Simulation-based Analysis of a Dynamic Voltage Restorer under Different Voltage Sags with the Utilization of a PI Controller

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***Abstract*-Power quality problems are becoming a major issue. Every utility company consumer desires to receive steady-state voltage, i.e. a sinusoidal waveform of constant frequency as generated at power stations, but the influence of disturbances in the shape of sags and swells, interruptions, transients and harmonic distortions which affect power quality, resulting in loss of data, damaged equipment, and augmented cost. The most powerful voltage disturbance is the sag voltage. In this paper, a Dynamic Voltage Restorer (DVR) is proposed for sag voltage compensation. It is cost-effective and protects critical loads in a good manner from balanced or unbalanced sag voltage. Control strategy (such as a PI controller) is adopted with DVR topology and the performance of such a device with the proposed controller is analyzed through simulation in MATLAB/Simulink. Three types of faults are utilized, which are available in MATLAB/Simulink pack, for obtaining the sag voltage. The specific range of total harmonic distortion percentage is also discussed. After the result validation of the DVR topology in MATLAB/Simulink, it has been seen that the proposed topology is able to compensate the sag voltage of any type of fault and reduce the unbalancing and voltage distortions of the grid.**

Keywords-Dynamic Voltage Restorer (DVR); Voltage Source Inverter (VSI); faults; power quality

I. INTRODUCTION

Globally, power quality problems are becoming a major issue. The distribution system network supplies voltage to consumers for utilization [1, 2]. Every consumer desires to receive a steady state voltage, i.e. a sinusoidal wave form of constant frequency as generated at power stations but disturbances produced on the distribution system [3] result in distorted waveforms, which create a difficulty in the operation of electrical and electronic equipment in industries risking production loss, restarting expenses, and breakdown [4]. Voltage disturbances are sag and swell voltage, unbalance voltage, voltage fluctuations, small and large interruptions, harmonic distortions, and transients [5]. The most powerful disturbance is sag voltage: it is defined as a decrease in voltage from 10% to 90% for durations up to one minute [6]. Mostly voltage sags are observed during the start of an induction motor, the energization of a transformer, system faults, or non-liner loads [7-9]. The problem of sag voltage can be avoided through the application of voltage compensation devices such as a Dynamic Voltage Restorer (DVR) [10, 11].

II. DYNAMIC VOLTAGE RESTORER

DVR is a commonly used device for sag voltage compensation. The DVR is connected in series to the sensitive loads and adds the needed voltage when necessary. DVR voltage sag compensation is a cost effective method applicable in small and large loads up to 45MVA or even larger [9]. DVR is mainly composed of components such as the Voltage Source Inverter (VSI), a voltage injection device, a filter, an energy storage device, and a controlling device [12, 13]. Figure 1 shows the proposed DVR topology.

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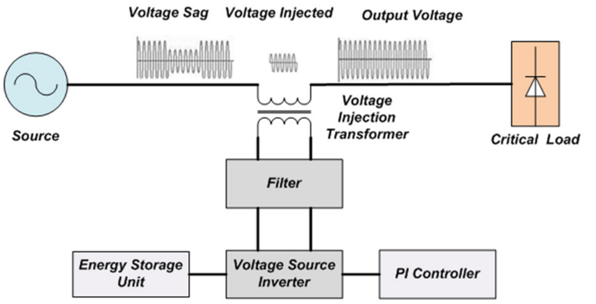

Fig. 1. Proposed DVR

III. DVR COMPONENTS

A. Energy Storage Unit

Through this commonly used in DVR topology unit, low and high values of voltage are compensated and the efficiency of DVR increases. Usually batteries, superconducting magnetic and super capacitor energy storages are utilized as energy storage units [12-14].

B. Voltage Source Inverter

This is the most valuable component in DVR topology. It allows supplying the necessary voltage to the load for compensation. VSI is composed of power electronic components and has the capability of changing the direct current (DC) into a sinusoidal current (AC) with the desired amplitude, frequency and phase angle supplied by the energy storage unit. VSI is switched ON through DC voltage supply of small input impedance and output voltage is independent of load current [9].

C. Filter

DVR is a non-linear device because of its semiconductor components. This would result in distortion in the output voltage waveforms. To avoid the problem of distorted wave forms, a filter is employed to get distortion free voltage to the load [9, 12, 15].

D. Voltage Injection Device

A voltage injection device such as the power transformer is employed in DVR topology and connected with each phase individually. Its main purpose is to add the needed voltage to the load. Better performance and reliability of voltage injection transformer is based on the selection of MVA rating, impedance and turns ratio [9, 14].

E. By-pass Switch

Large current flows after the occurrence of fault on the power system will result in excessive current flows through the DVR, so it is essential to give another path to the current. This can be achieved through the by-pass switch.

F. Controlling Device

The controller has an imperative role in any system. In DVR, the controller is contributed to the role of an observer of bus-bar voltage. If voltage sag is detected then it closes the by-pass switch and the required voltage is added to the load.

IV. DVR OPERATING MODES

The DVR operates in three modes [9, 16], which are presented below.

A. Standby Mode

The DVR is not supplying voltage to the load during this mode but due to transformer reactance it may inject some voltage for voltage drop compensation [9].

B. Protection Mode

Faults on the power system result in the flow of heavy currents which result in damaging the DVR [9]. So, protection of the DVR is necessary by using protective devices such as breakers [17, 18].

C. Injection Mode

When a voltage sag is sensed, the DVR comes into operation very quickly [15] and the required voltage value is added to the load. In this way, the voltage sag is compensated [9].

V. VOLTAGE INJECTION TECHNIQUES

There are four voltage injection techniques employed in DVR topology [19]:

A. Pre-sag Technique

This technique is superior, because through it, the voltage difference before and after the sag is added to the load but it needs an energy storage unit of large capacity because of the un-controlled injected active power.

B. Phase Advance Technique

In this technique, DVR use of real power is trimmed-down through the reduction in power angle.

C. Voltage Tolerance with Minimum Energy Technique

In this technique, we can retain the load voltage in the patience area of less variation of voltage magnitude.

D. In-phase Voltage Injection Technique

In this technique, the non-variable value of load voltage is achieved despite different phase angles of pre-sag and load voltage due to in-phase association of the added voltage with supply voltage.

VI. PROPOSED METHODOLOGY

A. Voltage Sag Calculation

Source voltage and source reactance (V_s and X_s) are shown in the equivalent circuit in Figure 2 and loads such as Z_1 and Z_2 are supplied through two feeders named F_1 and F_2. Under normal operating condition, the supply current I_s and pre-sag voltage at the common coupling point are shown in (1):

$$I_s = I_1 + I_2 = \frac{V_{pre\ sag}}{Z_1+X_{F1}} + \frac{V_{pre\ sag}}{Z_2+X_{F2}} \quad (1)$$

where Z is the impedance of the load, X_F is the feeder reactance magnitude, and I_s is the supply current. When abnormal conditions occur (fault on feeder F_1) the result is the flowing of large load and supply current. Equations (2)-(3) show the supply voltage and fault current at the common coupling point.

$$V_s = V_s - I_{s,fault} X_s \quad (2)$$

$$I_{s,fault} = \frac{V_{sag}}{X_{F1}} + \frac{V_{sag}}{Z_2 + X_{F2}} \quad (3)$$

It has been seen that, the voltage across F_2 is decreased because of the large voltage drop, also called sag voltage, produced across the X_s (source reactance). Figure 3 shows the equivalent circuit where the DVR is connected and adds the needed voltage V_{DVR} to the critical load to compensate the value of sag voltage.

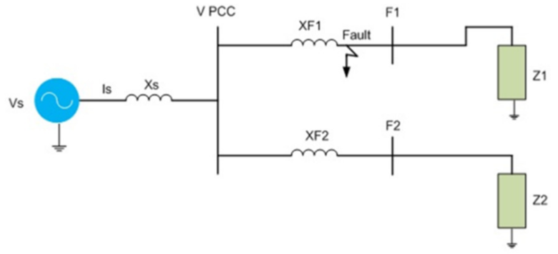

Fig. 2. Sag voltage calculation.

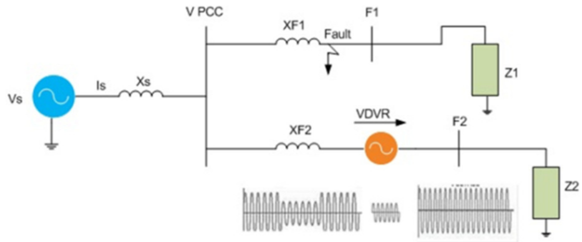

Fig. 3. Voltage injection through the DVR.

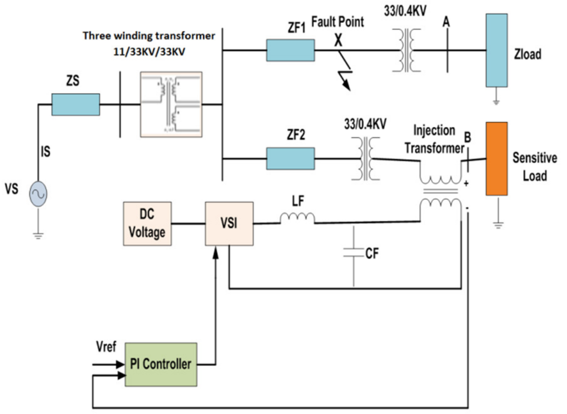

Fig. 4. Proposed one line diagram.

Figure 4 shows the one line diagram of the 11kV, 50Hz power system, which generates voltage, the three winding power transformer of star grounded/delta/delta, which supplies voltage to two transmission lines. These two transmission lines supply voltage to two distribution systems and these two supply voltages are stepped down to 0.4kV through the distribution transformer which is connected in star and delta. The faulty feeder where different faults will occur at point X is connected through bus-A and the neighboring feeder where sensitive loads are connected is represented by bus-B. The DVR performance is authenticated by applying different types of faults with 130ms fault time.

B. Voltage Total Harmonic Distortion

Power quality (system output voltage) is well defined through Total Harmonic Distortion (TDH) method. A 5% or less voltage TDH is acceptable when the voltage magnitude is up to 69kV. The border line for single frequency voltage harmonic is 3% [21]. Equations (4)-(5) show the voltage TDH calculated at the common coupling point, where the harmonic number is symbolized by h and the phase order is symbolized by p, so p is equal to a, b, c [22, 23].

$$THD_v = \frac{THD_{v_a} + THD_{v_b} + THD_c}{3} \quad (4)$$

$$THD_{Vp} = \frac{\sqrt{\sum h \geq 2\, V^2\, phase}}{Vp} \times 100 \quad (05)$$

C. Voltage Sag Indice

Sag voltage and recovered voltage quality is pointed-out through sag voltage indices which are very sensitive to voltage disturbances and provide a precise response on the performance of the system. The below mentioned indices are also conversed in simulation outcomes.

1) Detroit Edison Sag Score (SS):

For contracts between utilities and customers, the first utilized index was s Detroit Edison Sag Score. It is defined by [24]:

$$SS = 1 - \frac{V_a + V_b + V_c}{3} \quad (6)$$

where V_a, V_b and V_c are the phase voltages. If we get the outcome of $SS\%$ near to 0, then we can say that, after sag voltage compensation, the recovered voltage is better.

2) Voltage Sag Lost Energy Index (VSLEI)

This type of index provides the lost energy (W) when a reduction in voltage is observed for short duration. The same is applied to the load as shown in (7):

$$W = \sum_P V_p = \sum_P T_p \times \left(1 - \frac{V_p}{V_{nominal}}\right)^{3.14} \quad (7)$$

where $P = a, b, c$, V_p is the phase voltage during the occurrence of sag and T_p is the sag period (ms) for every phase [25]. When the calculations are carried out for the three phases, the required energy is added to the phases individually.

3) Phase Voltage Unbalance Rate (PVUR)

PVUR [25] is given by:

$$PVUR = \frac{Maximum_{vd}}{V_{avg}} \times 100 \quad (8)$$

where V_d shows the variation in phase voltage from V_{avg}.

VII. DVR CONTROL ALGORITHM

In this study, the PI controller is proposed for the DVR and Parks transformation dq_o method is used for the generation of the reference voltage as shown in (9) to the series voltage source inverter to search for and maintain the load side voltage at its actual value. ω represents the angular frequency (rad/s).

Through this method, the three phase voltages are easily controlled because of the transformation from three phase to two voltage components ($\boldsymbol{V_d}$ and $\boldsymbol{V_q}$) while the zero sequence components of phases abc are neglected. As shown in control block diagram in Figure 5, free wave distortion is basically generated through a Phase Locked Loop (PLL) circuit [26].

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2\sin\omega t & 2\sin(\omega t - \frac{2\pi}{3}) & 2\sin(\omega t + \frac{2\pi}{3}) \\ 2\cos\omega t & 2\cos(\omega t - \frac{2\pi}{3}) & 2\cos(\omega t + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (9)$$

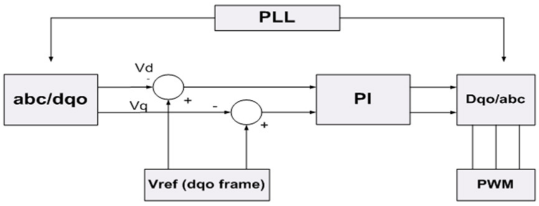

Fig. 5. DVR controller scheme.

The DVR controller is employed to observe the load voltage on bus-bar and the load voltage components are compared with *dq* components. When the voltage is trimmed-down, an error signal is produced between the measured and the reference voltage to activate the controller whereas the output signal is produced from the proposed controller to add the needed voltage to the load. In-order to get a distortion-free output voltage, it is necessary to add a filter. In this study, a LC low pass filter is proposed for the suppression of harmonic distortion and switching signals of 5.5kHz for frequency modulation are considered. Pulse Width Modulation (PWM) technique is used for VSI for the production of three 50Hz phases at load terminals. An IGBT switching device for VSI is selected for the study of the DVR operation.

VIII. SIMULATION RESULTS

The controller's performance under harmonic distortions and non-linear load is analyzed by applying three conditions in MATLAB simulation scenarios. The applied mathematical statistics is available in [26]. The three fault conditions which are applied to the system to evaluate the performance of DVR are presented in Table I and are discussed below.

TABLE I. FAULT CONDITIONS

Condition	Fault Type
Condition I	Three phase to ground fault
Condition II	Double line to ground fault
Condition III	Single line to ground fault

- Fault condition I: Under this fault condition, the system will be in type A voltage sag. The value of voltage sag is equal in the three phases (balanced voltage sag condition).
- Fault condition II: Under this fault condition, the system will be in types E, F, and G sag voltage depending on the transformer connection between fault point and bus. If the measured bus is with D/Y_g transformer then the observed sag voltage is of the F type.
- Fault condition III: Under this fault condition, the system will be in types B, C, and D sag voltage, depending on the value and direction of healthy phases. When a change in direction is observed with no change in magnitude, then we can say that the system is under voltage sag of C-type.

TABLE II. DVR SYSTEM STRICTURE

S.No	Strictures	Value
1	Line resistance	1.0Ω
2	Line inductance	5.8mH
3	Line frequency	50Hz
4	Phase voltage of the load	220V
5	Per phase power of the load	100Ws
6	Per phase inductive power of the load	0.3kVar
7	Per phase capacitive power of the load	0.6kVar
8	Turns ratio of injection transformer	1:1
9	DC voltage	200V
10	Filter inductance	70mH
11	Filter resistance	0.2Ω
12	Filter capacitance	5.0μF

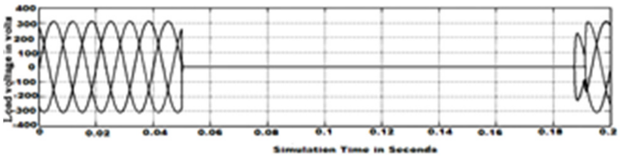

Fig. 6. Voltage vs time in faulty feeder at fault condition I.

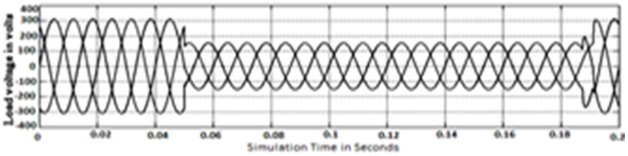

Fig. 7. Un-compensation of voltage vs time at fault condition I.

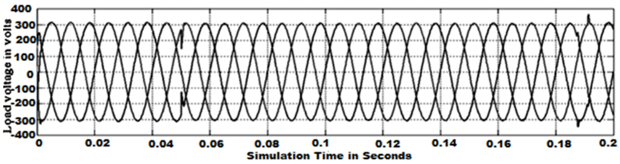

Fig. 8. Voltage compensation vs time at fault condition I.

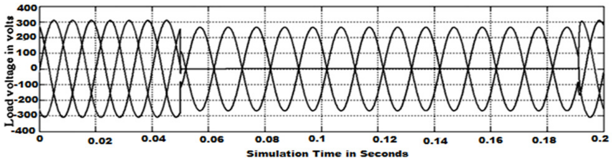

Fig. 9. Voltage vs time of faulty feeder at fault condition II.

For observing voltage sags, each fault condition is applied to the system for 130ms. Table III shows the outcome when the voltage sag is not compensated. Table IV shows the outcome when the voltage sag is compensated after the application of the DVR. It has been seen that, *THDV%* and *PVUR%* are as per [25]. So it is observed that the proposed topology is suitable for sag voltage compensation under three conditions (in condition I-50%, in condition II-24.2% and in Condition III-

1.85%). Figures 6–14 show the voltage waveforms (faulted, un-compensated and compensated voltage waveforms) under the three fault types.

TABLE III. SYSTEM OUTCOME AFTER VOLTAGE SAG OCCURENCE

Stricture	Fault condition		
	I	II	III
$THD_{Va\%}$	4.20	3.20	0.94
$THD_{Vb\%}$	8.10	8.15	0.98
$THD_{Vc\%}$	8.61	2.90	0.44
$THD_{V\%}$	6.95	4.80	0.80
$PVUR_{\%}$	8.94	16.32	1.48
$SS_{\%}$	50.01	24.23	1.87
$VSLEI_J$	47.48	17.20	0.02

TABLE IV. SYSTEM OUTCOME AFTER VOLTAGE SAG COMPENSATION

Stricture	Fault condition		
	I	II	III
$THD_{Va\%}$	0.48	0.99	0.57
$THD_{Vb\%}$	1.79	1.7	0.56
$THD_{Vc\%}$	1.70	1.10	0.010
$THD_{V\%}$	1.29	1.25	0.38
$PVUR_{\%}$	0.50	0.70	0.02
$SS_{\%}$	1.99	0.69	0.23
$VSLEI_J$	0.0020	0.000320	0.0000020

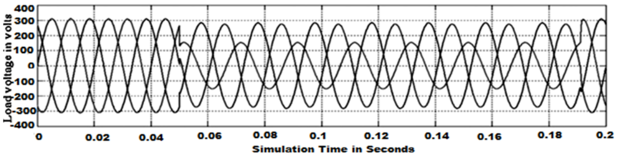

Fig. 10. Un-compensation of voltage in volts versus time at condition-II.

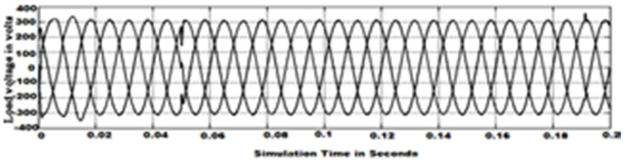

Fig. 11. Compensation of voltage vs time at fault condition II.

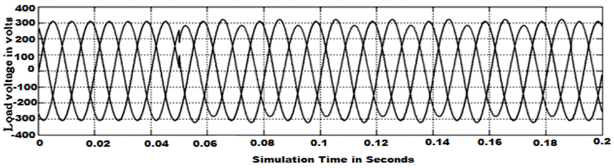

Fig. 12. Voltage vs time of faulty feeder at fault condition III.

Figure 15 shows the voltage *THDV%* of the energy storage capacity. It has been seen that the smallest value of voltage *THDV%* is achieved by the utilization of 200DC voltage. The Variation of *SS%* according to the change of energy storage capacity is shown in Figure 16. It has been seen that 200DC voltage is a suitable choice which attains the lowest SS%. Figure 17 shows the *PVUR%* according to the change in produced energy after the compensation as per change of storage capacity. It has been seen that 130DC voltage is the smallest voltage which is able to meet the terms of the IEEE Standard 112-1991 with less than 2% of phase unbalance rate.

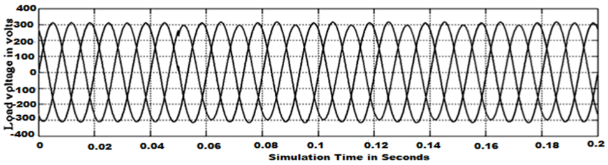

Fig. 13. Un-compensation of voltage vs time at falut condition III.

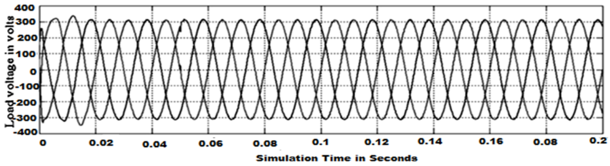

Fig. 14. Compensation of load voltage vs time at fault condition III. The DVR is connected to the linear load.

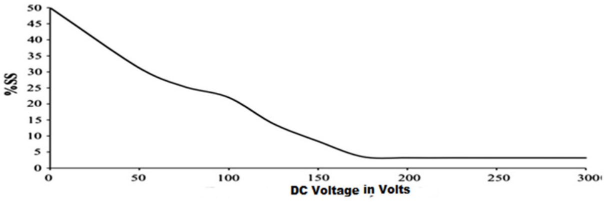

Fig. 15. Variance of $THDV\%$ in competition with energy storage.

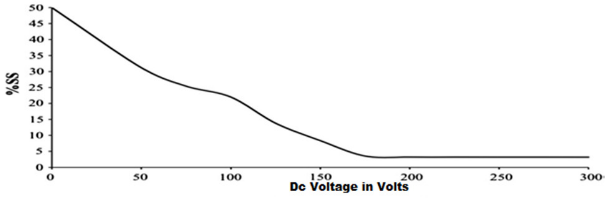

Fig. 16. Variation of $SS\%$ in competition with energy storage .

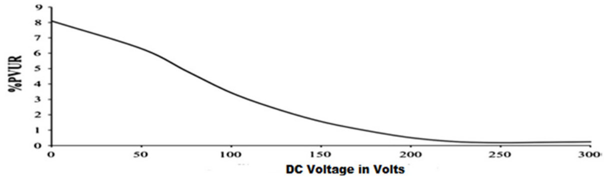

Fig. 17. Variation of $PVUR\%$ in competition with energy storage.

TABLE V. SYSTEM OUTCOME AFTER VOLTAGE SAG OCCURENCE WITH LINEAR AND NON LINEAR LOADS

Stricture	Fault condition		
	I	II	III
$THD_{Va\%}$	5.49	3.97	4.39
$THD_{Vb\%}$	7.49	9.68	5.67
$THD_{Vc\%}$	9.60	3.35	5.58
$THD_{V\%}$	7.52	5.67	5.19
$PVUR_{\%}$	7.90	14.58	1.24
$SS_{\%}$	50.63	30.99	12.00
$VSLEI_J$	47.73	18.57	0.57

TABLE VI. SYSTEM OUTCOMES AFTER VOLTAGE SAG COMPENSATION WITH OF LINEAR AND NON LINEAR LOADS

Stricture	**Fault condition**		
	I	**II**	**III**
$THD_{Va\%}$	0.83	2.39	1.17
$THD_{Vb\%}$	1.83	3.02	1.07
$THD_{Vc\%}$	1.96	1.30	1.63
$THD_{V\%}$	1.53	2.23	1.29
$PVUR_{\%}$	0.51	1.35	0.13
$SS_{\%}$	2.03	2.20	0.31
$VSLEI_{J}$	0.001	0.0069	0.000

IX. CONCLUSION

Voltage sag is a critical problem which affects a distribution system network causing loss of data, damaging equipment, reducing production loss, and increasing cost. In this paper, a Dynamic Voltage Restorer is proposed for voltage sag compensation as a cost effective solution that protects critical loads in a good manner from balanced or un-balanced voltage sag. Control strategy (i.e. a PI controller) is adopted within the DVR topology and the performance of such a device with the proposed controller is analyzed by simulations in MATLAB/Simulink. After getting the simulation outcome of DVR under three fault conditions, it has been concluded that the proposed DVR scheme is effective for voltage sag compensation. The robustness of the proposed PI controller is observed under linear and non-linear loads and it is concluded that the PI controller is most suitable for linear loads or for loads with small value of voltage distortion.

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