A Novel Three-Phase Low Voltage (LV) Dynamic Voltage Restorer (DVR) Employing Semi-Z-Source Inverter

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***Abstract*— This paper presents the design and control of a Low Voltage (LV) Dynamic Voltage Restorer (DVR) for a three-phase power system. The DVR is designed to protect a three-phase load of 3 kVA from the voltage sags and swells ranging up to 0.5 p.u of the supply voltage. The proposed DVR utilizes semi-Z-source (SZS) inverter as the power converter in each phase of the DVR. The SZS inverter offers many advantages such as reduction in cost, size, weight, elimination of filter etc. compared to the conventional Full Bridge (FB) inverter based DVR. Each phase is controlled independently which offers mitigation of both symmetrical and asymmetrical sags. The proposed DVR employs the modified feedback control technique. The simulation results from MATLAB/Simulink environment verify the efficacy of the proposed DVR topology. The proposed DVR topology is suitable for mitigation of sags and swells initiating at any point-on-wave.**

Keywords*— *Low Voltage Dynamic Voltage Restorer (LV DVR), Power Quality (PQ), Voltage Sag, Semi-Z-Source (SZS) inverter

I. INTRODUCTION

Dynamic Voltage Restorer (DVR) is a promising solution to replace the costly uninterruptible power supplies in the low voltage power system. DVR is a cost-effective voltage compensation device which protects the sensitive and critical loads from Power Quality (PQ) issues such as voltage sags, swells, harmonics, flickers etc. A DVR is a series voltage compensator which adds or subtracts voltage to the supply depending on the PQ problem in order to maintain the load profile at the predefined values. The basic structure of the DVR consists of energy storage, power converter, series injection transformer and a crowbar or by-pass circuit. The power converter synthesizes the missing voltage and with the aid of the injection transformer it is injected in series with the supply and the load. The by-pass equipment protects the DVR from short-circuiting currents and also connects or removes the DVR whenever required [1]–[5]

This paper introduces a novel LV DVR suitable for distribution line. The proposed LV DVR incorporates semi-Z-source (SZS) inverter as the power converter for synthesizing the missing voltage. The SZS inverter shares the same output voltage range with that of the FB inverter. With only two switches, the SZS inverter is capable of giving more sinusoidal output voltage compared to the FB inverter. The reduction in the number of switches, Z-source network in the ac-side of the inverter, no-shoot through condition, elimination of filter and dead-time control are some of the advantages of SZS inverter over the FB inverter [6], [7]. The circuit topology of the proposed three-phase SZS inverter based LV DVR is presented in Fig.1

The major requirements of an LV DVR such as low cost, small size and low weight are met satisfactorily by the proposed DVR. The compensation voltage of each phase is controlled independently in the proposed DVR topology. The merit of independent control of each phase offers the mitigation of both symmetrical and asymmetrical sags by the proposed topology compared to the three-phase DVR presented in [8]. The proposed DVR is employed with modified feedback control technique [9]. A single energy storage system supplies all the SZS inverters in the proposed DVR topology. The sharing of common energy storage among the three phases reduces the size, weight and cost of the proposed DVR. There is no possibility of energy storage short-circuiting as the switches are present in different legs. Both transformer-connected and transformer-less topology is possible with the proposed LV DVR.

This paper presents the protection of the critical load from balanced and unbalanced voltage sags using the proposed three-phase LV DVR. The following section gives design of the proposed DVR. The voltage sag detection method, reference generation and the control strategy are elaborated in the section III. The simulation results from the MATLAB/Simulink software validate the suitability of the proposed LV DVR for the tight restoration of load voltage

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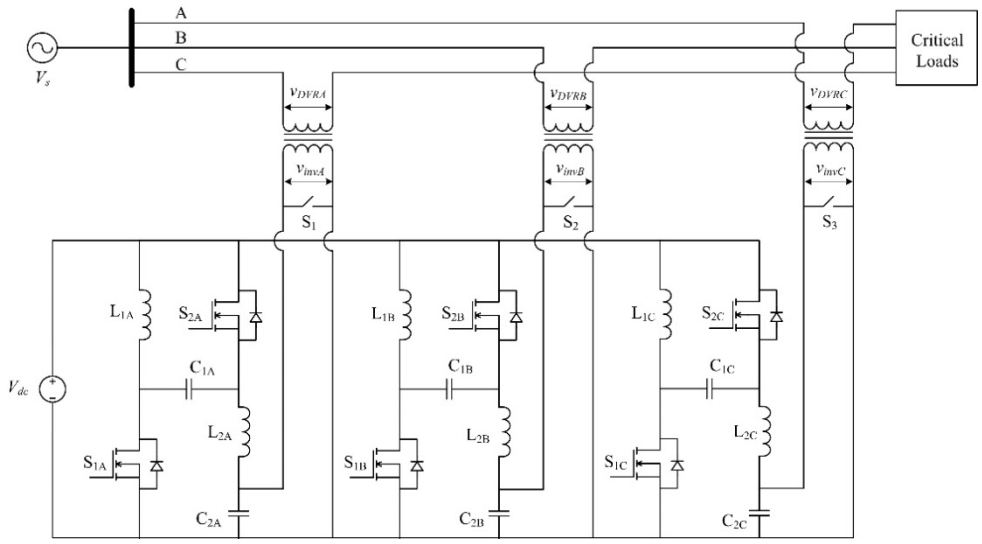

Fig.1 Proposed three-phase DVR employing SZS inverter.

during the PQ events.

II. Proposed Three-Phase LV DVR Based On Semi-Z-Source Inverter

The proposed three-phase LV DVR topology consists of three SZS inverters which share a common dc energy storage source V_{dc}. The SZS inverters are connected to each phase of the three-phase power system using separate injection transformers of turns ratio 1:1. The basic component of the proposed three-phase DVR system is the SZS dc-dc converter. Cao et.al proposed a buck dc-dc converter which can be operated as buck inverter by varying the duty cycle of the switches [10]. The SZS inverter consists of a Z-source network and two switches. The Z-source network is placed on the ac-side of the inverter, thereby reducing the size of the inductors and capacitors. The SZS converter shares the output voltage range same as the FB inverter with only two switches. The two switches are present in different legs [6], [10]–[12]. Owing to this, there is no risk of short-circuiting or need of dead-time control in the proposed DVR topology. The conventional LV DVR based on FB inverter requires dead-time control which adds fifth and seventh harmonics into the system [7].

MOSFET and IGBT are the regular choices of the SZS inverter switches as they fulfill the bidirectional current conduction and unidirectional voltage blocking property. With the reduction in the size of Z-source network and number of switches, the SZS inverter reduces the overall footprint of the proposed LV DVR compared to the FB inverter based DVR. The two switches in the SZS inverter are operated complementarily.

The SZS inverter in each phase generates the compensation voltage required in that particular phase to maintain the load profile constant. For the injection of the compensation voltage, the in-phase method is chosen which injects the compensation voltage or DVR voltage in-phase with the supply voltage. The generated compensation voltage is added in series with the supply and the load with the help of series injection transformer. The injection transformer serves the purpose of galvanic isolation and also offers voltage boosting function [13]–[15]. In this proposed topology, the task of the injection transformer is to provide only isolation. The DVR system connected to each phase namely A, B and C operate independently and identically. Hence, the operation of DVR and its related components in each phase is similar. The letter 'X' is used as the subscript in voltage, current, duty cycle, inductor, capacitor and switch notations to denote which phase it belongs to. The letter 'X' can be A, B or C depending on the phase under consideration. V_{DVR} represents the three-phase compensation voltage and V_{DVRX} denotes the compensation voltage in X phase.

When the three-phase system is healthy, the proposed LV DVR is in stand-by mode and is removed from the line using the by-pass switch. The bypass switches are S_1, S_2 and S_3 in phases A, B and C respectively. The proposed DVR shifts to the compensation mode under unhealthy supply conditions. Once the voltage sag is detected in a particular phase, the SZS inverter connected to that phase starts to synthesize the compensation voltage (V_{DVRX}) according to the reference voltage ($V_{DVRX,ref}$) generated. The SZS inverter output voltage (V_{invX}) is same as the compensation voltage (V_{DVRX}). The SZS inverter is capable of generating sinusoidal voltage by varying the duty cycle of switch S_{1X}. The voltage gain of the SZS inverter in the proposed DVR is given by equation (1)

$$\frac{\sqrt{2}*V_{DVRX}\sin\omega t}{V_{dc}} = \frac{1-2D_{1X}}{1-D_{1X}} \quad (1)$$

where D_{1X} represents the duty cycle of switch S_{1X}. The SZS

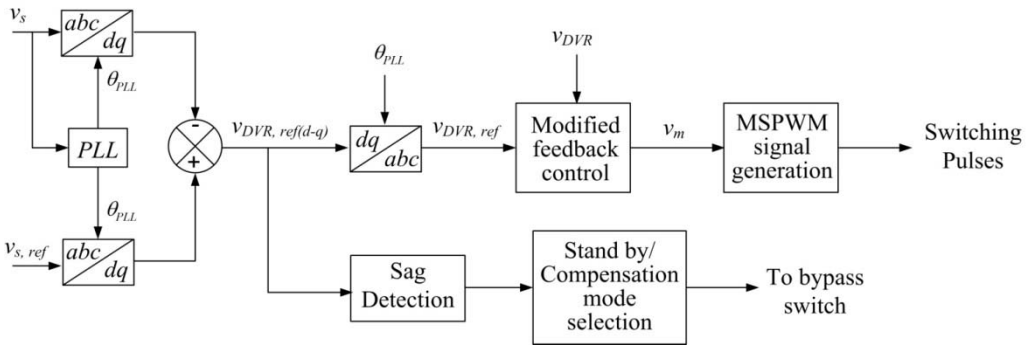

Fig.2 Control structure of the proposed LV DVR

inverter can output a sinusoidal voltage with peak voltage equal to $V_{dc}$by varying the duty cycle of switch S_{1X} from 0 to 0.6667. The SZS inverter generates the positive half cycle of the output voltage by varying the duty cycle D_{1X} from 0 to 0.5 and negative half-cycle when the same is varied from 0.5 to 0.6667.

From the equation (1), it is clear that the voltage gain of the SZS inverter is non-linear. This non-linearity in the voltage gain demands a modified reference voltage for the Sinusoidal Pulse Width Modulation (SPWM) of the switches in the SZS inverter. The left-hand side of equation (1) can be rewritten as $M_X \sin \omega t$ where M_X is the modulation index of the SZS inverter under operation and ω is the angular frequency of the three-phase system in radians. Rearranging equation (1), the duty cycle D_{1X}can be written as equation (2)

$$D_{1X} = \frac{1-M_X \sin \omega t}{2-M_X \sin \omega t} \tag{2}$$

which is the revised reference wave for the modified SPWM (MSPWM). For ease of implementation, the reference is normally generated for switch D_{2X} which requires less mathematical calculation and is given by equation (3)

$$D_{2X} = \frac{1}{2-M_X \sin \omega t} \tag{3}$$

The modes of operation and steady-state equations of the SZS inverter is given in [10].

The proposed LV DVR is designed for 50% compensation capability. A safety margin of extra 20% is included in the design of dc voltage and transformer. The dc energy storage voltage rating is selected by following equation (4) where V_S is the line-to-line voltage of the three-phase system.

$$V_{dc} = 1.2 * 0.5 * \frac{V_S}{\sqrt{3}} * \sqrt{2} \tag{4}$$

The maximum peak value of the compensation voltage in each phase ($V_{DVRX,max}$) of the proposed DVR is designed for 50% compensation capability and is given by equation (5)

$$V_{DVRX,max} = 0.5 * \frac{V_S}{\sqrt{3}} * \sqrt{2} \tag{5}$$

For the design of the Z-source network, the maximum modulation index (M_{Xmax}) is calculated by dividing the equation (5) by equation (4). For the maximum modulation index obtained, duty cycle is calculated for the maximum positive voltage using equation (2) by substituting $\omega t = \frac{\pi}{2}$ and $M_X = M_{Xmax}$. With the obtained duty cycle D_{1X}, the maximum possible capacitor voltage and inductor currents are calculated for the given load connected to the SZS inverter. The capacitor voltage ripple and inductor current ripple in the SZS inverter are given by equations (14) and (15) of [10] and are presented as equation (6) and (7) in the context of proposed DVR topology.

$$\Delta V_{C1X} = \frac{(1-D_{1X})T_S I_{L1X}}{C_{1X}} = \frac{-\sin \omega t + M_X (\sin \omega t)^2}{2-M_X \sin \omega t} \frac{T_S}{C_{1X}} I_X \tag{6}$$

$$\Delta I_{L1X} = \Delta I_{L2X} = \frac{V_{dc} T_S D_{1X}}{L_{1X}} = \frac{V_{dc} T_S}{L_{1X}} \frac{1-M_X \sin \omega t}{2-M_X \sin \omega t} \tag{7}$$

where $\Delta V_{C1X}, \Delta I_{L1X}, \Delta I_{L2X}$ and T_s gives the capacitor C_{1X} voltage ripple, inductor L_{1X} current ripple, inductor L_{2X}current ripple and switching time period respectively. The peak value of the load current in each phase is represented by I_X. The value of both the capacitors and inductors are calculated using the equations (6) and (7) respectively. Furthermore, the injection transformer power rating is selected by taking into consideration the maximum

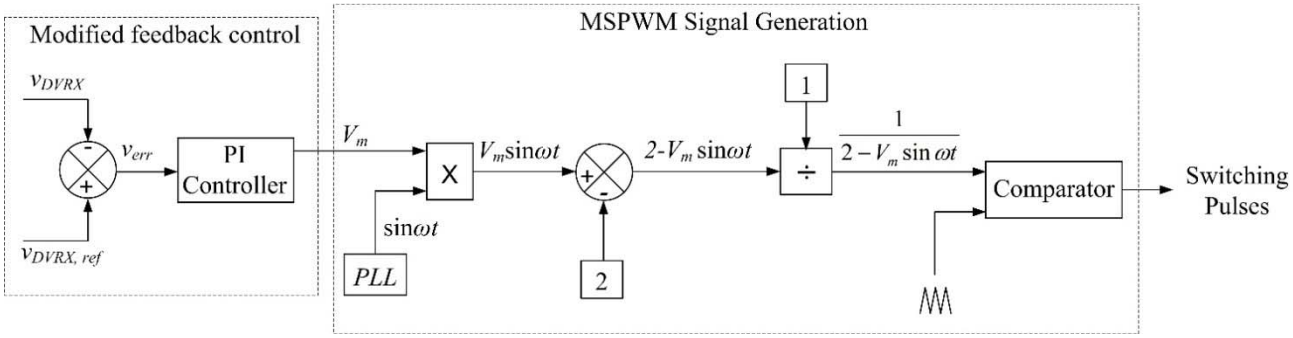

Fig.3 Modified feedback controller and MSPWM signal generation in phase X of the proposed LV DVR

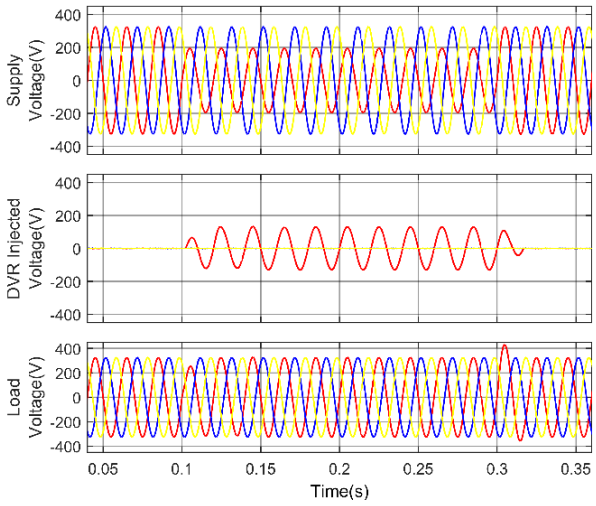

Fig.4 Performance of proposed LV DVR during voltage sag in phase A

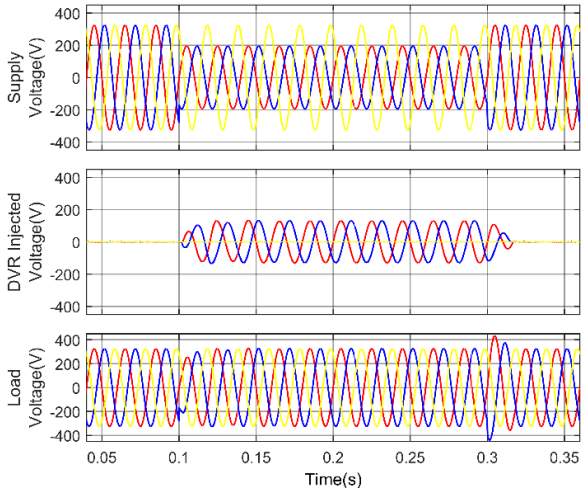

Fig.5 Performance of proposed LV DVR during asymmetrical voltage sag.

injection voltage and the maximum load current possible.

III. Control Of The Proposed LV DVR

In the proposed three-phase LV DVR, phase locked loop (PLL) is used to create the supply voltage references essential for the d-q co-ordinate system as shown in Fig.2 [8]. The instantaneous values of the three-phase supply voltage reference ($V_{s,ref}$) and actual supply voltage (V_s) are continuously compared and a flag equal to 1 is generated whenever the difference goes non-zero. The flag generated brings the proposed DVR in the sag affected phase to compensation mode from stand-by mode by opening the by-pass switch. The difference three-phase voltage $V_{DVR,ref}$ generated as mentioned above is the required compensation voltage or the reference DVR voltage. The SZS inverter starts synthesizing the required compensation voltage when the sag or swell is detected. The modified feedback controller is utilized which takes the actual DVR voltage V_{DVRX} as the feedback parameter [9]. This control strategy offers better dynamic response over the feed-forward control.

In the modified feedback control as shown in Fig.3 (given for phase X), the reference DVR voltage $V_{DVRX,ref}$ and the actual DVR output V_{DVRX} are compared, and the error V_{err} is minimized using a PI controller. The output of the PI

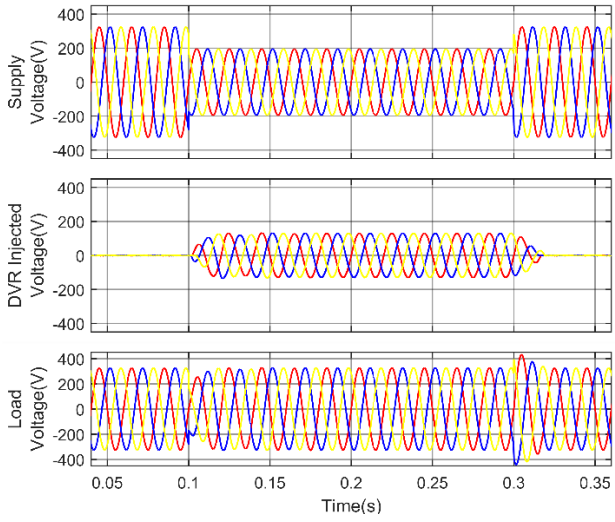

Fig.6 Performance of proposed LV DVR during symmetrical voltage sag

controller is analogous to the modulation index given by M_X. The PI controller parameters K_{pX} and K_{iX} are designed using trial and error method. As the first step for obtaining the modified reference sinusoidal voltage required in the MSPWM, the output of the PI controller V_m is multiplied by $\sin\omega t$ which phase-locks with actual supply voltage.

The modified reference signal given by equation (3) is developed b conducting mathematical operations on the obtained $V_m \sin \omega t$. The developed modified reference signal is compared with the high-frequency triangular wave and the switching pulses for switch S_{2X} are obtained. The switching pulses for the switch S_{1X} is given by complementing the pulses of S_{2X} . In modified feedback control method, the SZS inverter is always operated appropriately to tightly track the reference DVR voltage.

IV. Simulation Results

This section presents the simulation results in MATLAB/Simulink platform for validating the feasibility of the novel LV DVR. The system parameters are designed as discussed in the previous section and is given in Table I. The proposed LV DVR is capable of restoring the load voltage during abnormal supply voltage conditions. Fig.4 shows the compensation of load voltage by the proposed three-phase LV DVR during voltage sag in phase A. The phase A voltage is subject to a sag of depth 40% during the time interval from 0.1s to 0.3s. As soon as the sag is detected, the SZS inverter initiates the operation and synthesizes the required compensation voltage. The DVRs connected to the other phases B and C remain in the stand-by mode during this time interval. The operation of DVR in phase A does not affect the DVR present in B and C. Fig. 5 shows the simulation of the proposed LV DVR compensating asymmetrical sag present in phase A and B. The by-pass switch (S_3) in the phase C remains closed even when the other phase DVRs is compensating the sag present in the system. The independent control of the DVRs present in each phase makes possible the smooth mitigation of asymmetrical sags. Even though symmetrical sags occur very rarely, the restoration of load voltage under this abnormal condition is also possible with the proposed LV DVR. The compensating voltages for each phase (V_{DVRX}) are supplied by the respective DVRs and the sag is mitigated completely as shown in Fig.6. Fig.6 illustrates the symmetrical sag compensation by the proposed DVR for

Table I
System Parameters

Parameters	Values	
Line-to-line three phase voltage and frequency	230*√3 V and 50 Hz	
Load power per phase	Linear load-800 + j600 VA Nonlinear load- FB diode rectifier with 800 + j600 VA load	
Single phase Injection Transformer	1:1,230 V, 1.6 kVA	
Semi-Z-Source Inverter	Dc-link voltage, V_{dc}	200V
	Switching frequency	50kHz
	Capacitor C_{1X} and C_{2X}	3.9μF
	Inductor L_{1X} and L_{2X}	320μH
PI Controller	K_{pX}	0.011
	K_{iX}	1.1

40% sag in all the three phases for the time interval 0.1s to 0.3s.

The proposed LV DVR employing SZS inverter is suitable for the mitigation of voltage swells also. During the swell events, the voltages with magnitude equal to the swell depth, but phase-opposed are generated and added in series with the supply and the load. Fig. 7 shows the restoration of load voltage during a swell event of depth 40% from time 0.1 s to 0.3s. The proposed DVR is also suitable for mitigating swells in single phase, two phases and all the three phases. From the simulation results presented so far with the connected linear load, it is clear that the SZS inverter is suitable for both sag and swell mitigation in the low voltage three-phase power system. It is applicable for non-linear loads also. A non –linear load of diode bridge rectifier is connected to the three-phase supply system. When the non-linear load is met with voltage sag of 40% in phase A from time 0.1s to 0.3s, the SZS inverter completely restores the load voltage to its presag values as presented in Fig.8. The proposed three-phase LV DVR is suitable for the load compensation during voltage sag and voltage swell. The SZS inverter based LV DVR can be used for both linear and non-linear loads. It offers complete regulation of load voltage during abnormal supply conditions such as voltage sag and swell. The proposed LV DVR is the cost-effective alternative for the conventional FB inverter based DVR.

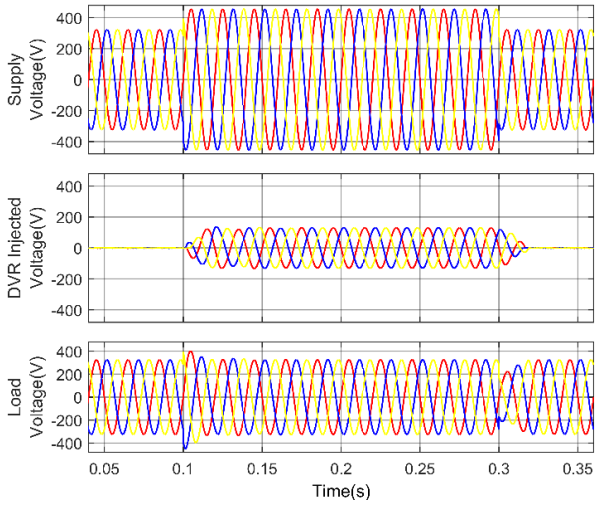

Fig.7 Performance of proposed LV DVR during voltage swell.

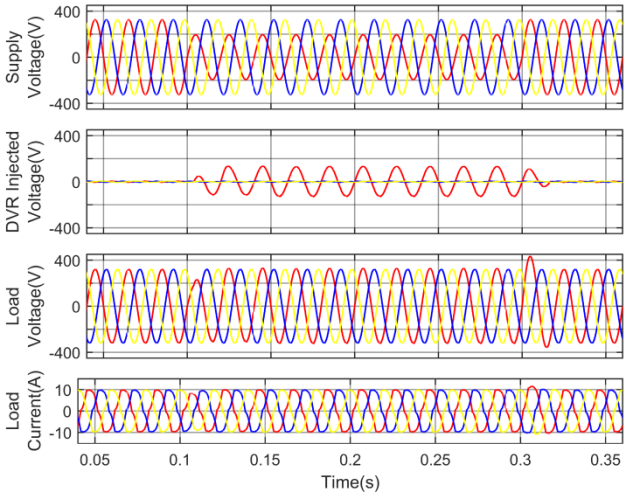

Fig.8 Performance of proposed LV DVR during voltage sag with a non-linear load connected.

V. Conclusion

A novel topology of three-phase LV DVR is proposed in this paper. The proposed topology employing SZS inverter reduces the overall footprint and the number of switches in each phase without compromising the compensation capability when compared to the conventional FB inverter based three-phase DVR. The short-circuiting of supply voltage, dead-time control and filter circuit essential in FB inverter based three-phase DVR are not required in the proposed DVR topology. The independent control of each phase makes the proposed three-phase LV DVR superior to the three-phase inverter based DVR in the distribution network. The d-q co-ordinate system is used to detect the sag and modified feedback control employed helps the DVR to effectively track the reference DVR voltage. The simulation results illustrate the feasibility and the practicality of the proposed LV DVR to restore load voltage of a three-phase system during symmetrical and unsymmetrical sag and swell. The linear and non-linear loads connected to the three-phase system can be protected effectively using the proposed LV DVR topology.

Acknowledgement

This publication is an outcome of the R&D work undertaken project under the Visvesvaraya PhD Scheme of Ministry of Electronics & Information Technology, Government of India, being implemented by Digital India Corporation.

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