Feed-Forward Control Strategy for the VSC of DVR for Smooth and Clean Power Flow to Load

AAMIR HANIF*, MOHAMMAD AHMED CHOUDHRY**, AND TAHIR MEHMOOD*

RECEIVED ON 07.06.2010 ACCEPTED ON 07.06.2011

ABSTRACT

VSC (Voltage Source Converter) feed-forward control strategy of DVR (Dynamic Voltage Restorer) for an in-phase voltage injection scheme is proposed in this paper to tackle not only voltage sags and swells in the utility supply but also phase jumps as well. The proposed strategy utilizes a time based ramp at a clock rate of 50Hz to obtain a 3-phase reference signal that is compared with actual 3-phase utility voltage to obtain an error signal. If the error in each phase of the utility voltage is greater than zero then appropriate control signals are generated. The switching devices in VSC are switched accordingly to compensate voltage sags, swells and phase jumps in the utility voltage that propagates to load. For the mitigation of voltage sags, swells and phase jumps, the unipolar SPWM control is used.

The proposed control system response time to compensate voltage sag, swell and phase jump through switching of VSC devices is less than 10ms whereas ITIC curve and SEMI-F-47 standard suggest a target of 20ms. Load voltage THD is below 5% as per IEEE Std. 519-1992.

These results show that employed control strategy has an excellent capability of voltage restoration with acceptable harmonic distortion, within specified time frame for smooth and clean power flow to load.

MATLAB®/Simulink® SimpowerSystem tool box has been used to obtain simulation results to verify the effectiveness and validity of the proposed control strategy to improve the quality of the power delivered to the load.

Key Words: Power Flow, VSC, Custom Power Devices, Unipolar SPWM Control Law, Power Quality, Sensitive Load, Dispersed Generation.

1. INTRODUCTION

The proliferation of sensitive loads in the electric utility system is increasing power quality concerns. The industrial consumers in particular are facing considerable financial losses due to power quality events. Therefore, the researchers are working hard to deal power quality issues including voltage sag-swell and phase jumps, etc in the utility supply for smooth and clean power delivery to load. Generally, the term power quality is used to mention availability of sinusoidal voltage with required amplitude and frequency at the load bus on consumer side [1]. An increase in supply voltage of more than 10% is called swell whereas a decrease of more than 10% is called sag [2]. Similarly, a positive or negative jump in phase can occur as well.

* Assistant Professor, ** Professor,
Department of Electrical Engineering, University of Engineering and Technology, Taxila.

When voltage sag occurs, it may or may not be associated with phase jumps [3-4]. However, our system should have the capability to detect and compensate the sag or swell in supply voltage that may or may not be accompanied with phase jump. As long as the phase jumps are not associated with any other PQ problem they are not critical to the loads, so the system should allow them to proceed onward and disappear. Another important parameter that affects the operation of alternating voltage systems is the frequency of supply voltage [5]. But the issues related to frequency variations are least reported in literature as compared to the above stated problems [6].

Nowadays voltage sag is one of the most concerning PQ (Power Quality) problems for both utilities as well as customers (especially industrial) because it puts monetary burden on them [7]. It can occur at any instant of time, with amplitudes ranging from 10-90% at power frequency and a duration that can last for 1/2 cycle to one minute [8]. Whereas, the voltage swell is sudden rise in the root mean square value of voltage for durations of 1/2 cycles to 1 minute, with typical amplitudes rang of 110-180% [9]. Besides the sudden switching of heavy loads, system faults are a major cause of voltage sags. Faults on system, sudden removal of heavy load and switching of capacitors are the key factors resulting in voltage swells. Voltage swells are of relatively low significance as compared to voltage sags because they are less common in distribution system [9].

PQ problems that are related with voltage e.g. sags, harmonics, and swells can result in undesirable interruptions to critical processes that may cause considerable economic and/or data losses [10]. Voltage sag is very hazardous to control/digital equipment in process industry. Any failure of control results in the breakdown of process and therefore, loss of raw material and production time and even risk to human life.

Different types of CPDs (Custom Power Devices) are now available to tackle voltage sag problem. These devices include UPS (Uninterruptible Power Supply), DSTATCOM (Distribution Static Compensator), DVR and UPQC (Unified Power Quality Conditioner). But, DVR has the capability to offer more quick response to wipe out voltage sags, swells and phase jumps related issues in main supply voltage. Moreover it provides an economic solution as compared to other CPDs [11]. To counter voltage sag, improve wave shape and remove phase shift. DVR provides desired AC voltage by injecting it in series with the utility network as shown in Fig. 1. Fig. 1 represents a one phase equivalent utility network. The ultimate objective of DVR voltage injection is to keep voltage at the load bus within allowable limits. However phase angle of injected voltage may or may not be in phase with the supply voltage [2,12].

DVR follows same principle as for sag compensation to counter voltage swell so that load voltage can be restored to its nominal value [13]. Hence DVR has the ability to generate active and reactive power during sag as well as absorb active and reactive power during swell. In case active power contribution from DVR is required to compensate larger voltage sags, DG (Dispersed Generation) resource can be utilized to supply active power. This active power is utilized to inject the deficit voltage in order to regulate the load bus voltage [14]. This shows that the difference in angle between the DVR injected voltage and

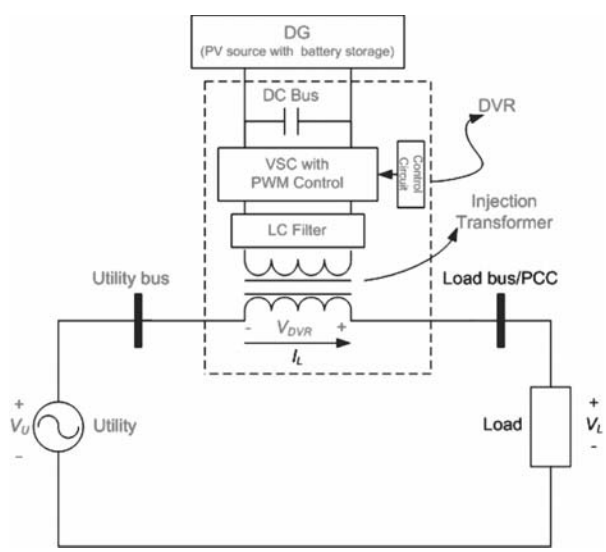

FIG. 1. SCHEMATIC DIAGRAM OF A DVR WITH ITS MAIN COMPONENTS

load current needs not be 90 and can theoretically have any value. A DG as an energy source connected to DC-link of DVR is shown in Fig. 1.

DVR control can be open loop, feed-forward or closed loop depending upon the application requirement. Various DVR control methods have been investigated in recent years to mitigate different PQ events [3,10,13,15-22]. Each method has its own pros and cons for its application. A unified approach of mitigating voltage sags, swells and phase jumps in the utility voltage using an efficient and a simple VSC based control strategy of DVR for an in-phase voltage injection scheme is proposed in this research work. This strategy inturn provides smooth and clean power flow to the load.

Each DVR control method is required to compute the DVR voltage to be injected during the compensation period. Sag, swell and phase jump detection is a key step in the DVR control method. There are number of methods that have been investigated for sag detection by researchers. Some of the commonly used sag detection methods are: Fourier-transforms, phase-locked-loop, software phase-locked-loop, peak value detection of the supply waveform and wavelet transformation. Each method has its associated advantages and disadvantages. However, a time based ramp at a clock rate of 50Hz is used to obtain 3-phase reference signal that is compared with actual 3-phase utility voltage to obtain an error signal. If the error in each phase of the utility voltage is greater than zero then appropriate control signals are generated. The switching devices in VSC are switched accordingly by following the unipolar SPWM control to compensate voltage sags, swells and phase jumps in the utility voltage that propagates to load. The proposed control system succeeds in voltage sags, swells and phase jumps detection and mitigation in less than 10ms whereas ITIC curve and SEMI-F-47 standard suggest a target of 20ms.

Conventional voltage compensation techniques utilized by the DVR are Pre-sag, In-phase and Phase advance [23-24]. Depending upon DVR application environment, each technique has its own merits and demerits. This work, however, evaluates in-phase compensation technique for the proposed control strategy to mitigate voltage sags, swells and phase jumps in the utility voltage with mathematical equations and the same have been validated by results obtained from MATLAB®/SIMULINK® SimPowerSystems™ simulations. In-phase voltage compensation strategy injects minimum voltage vector in the sagged voltage to have regulated load voltage. So size of the energy storage device and injection transformer is reduced as compared to pre-sag compensation technique. Phase advance compensation technique, however, uses only reactive power to mitigate voltage sag. But, all types of sags cannot be mitigated without real power injection especially when power factor of the load is high. Usually, it is stated in the literature that in-phase compensation scheme compensates only voltage magnitude and is not able to mitigate phase jump in the utility voltage hence load voltage observes phase-shifts. However, the proposed feed-forward control scheme is also investigated to tackle phase jumps in the utility voltage and it responded excellently by compensating the phase jumps.

Section 2 of this paper describes mathematical model for in-phase injection scheme. Model equations provide guidelines for the restoration of load bus voltage to its nominal value. Section 3 includes design specifications that are considered while developing proposed control strategy. Proposed feed-forward VSC control strategy of DVR for in-phase injection scheme is presented in Section 4. Simulation results and discussions of 3-phase implementation for three separate cases are provided in Section 5. Section 6 prsents the conclusions made from results.

2. MATHEMATICAL MODEL FOR IN-PHASE INJECTION TECHNIQUE

Phasor diagram of Fig. 2 represents the concept of in-phase injection by the DVR. The DVR injected voltage and utility voltage phasors after sag add up to make load voltage phasor.

From Fig. 2, if

V_U is Supply/Utility voltage phasor at the PCC taken as reference, V_{DVR} is DVR injected voltage phasor, and V_L is Load voltage phasor.

Then in phasor notation, the load voltage for the system of Fig. 1 can be written as [2, 6, 24-26]:

$$V_U + V_{DVR} = V_L \tag{1}$$

Above equation can be re-arranged as [27]:

$$V_{DVR} = V_L - V_U \tag{2}$$

Equation (2) can also be written as [28]:

$$V^*_{DVR} = V^*_L - V_U \tag{3}$$

Where V^*_{DVR} is reference voltage phasor for DVR, and V^*_L is required load voltage phasor.

Although, DVR injects minimum voltage vector for in-phase injection scheme [12], however, active power supply from some kind of energy storage device is required from DVR to mitigate sag using the scheme. The DC-bus in the structure of DVR may be provided energy from the incoming network through a rectifier. Although engine driven generating sets fueled by gas, gasoline or diesel can also serve the same purpose, alternate energy resources or DG in the form of fuel cells, wind or solar can also meet the energy requirement of DC-bus. However, it is assumed here, that DC-link of DVR is fed from PV source with battery storage to have constant voltage across it. This configuration is shown in Fig.1. If the energy source is not available, the DC-bus includes capacitors and the ability to mitigate PQ problems is limited.

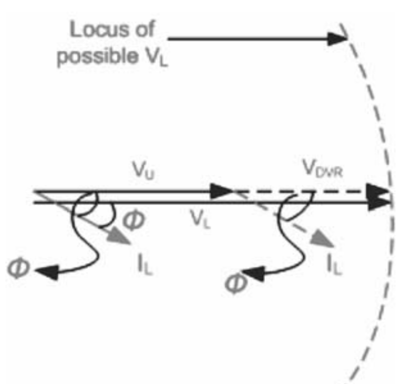

FIG. 2. PHASOR DIAGRAM SHOWING IN-PHASE INJECTION TECHNIQUE FOR A SYSTEM

Active and reactive power flow equations of LSVI (Leading Series Voltage Injection) mathematical model [2] at utility bus (P_U, Q_U), load bus (P_L, Q_L) and power injected by DVR (PDVR, QDVR) can be modified for in-phase injection scheme as under:

$$P_U = V_U I_L \cos \Phi \tag{4}$$

$$Q_U = V_U I_L \sin \Phi \tag{5}$$

$$P_{DVR} = V_{DVR} I_L \cos \Phi \tag{6}$$

$$Q_{DVR} = V_{DVR} I_L \sin \Phi \tag{7}$$

$$P_L = V_L I_L \cos \Phi \tag{8}$$

$$Q_L = V_L I_L \sin \Phi \tag{9}$$

As utility and DVR supplies active and reactive power during sag to serve load power demand, hence Equations (8-9) can also be written as [28]:

$$P_L = P_U + P_{DVR} \tag{10}$$

$$Q_L = Q_U + Q_{DVR} \tag{11}$$

Substituting Equation (4 and 8) in Equation (10) to obtain equation for PDVR as:

$$P_{DVR} = V_L I_L \cos \Phi - V_U I_L \cos \Phi \tag{12}$$

Rearranging last equation, we get:

$$P_{DVR} = (V_L - V_U) I_L \cos \Phi \tag{13}$$

Now Substituting Equation (5 and 9) in Equation (11) to obtain equation for QDVR as

$$Q_{DVR} = V_L I_L \sin \Phi - V_U I_L \sin \Phi) \tag{14}$$

Rearranging last equation, we obtain

$$Q_{DVR} = (V_L - V_U)\, I_L \sin \Phi \quad (15)$$

The Equations (4-15) provide guidelines for dynamically restoring load bus voltage using in-phase injected voltage technique for the intended control strategy to attain regulated load voltage. This inturn results in smooth and clean power delivery to the load.

3. CONTROL STRATEGY REQUIREMENTS AND ITS DESIGN

There are two control strategy requirements that are considered while developing a proposed control strategy to mitigate voltage sags, swells and phase jumps in utility voltage for the above explained in-phase voltage injection scheme of the DVR.

(1) Voltage-tolerance curve (or equipment sensitivity curve) provided by ITIC and SEMI-F47 standard show that one-cycle outage is tolerable for sensitive loads [29]. Therefore, time required for the detection and mitigation of voltage sag is one cycle (20ms) at 50Hz.

(2) Another important design consideration is the sag magnitude. Although sag amplitude may vary from 10-90% of the nominal system voltage but, majority of power quality events result in sags that have magnitude not less than 50%. Hence, in this work 50% balanced sag is considered in 3-phases of utility voltage whereas 15, 25 and 35% unbalanced sag is taken in phase A, B and C respectively of utility supply.

4. CONTROL STRATEGY FOR THE VSC OF DVR

It is evident from the above mentioned response time requirements that comparison of a reference and the actual source voltage is required to detect sag. Literature studies show that there exist various methods to instantaneously detect voltage sag and mitigate it. However, a simple control approach is used here to generate gate pulse signals for VSC valves to switch them on and off considering the limitations of implementation. A control strategy employing unipolar switching strategy is developed which does not use PI controller due to which problem of gain tuning of controller is avoided. The control approach used over here follows the error signal to correctly inject the desired voltage to compensate any sag, swell or phase jump in the utility supply.

4.1 Generation of Reference Wave

In order to control the switching of the VSC, a 3-phase sinusoidal reference signal of similar amplitude and phase as to that of utility voltage has to be generated for comparison with actual utility voltage in the control system. Block diagram for the reference signal generation is shown in Fig. 3 where first of all a time based ramp at a clock rate of 50Hz is generated. For an in-phase injection scheme, DVR injects voltage in phase to the utility voltage. Hence three reference signals are generated so as to follow the phase sequence of 3-phases of utility voltage i.e. reference signals are phase locked with utility voltage.

To adjust the amplitude of the generated sinusoidal reference signal to an appropriate level, a constant value block has to be used. A system is incorporated as shown in Fig. 4 that steps down the utility voltage to a sinusoid with 1V peak. Hence, the constant value block at the input of multiplier block is set so as to transform its output a sinusoid of 1V peak.

4.2 Generation of Error Signal

Generation of error signal is a key step in the control system design. Subtraction of 3-phase actual utility voltage from the generated 3-phase reference provides a 3-phase error signal. This error signal is then separated for each phase through demultiplexer block. Each of the error signal drives the corresponding phase pulse generator which in turn provides control signals (pulses) to the corresponding PWM-IGBT VSC switch to turn on and off according to requirement.

An equation for error signal in phase-a of utility voltage can be written as:

$$\nu_{Ra}(t) - \nu_{Ua}(t) = e_a(t) \quad (16)$$

Similarly for other 2-phases equations for error signal can be written as:

$$\nu_{Rb}(t) - \nu_{Ub}(t) = e_b(t) \quad (17)$$

$$\nu_{Rc}(t) - \nu_{Uc}(t) = e_c(t) \quad (18)$$

Block diagram representation of error signal generation is shown in Fig. 4.

4.3 Unipolar SPWM Control Law

The generated 3-phase sinusoidal reference signals have constant amplitude and each separated by 120° phase apart whereas the utility voltage follows the reference signals so that there is minimum error in each phase. The bottom line, therefore, for the control is to try and make

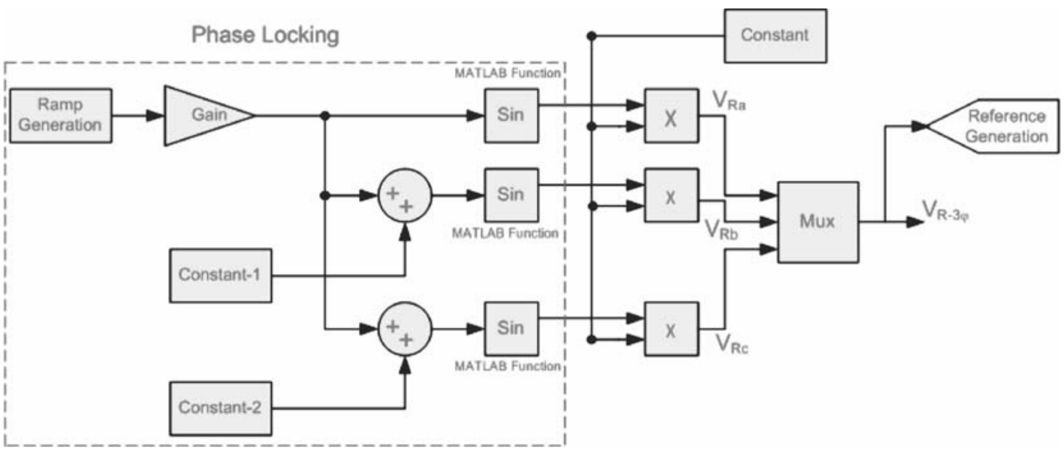

FIG. 3. BLOCK DIAGRAM REPRESENTATION OF REFERENCE VOLTAGE GENERATION

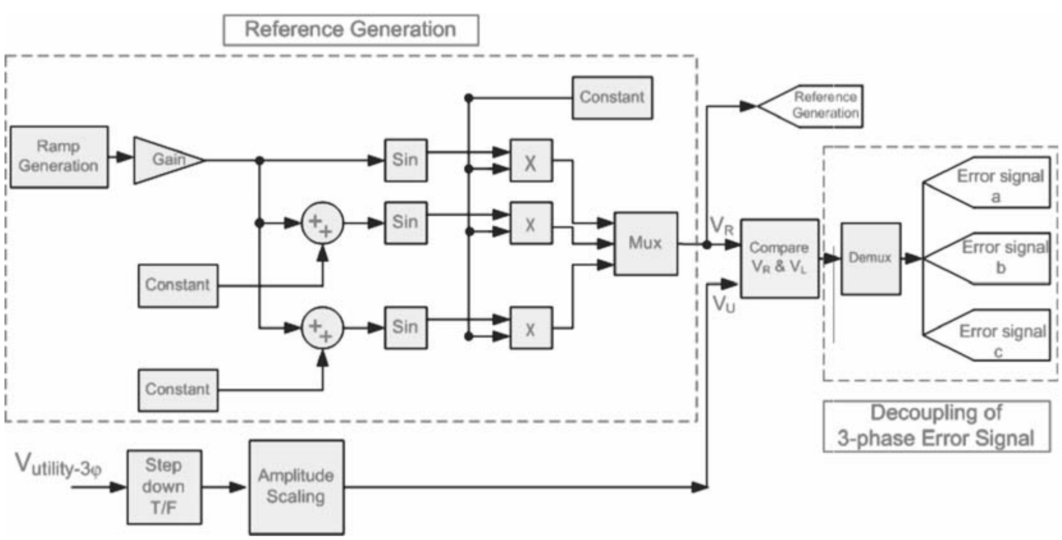

FIG. 4. BLOCK DIAGRAM REPRESENTATION TO GENERATE ERROR SIGNAL

the error signal zero. There are various methods that can be used to implement such a control. However, this research work utilizes unipolar "SPWM Control" to obtain the control targets [30].

In the unipolar control law, the states of four switches (IGBTs) of H-bridge configuration will be as shown in the Table 1. In it, the two sinusoidal modulated signals (here error signals) $\pm V_{mod}$ are compared with triangular (carrier) wave (V_{carr}) so that switching signals can be generated for the H-bridge VSC valves. These switching signals are generated according to following unipolar SPWM control law.

- If modulating signal ($+V_{mod}$) is greater than the carrier signal (V_{carr}) then switch T_a+ is ON otherwise switch T_a+ is OFF. However, if modulating signal ($+V_{mod}$) is less than the carrier signal (V_{carr}) then, switch T_a- is ON otherwise switch T_a- is OFF.
- If modulating signal ($-V_{mod}$) is greater than the carrier signal (V_{carr}) then switch T_b+ is ON otherwise switch T_b+ is OFF. However, if modulating signal ($-V_{mod}$) is less than the carrier signal (V_{carr}) then, switch T_b- is ON otherwise switch T_b- is OFF.

H-bridge configuration is usually preferred for single-phase DVRs due to it simplicity, however it can also used in a 3-phase system by connecting it with each individual phase as DVR are usually meant to provide individual phase compensation independently. In this work, control of the three VSC bridges is managed to compensate each phase independently.

The block diagram of entire unipolar SPWM control law is incorporated in Fig. 5.

4.4 VSC Output Filter

Control actions generate the firing signals for each VSC switch with controllable amplitude, phase, and frequency,

TABLE 1. STATES OF FOUR SWITCHES OF H-BRIDGE VSC CONFIGURATION

No.	Switch T_a+ Status	Switch T_b+ Status	Switch T_a- Status	Switch T_a- Status	VSC Output Voltage (V_{AB})
1.	ON	OFF	OFF	ON	$+V_{dc}$
2.	ON	ON	OFF	OFF	0
3.	OFF	OFF	ON	ON	0
4.	OFF	ON	ON	OFF	$-V_{dc}$

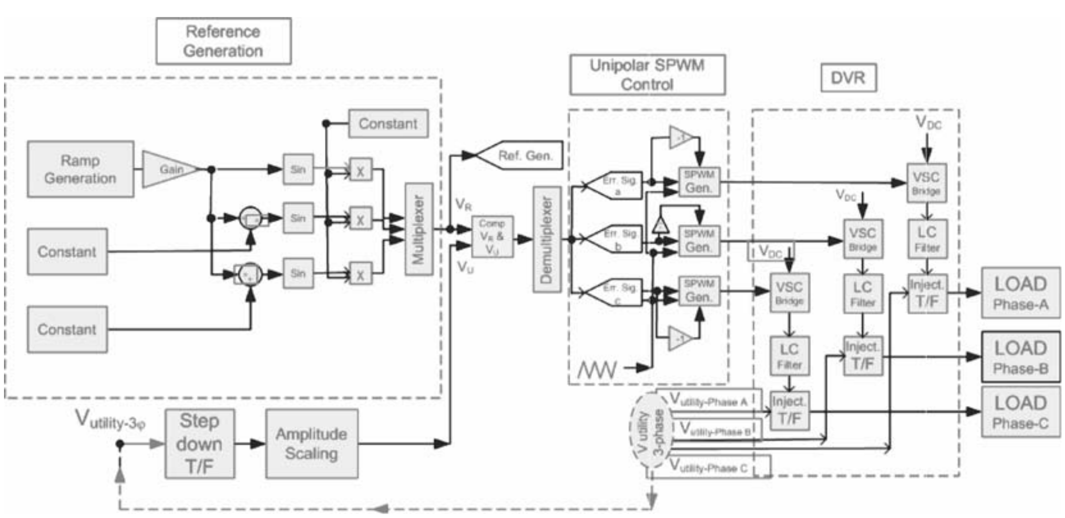

FIG. 5. BLOCK DIAGRAM OF FEEDFORWARD CONTROL SYSTEM OF DVR

whenever sag, swell and phase jump is detected. These firing signals are high frequency pulses with polarity as controlled by the control action at the output of VSC. However, DVR has to inject a voltage having sinusoidal waveform at 50Hz frequency. This requires that high frequency pulses at the output of VSC have to undergo filtering process. Hence they are passed through a series LC filter. The per phase inductance value as well as capacitance value chosen for the LC filter after extensive simulations are 0.8mH and 300μF, respectively. This selection of C and L values keep load voltage THD (Total Harmonic Distortion) below 5% according to international standards. The Table 2 provides a summary of design specifications and different component values for the simulated system.

5. SIMULATION RESULTS

The simulation setup for the block diagram of Fig. 5 is developed according to the design of the DVR and the proposed control strategy. A MATLAB®/SIMULINK® simulation for 3-phases of a system compensated by DVR in each individual phase is carried out for different balanced as well as unbalanced sag/swell and ±25° phase jumps in utility voltage using SimPowerSystems™ environment. DVR Set up consists of DC-bus, PWM-IGBT based VSC, harmonic (LC) filter and injection transformer of 1:2 ratio. The rated voltage for a 3-phase system is 415V at system frequency of 50Hz. This means that the desired load voltage per phase is 240V. Though, DVRs are usually used for voltage sag mitigation where consumer supplied voltage is in general 11kV, the selected voltage level is suitable while designing a prototype in a laboratory environment. The per phase load power consumption is chosen as 750VA which is chosen for simplicity of calculation. This corresponds to a rated current of 3.125A at 240V. The volt-ampere rating of injection transformer per phase has been taken as 750VA which is the same as

TABLE 2. 3-PHASE SIMULATED SYSTEM DESIGN SPECIFICATIONS

No.	Component/Parameter Description		Value/Range
1.	Rated Load Voltage 3(Φ)		415V
2.	Load Power Factor		0.85 Lagging
3.	Rated Load Voltage (Per Phase)		240V
	Maximum Load Apparent Per (Per Phase)		750VA
	Maximum Load Current (Per Phase)		3.125A
4.	VSC DC-Bus Voltage (Per Phase)		120 VDC
5.	System Frequency		50 Hz
6.	Maximum Sag Depth: -3Φ Balanced Sag		50%
	-3Φ Unbalanced Sag	Phase-A	15%
		Phase-B	25%
		Phase-C	35%
	-3Φ Unbalanced Sag	Phase-A	45%
		Phase-B	45%
		Phase-C	No Sag
7.	Sag Detection and Mitigation Time		<20ms
8.	Injection Transformer Turns Ratio (VSC Side/Power Circuit Side)		1.2
9.	Control Action		SPWM
10.	Filter Type (Per Phase)		Low Pass LC
11.	Filter Inductor (Per Phase)		0.8mH
12.	Filter Capacitor (Per Phase)		300μF

the maximum load power. Voltage rating of each single phase transformer connected to the main circuit is 240V whereas that of the winding connected to the VSC side as 120V. DC-bus has been taken as an ideal DC source of 120V. It is assumed that significant power from DG is available for conversion to AC and contribution to the main system.

Three different cases have been simulated using proposed Unipolar SPWM VSC control strategy.

Case-I: Compensation of voltage sags in utility voltage.

Case-II: Compensation of voltage swells in utility voltage.

Case-III: Compensation of phase jumps in utility voltage.

5.1 Compensation of Voltage Sags in Utility Voltage (Case-I)

There are further three categories in Case-I.

Category-A: Compensation of 3-phase balanced sag.

Category-B: Compensation of unbalanced sag in all 3-phases.

Category-C: Compensation of unbalanced sag in 2-phases.

5.1.1 Compensation of 3-Phase Balanced Sag (Category-A)

Fig. 6 illustrates a 50% 3-phase balanced sag in the utility supply which is introduced in the time interval from 0.06-0.12s. 3-phase balanced sag can be caused by a 3-phase balanced fault, though it is rare. Comparison of utility voltage with generated 3-phase reference signal produced an error signal which is shown in Fig. 7. Using feed-forward VSC control, DVR instantly injected the missing voltage to regulate the load bus voltage at its nominal value as shown in Fig. 8. ITIC curve and SEMI-F47 standard suggest a value of 20ms for the sag/swell restoration however, in our case the simulation shows far better results in which the load voltage is restored even in less than 10ms.

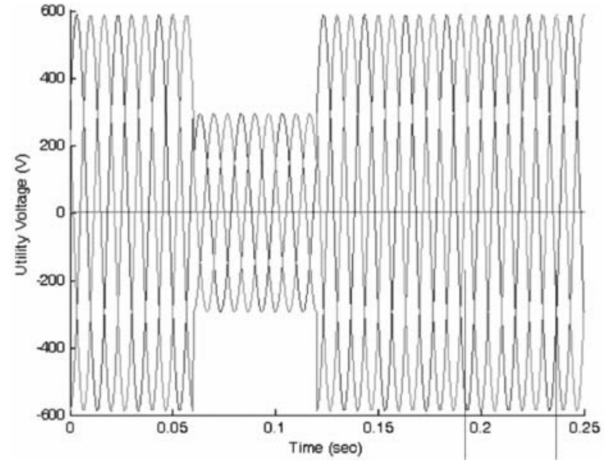

FIG. 6 . THREE-PHASE 50% BALANCED SAG IN UTILITY VOLTAGE

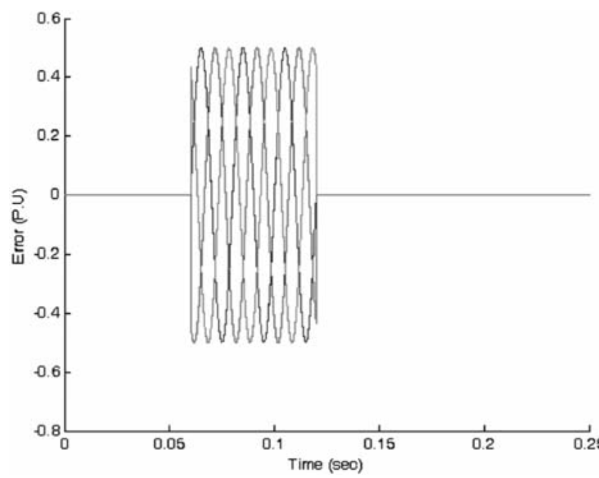

FIG. 7. GENERATED ERROR SIGNAL FOR A 50% BALANCED SAG ON ALL 3-PHASES OF UTILITY VOLTAGE

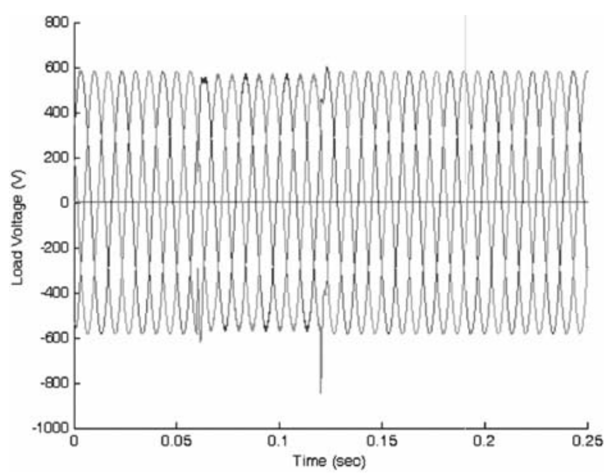

FIG. 8. LOAD VOLTAGE AFTER COMPENSATING A 3-PHASE 50% BALANCE SAG

Load voltage waveform of Fig. 8 shows large spikes that occur during transient period. These spikes appear when DVR is involved for the mitigation of sag as well as brought out after sag termination. These spikes in load voltage remain for 0.81ms. However, the duration is 0.85ms when sag disappears. Sudden involvement of DVR for sag mitigation results in load voltage spikes that reach -618V at the start of sag and -844V when sag terminates. The spikes that appear in the compensated load voltage waveform are to be avoided though; they do not distort the waveform considerably. Load voltage THD after sag mitigation is found to be 0.25% that lies within the acceptable range as suggested by IEEE Std. 519-1992.

5.1.2 Compensation of Unbalanced Sag in All 3-Phases (Category-B)

Most of the faults in distribution systems are of unbalanced type leading to unbalanced sags [31]. For determining the DVR response to counter unbalanced sag using the proposed strategy, voltage sags of 15, 25 and 35% in phase-A, B and C respectively have been initiated at 0.06 s and kept until 0.12s.

Instead of normal peak value of 586V for each phase of 3-phase utility voltage, phase-A, B and C peak voltage reduces to 498V, 439V and 381V respectively during the sag period according to the above mentioned induced sag values. Fig. 9 shows that DVR has responded quickly to compensate the 3-phase unbalanced sag by injecting the missing voltage of each phase according to the error signal. Hence, voltage at the load bus is maintained constant and balanced during simulation. This shows that, an unbalanced voltage disturbance can be treated in a similar manner as a balanced voltage disturbance for the proposed strategy. THD measured in compensated load voltage is 0.35% and lies within acceptable range.

5.1.3 Compensation of Unbalanced Sag in 2-Phases (Category-C)

Literature studies reveal that 66% of the voltage sags are that of single-phase whereas 16% of sags are of 2-phase type [25]. Hence, DVR is required to have the ability to mitigate sag in any of the phase, or in combination of phases. Fig. 10 illustrates a 3-phase utility voltage having 45% sag on its 2-phases. Using the proposed feed-forward control strategy of DVR, compensated load voltage is as shown in Fig. 11. Fig. 11 shows DVR response is quick in generating desired voltages to compensate 45% sag in 2-phases of utility voltage. In this way, it maintains a balanced and constant load voltage. THD measured for the compensated load voltage is 0.25% that lies within permissible limits.

Fig. 12 shows 45% voltage sag initiated in phase-A at 0.06s which is kept until 0.12s, with sag duration of 0.06s.

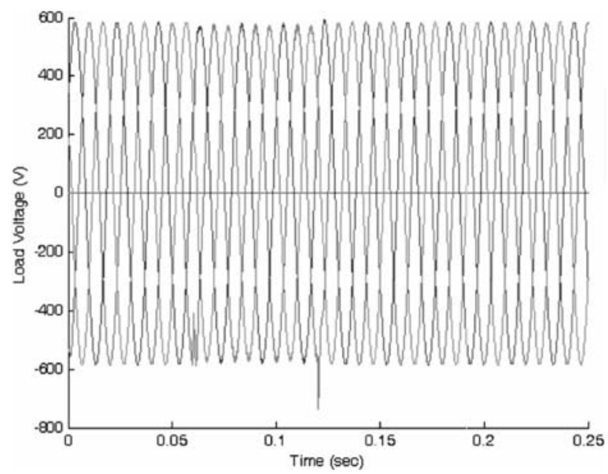

FIG. 9. LOAD VOLTAGES AFTER COMPENSATING AN UNBALANCE SAG ON ALL 3-PHASES

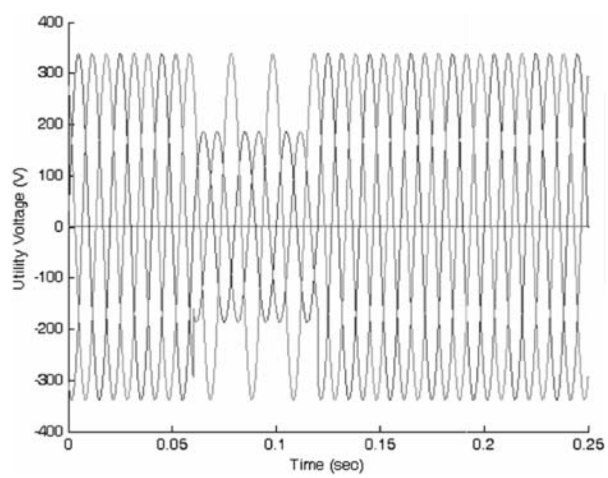

FIG. 10. UTILITY VOLTAGE SHOWING 45% SAG ON 2-PHASES

Both utility and load voltage plots overlap other than this sag duration. Dashed and solid line in the plot show utility voltage with sag and with compensated load voltage, respectively. However, voltage injected by the DVR is represented by dotted line in Fig. 12. As a result of the employed control strategy, DVR voltage injection is almost zero during normal operation. However, it responds quickly by adding missing voltage to compensate the sag in utility voltage after its detection and regulates the load voltage. It is evident from the simulation that the voltage is restored in less than 10ms against a target of 20ms as suggested by ITIC curve and SEMI-F47 standard. In addition, DVR also smoothen the active and reactive power delivered to load in its compensation mode as illustrated Figs. 13-14.

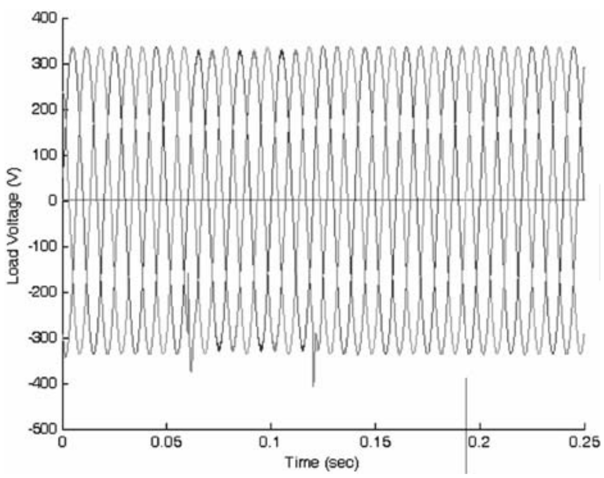

FIG. 11. LOAD VOLTAGES AFTER COMPENSATING 45% SAG ON 2-PHASES OF UTILITY VOLTAGE

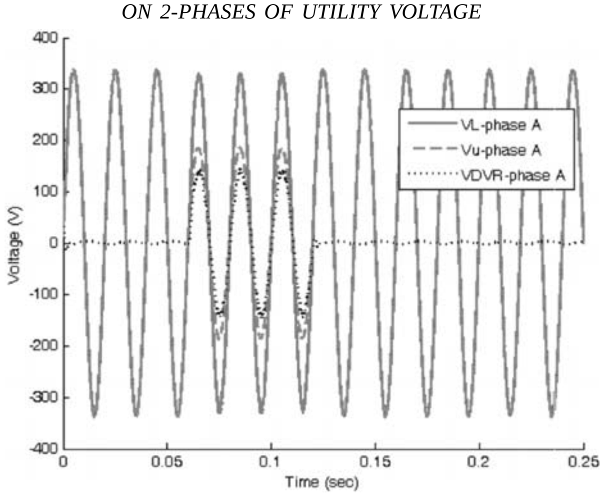

FIG. 12. DYNAMIC VOLTAGES FOR 45% SAG IN PHASE-A OF UTILITY VOLTAGE

The dynamic voltages, active powers and reactive powers for load, utility and DVR are plotted for only Phase-A of 3-phase system to show sag mitigation by the DVR for the proposed control strategy. However, plots of dynamic voltages, active powers and reactive powers for the other 2-phases can be obtained on the similar analogy.

5.2 Compensation of Voltage Swells in Utility Voltage (Case-II)

There are further three categories in Case-II.

Category-A: Compensation of 3-phase balanced swell.

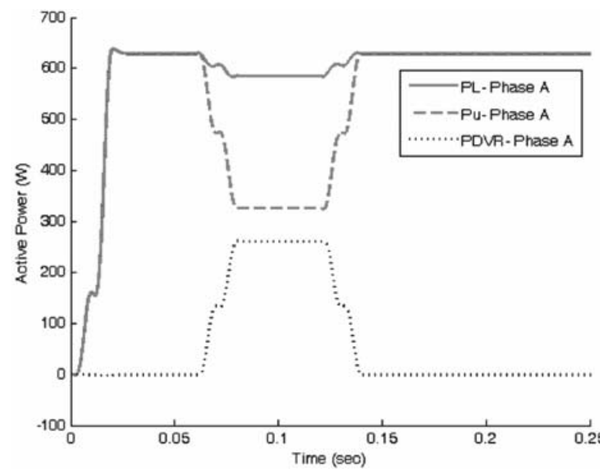

FIG. 13. DYNAMIC ACTIVE POWERS FOR 45% SAG IN PHASE-A OF UTILITY VOLTAGE

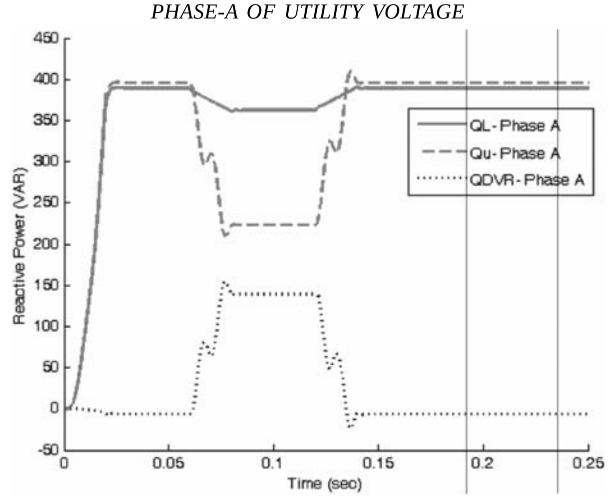

FIG. 14. DYNAMIC REACTIVE POWERS FOR 45% SAG IN PHASE-A OF UTILITY VOLTAGE

Category-B: Compensation of unbalanced swell in all 3-phases.

Category-C: Compensation of unbalanced swell in 2-phases.

5.2.1 Compensation of 3-Phase Balanced Swell (Category-A)

A balanced swell of 50% in all the 3-phases of utility voltage is introduced from 0.06-0.12s as shown in Fig. 15. Fig. 16 shows that DVR is quickly involved to inject the required 3-phase voltage components in the utility voltage to compensate swell according to the proposed VSC control strategy. In this way, load voltage is kept near to its nominal value.

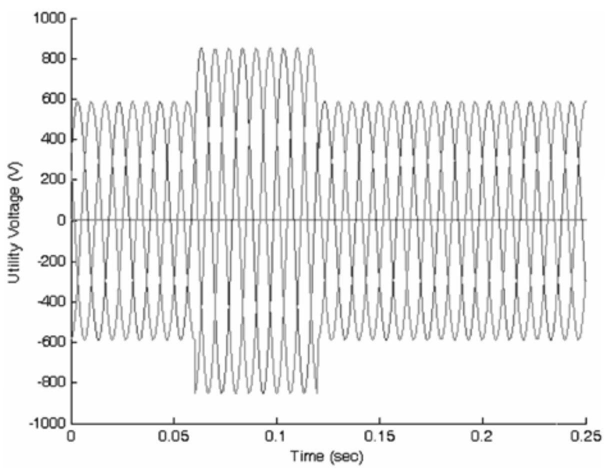

FIG. 15. UTILITY VOLTAGE SHOWING 50% BALANCED 3-PHASE SWELL

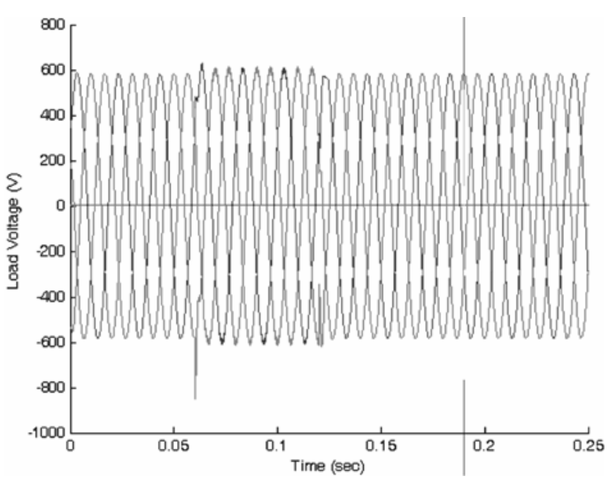

FIG. 16. LOAD VOLTAGE AFTER COMPENSATING A 50% BALANCED SAG ON ALL 3-PHASES OF UTILITY VOLTAGE

Voltage spikes that appear in load voltage during transient period are shown in Fig. 16. These spikes (or transient disturbances) occur when DVR is suddenly activated for swell mitigation and sudden injection of energy takes place by switching. Spikes in load voltage last only for 0.81ms after the occurrence of swell. When the DVR is suddenly involved for swell mitigation then spikes in load voltage reaches -844V at the beginning of swell. Though spikes that appear in compensated load voltage are to be avoided but they have not distorted the load voltage waveform considerably. Harmonic content in the compensated load voltage is found 0.28% (THD=0.28%) that lies within the acceptable range.

5.2.2 Compensation of Unbalanced Swell in All 3-Phases (Category-B)

To analyze the behavior of DVR for an unbalanced swell using the proposed VSC control strategy, a 3-phase unbalanced voltage swell in utility voltage is introduced with 15, 25 and 35% magnitudes in phase A, B and C, respectively from 0.06-0.12s.

Instead of normal peak value of 586V for each phase of 3-phase utility voltage, phase-A, B and C peak voltage rises to 674V, 732.5V and 791V respectively during the swell period according to the above mentioned induced swell values. Fig. 17 shows the quick response of DVR to inject the required compensating voltage in each phase of utility voltage to mitigate 3-phase unbalanced swell. This leads to a constant and balanced voltage at the load bus. Harmonic content of 0.37% (THD=0.37%) is measured in the compensated load voltage and lies within satisfactory range.

5.2.3 Compensation of Unbalanced Swell in 2-Phases (Category-C)

DVR is required to have the ability to overcome swell in any of the phase or in combination of phases. Hence, a category of 45% swell in 2-phases of a 3-phase utility voltage is simulated with the same swell duration as that for the cases 5.2.1 and 5.2.3. Similar to the 3-phase swell mitigation of category A and B, the DVR is able to produce the required voltage components for the 2-phases rapidly to mitigate 45% swell in the utility voltage and helped to maintain a balanced and constant load voltage as shown in Fig. 18. THD measured for the compensated load voltage is 0.28% and lies within the acceptable range.

Besides having measurements for the dynamic behavior of different voltages and powers for 45% sag in Phase-A of utility voltage, dynamic voltages and powers for 45% swell in Phase-A of utility voltage are also shown in Figs. 19-21, respectively. Power factor of the load has been taken 0.85 lagging as mentioned in Table 2. Dotted line in Fig. 22 shows the injected voltage that is generated by DVR according to the developed control strategy to regulate load voltage. The load voltage is kept near to its nominal value as evident by solid line in the plot.

Because DVR follows same principle as for sag compensation to regulate load voltages during swell, hence simulation results in Figs. 20-21 show that DVR absorbs excess power during swell to regulate load voltage to smoothen the power flow to load. The comparison of above two cases (5.1 and 5.2) shows that the DVR reacts instantly during sag/swell to correct load voltage to its nominal value according to developed VSC control scheme.

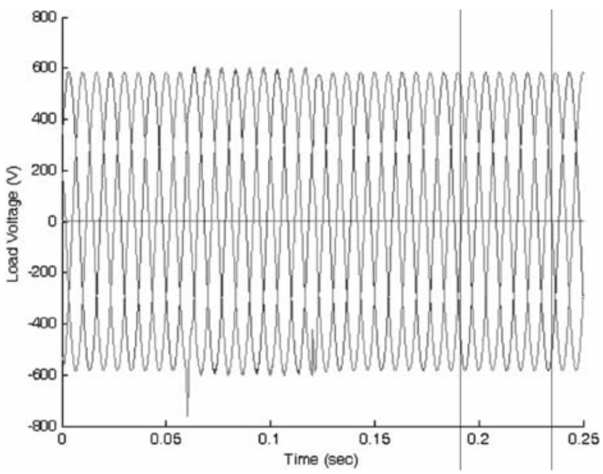

FIG. 17. LOAD VOLTAGE AFTER COMPENSATING AN UNBALANCED SWELL IN 3-PHASE UTILITY VOLTAGE

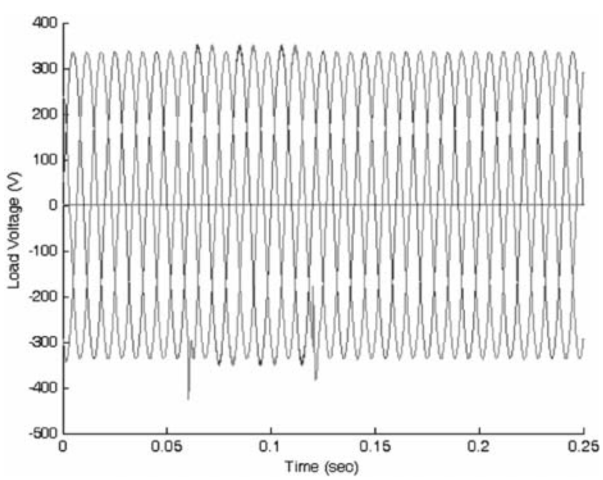

FIG. 18. LOAD VOLTAGE (LINE-TO-GROUND) AFTER COMPENSATING 45% SWELLS ON 2-PHASES

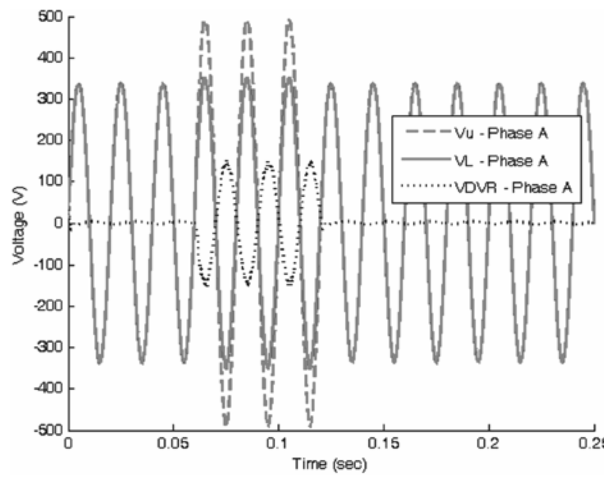

FIG. 19. DYNAMIC VOLTAGES FOR 45% SWELL IN PHASE-A OF UTILITY VOLTAGE

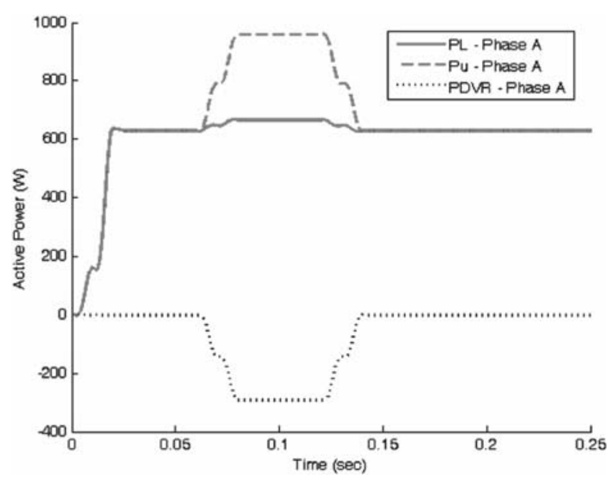

FIG. 20. DYNAMIC ACTIVE POWERS FOR 45% SWELL IN UTILITY VOLTAGE

The dynamic voltages, active powers and reactive powers for load, utility and DVR are plotted for only phase-A of 3-phase system to show voltage swell mitigation by the DVR for the proposed control strategy. However, plots of dynamic voltages, active powers and reactive powers for the other 2-phases can be obtained on the similar analogy.

5.3 Compensation of Phase jumps in Utility Voltage (Case-III)

There are further two categories in Case-III.

Category-A: Compensation of +25° phase jump in Phase -A of utility voltage.

Category-B: Compensation of -25° phase jump in Phase -A of utility voltage.

5.3.1 Compensation of +25° Phase Jump in Phase-A (Category-A)

Proposed VSC Control strategy is also investigated to compensate for phase-angle jumps in the utility voltage because some loads such as AC motors, line commutated converters, etc are sensitive to phase-angle jumps. The effects of phase jumps on AC motors and their drives are discussed in [32-33]. Simulations are performed to investigate the response of proposed control strategy to handle phase jump in supply voltage. Fig. 22 shows dynamic voltages for a +25° phase jump. It is evident from this figure that there is injection of voltage from DVR until phase jump persists so that an effect of utility voltage phase-shift on load voltage is nullified. However system returns to normal state when phase jump disappears.

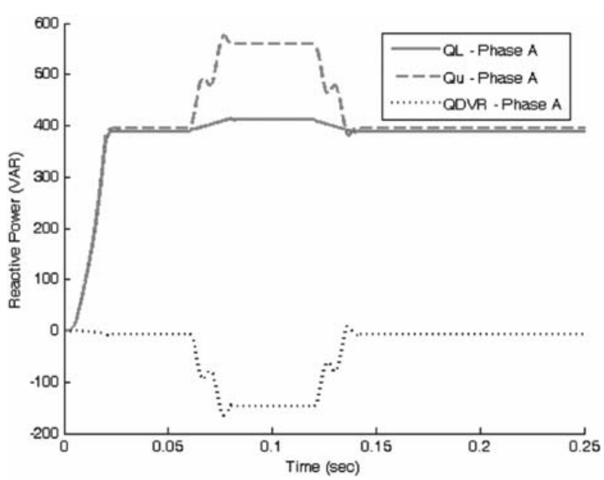

FIG. 21. DYNAMIC REACTIVE POWERS FOR 45% SWELL IN UTILITY VOLTAGE

5.3.2 Compensation of -25° Phase Jump in Phase-A (Category-B)

Fig. 23 shows dynamic voltages for a -25° phase jump. It is evident from this figure that there is injection of voltage from DVR until phase jump persists so that an effect of utility voltage phase-shift on load voltage is nullified. After the termination of the phase jump, there is zero injection of voltage from DVR and normal operation is restored.

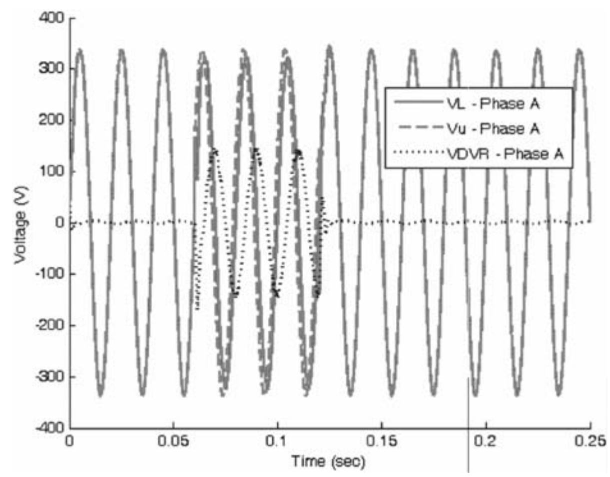

FIG. 22. DYNAMIC VOLTAGES FOR +25° PHASE JUMP IN PHASE-A OF UTILITY VOLTAGE

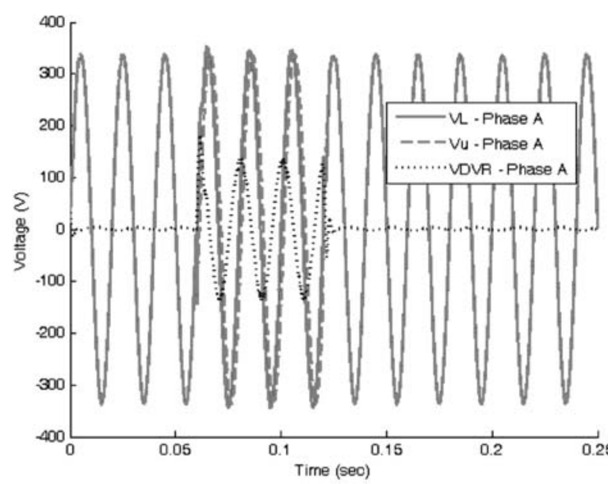

FIG. 23. DYNAMIC VOLTAGES FOR -25° PHASE JUMP IN PHASE-A OF UTILITY VOLTAGE

6. CONCLUSIONS

This paper presented a feed-forward control strategy to mitigate different power quality issues including voltage sags, swells and phase jumps with the help of in-phase series injection technique for smooth and clean power flow to load. DVR is a CPD that acts as series compensator to restore and regulate load voltage. A new but a simple control strategy is proposed for the VSC of DVR so that the converter not only converts DC-AC but also mitigates sags, swells and phase jumps in the utility supply by acting as power flow controller. The proposed control strategy succeeds in achieving load voltage THD limit within 5% for different loads.

The power sharing of the DVR and utility to serve load is according to demand for sag or swell mitigation keeping in view the DG available capacity.

With the help of proposed control scheme of DVR, the dynamic performance capability of DVR increases the sensitive load penetration in the distribution system.

ACKNOWLEDEMENTS

The authors are thankful to Prof. Dr. Saeed-ur-Rehamn, Prof. Dr. Khalid Munawar, and Prof. Dr. Khawar Islam, for their important discussions and helpful comments in achieving the objectives of this research work. The authors also greatly acknowledge the facilitation provided by the Directorate of Advanced Studies Research and Technological Development, University of Engineering & Technology Taxila, Pakistan with the financial support from Higher Education Commission Pakistan via Project No. UET/ASR&TD-251/2006.

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