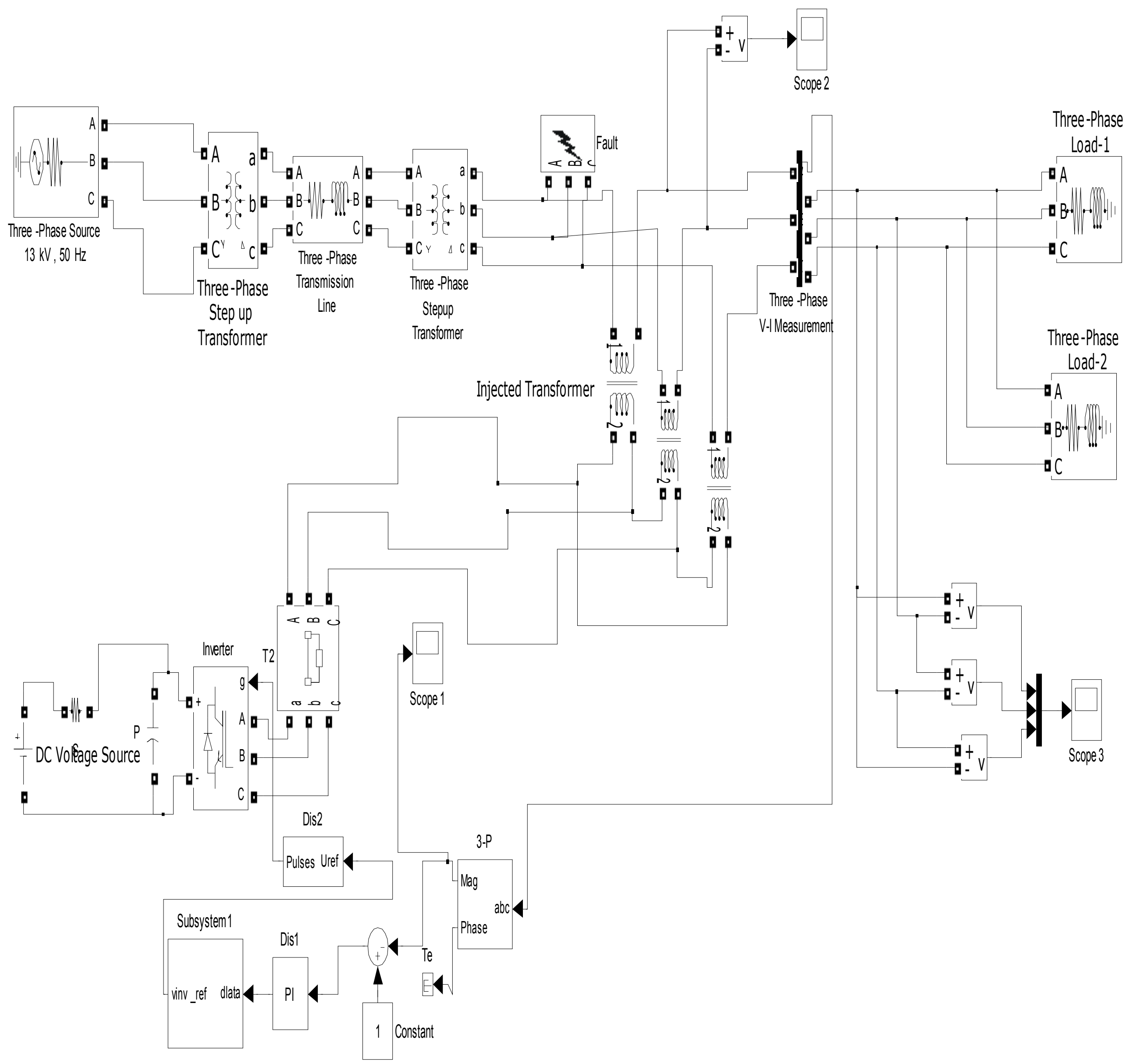

Fig.3. Simulation Model of DVR Test System