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Interlined dynamic voltage restorer using time-domain methodologies with Z-source inverter/voltage source inverter

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ABSTRACT

Electronic devices and loads are very sensitive to the voltage disturbances like voltage sag and voltage swell. Significant financial losses and safety issues may emerge from voltage sags and interruptions, which can be caused by variables such as system breakdowns and load changes. In order to protect against voltage fluctuations and keep vital loads running, dynamic voltage restorers (DVRs) have become more popular. To mitigate the voltage disturbances, an interlined DVR (IDVR) using a Z-source inverter (ZSI) is developed to protect the sensitive devices and loads. Back-to-back DVR connects the distributed feeders with a common direct current (DC) link. The IDVR compensates for the sag voltage and supplies the energy to control the power flow. In addition, proposed a modified synchronous reference frame (MSRF)/direct quadrature theory, hysteresis controller, and proportional integral (PI) controller, which provides the required amount of control signals for a ZSI and voltage source inverter (VSI). MATLAB/Simulink validated the simulation results. The experimental findings show that the suggested system can be implemented successfully and is effective at reducing voltage dips and interruptions, allowing crucial loads to keep operating consistently and without interruption in residential as well as commercial environments.

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1. INTRODUCTION

Voltage fluctuations are a power quality issue that can seriously harm users with sensitive loads [1]. System errors, load fluctuations, energization of heavy loads, and poorly built systems are typically to blame for these disruptions. Uninterruptible power supply (UPS), constant voltage transformers, and tap-changing transformers are common traditional techniques for reducing voltage fluctuations. Utilizing specialized power

equipment, such as a dynamic voltage restorer (DVR), is a way to improve the quality of the power [2]. To meet the need for actual power, external energy storage is required. Therefore, a DVR's capacity is determined by the highest actual power delivered to the load during voltage sag mitigation. The DVR is a device circuit that recognizes sags or swells and links a voltage source in series with the supply voltage to maintain the load voltage within the set tolerance limits [3], [4]. It is often put in a distribution network at the point of common coupling (PCC) between the essential load feeder and the supply. The IDVR structure comprises many DVRs connected by a common DC connection. Each is situated in a separate feeder, protecting sensitive loads from voltage sags [5]. The other DVRs in an IDVR structure work in a rectification state and provide the direct current (DC) link with power to keep its voltage constant when one of them begins to absorb the power factor from a common DC link to correct the voltage sag [6], [7].

One of the most recent power electronics designs is ZSI. The ZSI features a special impedance network of two capacitors and inductors to couple the power source with the inverter's main circuit. Combining two linear energy storage components, L and C, creates the fundamental impedance source network. Inverters can function in the shoot-through mode because ZSI can improve the boost performance of the inverter's alternating current (AC) output voltage [8]. ZSI is a one-stage energy processing buck-boost inverter with unique passive input circuits that use the shoot-through of the power supply. An inverter bridge is used to increase the DC input voltage. The ZSI impedance network stores electricity and ensures a double filtration grade at the inverter's input [9]. The DC supply is converted to AC by the DVR with Z-source, reducing voltage-related problems such as voltage swells or sags in a distribution network caused by abruptly switching a balanced three-phase non-linear load [10].

By a tiny difference, the modified synchronous reference frame (MSRF) approach is identical to the SRF [11]. The (Idq) instantaneous current component technique is another term. In contrast to the phase-locked loop (PLL) [12] used in the SRF approach, the MSRF method obtains the transformation angle using the voltages of the AC network. For this, in a process known as clark's transformation, comparable to the approach, the stationary coordinate system of three-phase a-b-c would be first changed to a two-phase α-β system [13]. The next transformation, park's transformation, turns this two-phase α-β stationary coordinate system into a two-phase d-q rotating coordinate system [14]. A hysteresis controller raises the load voltage and chooses the inverter gates' switching signals [15]. Between the DVR reference voltage (Vref) and injection voltage (Vinj), an error signal that generates appropriate control signals is the basis of the hysteresis voltage control. A hysteresis relay will set a hysteresis band with a specific tolerance value [16]. It provides the inverter'sswitches with suitable gate pulses, generating the necessary voltage to mitigate power quality issues [17]. The use of DVR may be improved to lower the dynamic response time for managing voltage sag in the power system by employing the ZSI system under the control of a proportional integral (PI) controller layout [18]. The steady-state error for a step input is zero due to the PI controller's integral term.

The design of a discrete-time control strategy for mitigating unbalanced and balanced voltage instability in a DVR is presented [19]. To obtain an error of zero-tracking for the fundamental element in the event of balanced voltage sags, the system is based on a design with two nested regulators, one of which employs a necessary action, and the scheme is implemented in the SRF [20]. Uncertainty and disturbance estimator (UDE)-based framework control technique is presented to enhance the DVR's reaction to correctly adjust the load voltage under a range of power quality challenges, especially those connected to grid voltage disturbances [21]. Every type of disruption in the power system must be compensated for and acknowledged for it to function normally and efficiently [22]. Various custom power devices (CPDs) are utilized to address these problems [23]. DVR controls voltage under unbalanced load conditions and load imbalance [24]. The power quality enhancement uses fuzzy logic controllers and PI controllers. Total harmonic distortion (THD) and the device's performance are compared. A battery performance-monitoring device is used for photovoltaic control and monitoring system [25]. The conventional ziegler-nichols (ZN) technique tunes the PI derivative (PID) controller parameters. Subsequently, the adjusted parameters acquired from the ZN-PID controller are optimized via a method of optimization that relies on the reduction of the incorporated absolute error [26], [27]. The smart energy meter controls and computes the energy expenditure utilizing Espressif Systems8266 [28], [29]. The objective of Bayesian algorithm to improve energy and share the data well [30].

Problem statement and main contribution: existing DVRs can only manage voltage disturbances at a high cost and with limited efficiency. VSIs are common in conventional DVRs, and these devices use complex control techniques based on the SRF and PI controllers. These devices are helpful in decreasing voltage dips and power cuts, but they have certain drawbacks. Energy efficiency cannot always be maximized, and VSIs may limit the voltage increase capabilities of DVRs. This creates a serious problem for DVRs, which must keep voltage quality at a high level while using as little energy as possible.

The suggested system's main contribution is the novel and efficient method that it employs to restore voltage and improve power quality in electrical distribution networks. With Z-source inverters (ZSI) and the SRF direct quadrature control approach, voltage restoration may be precisely and quickly controlled.

ZSIs provide a number of integrated benefits that make them ideal for resolving voltage drops and power outages quickly and effectively. When compared to conventional DVRs based on VSI, the system's capacity to maintain greater voltage levels during disruptions is remarkable. IDVR and related advancements will be extensively explored in the subsequent sections of this article.

2. PROPOSED METHOD

2.1. Basic operations of IDVR

Thesystem comprises many DVRs in various feeders (F) with a common DC-link. A two-line IDVR system utilizes two DVRs that are back-to-back coupled to two Fs, with one of the DVRs compensating for voltage swell/sag and another DVR operating in power-flow control mode. The DC source is supplied through the commonly linked capacitor between the two Fs.The IDVR system comprises many DVRs in various F that share a common DC-link. A two-line IDVR system utilizes two DVRs that are back-to-back coupled to two Fs, with one of the DVRs compensating for voltage swell/sag and another DVR operating in power-flow control mode. The DC source is supplied through the commonly linked capacitor between the two Fs. Generally, due to the more considerable electrical distance of the transmission system, the voltage sag/swell is produced. The IDVR system connects the two different Fs with two grid substations. It implies in F1. The voltage distortion would be a lesser impact on F2. The DVR is coupled in series with the F, and a common DC link links DVRs from different Fs. The DVR is connected in series to the non-linear loads (1&2) across each F. Figure 1 explains a schematic diagram of IDVR.

The injection of a suitable voltage necessitates a particular quantity of reactive power (Q) and real or active (P), which the DVR must supply. P is provided by an energy storage facility linked to the DC link. In an AC power system, capacitors are often employed to create Q. Capacitors, on the other hand, may be utilized to store energy in a DC system. The capacitor terminal voltage lowers when energy is extracted from the capacitors. As a result, considerable capacitors in DC-link energy storage are required to efficiently minimize voltage swell of great depth and length. After the fault can be corrected and the supply can be operated under normal conditions, the DVR supplies the energy from the normal system. The capacitor bank rating depends on the load, which can protect the duration of sag depth. Whereas the sag correction uses P, the power electronics are fed from the capacitor bank and ZSI.

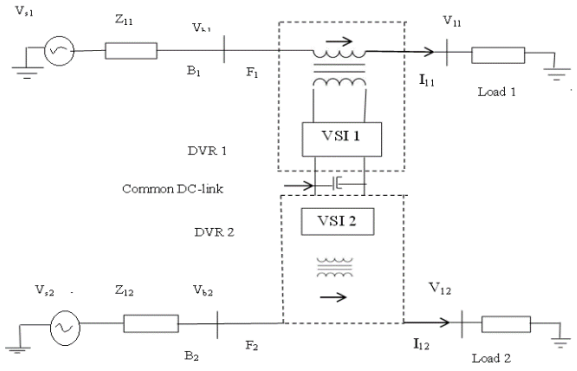

Figure 1. Schematic diagram of IDVR

2.2. Time domain methodologies

The SRF direct quadrature control method is based on a series APF compensator shown in Figure 2. During the on-grid condition, series APF provides source voltage against voltage fluctuations in the PCC. The injected source voltage and the PCC current act in the same phase. At the point when the series APF signals are sent into the PID controller, which in turn generates control signals that are transformed into pulse width modulation (PWM) switching signals in the abc domain, the synchronized decision-making process returns the pulse to the series APF converter. For a deeper understanding of the functioning controller, consider the (1) and (2).

$$V_{ED} *= V_D * -I_D, V_{ED} = V_D - I_D \quad (1)$$

$$V_{EQ} *= V_Q * -I_Q, V_{EQ} = V_Q - I_Q \quad (2)$$

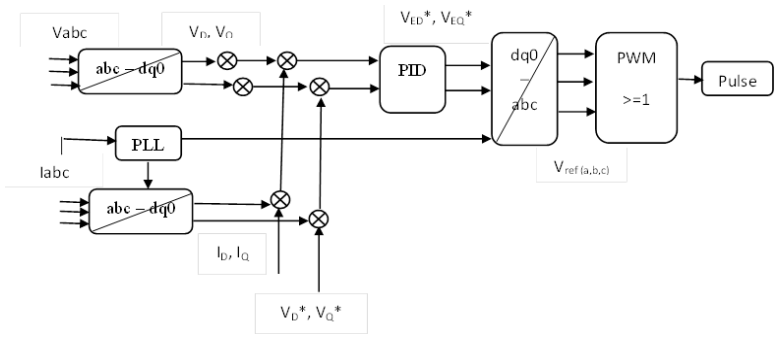

Figure 2. Direct quadrature theory

2.3. Hysteresis control method

The switching sequence of the inverter, which is coupled to the shunt APF, is generated via this control mechanism. This control approach knows the stability of the systems completely, is simple to apply, and is basic. Both the reference and the current that is injected from the controlling signal are crucial to this approach. The hysteresis current regulator determines the switching pattern. When the error approaches the top of the bands, the current immediately drops since this action is established as the reference current. The current is increased automatically when the error reaches a lower limit. The relevant framework can be seen in Figure 3.

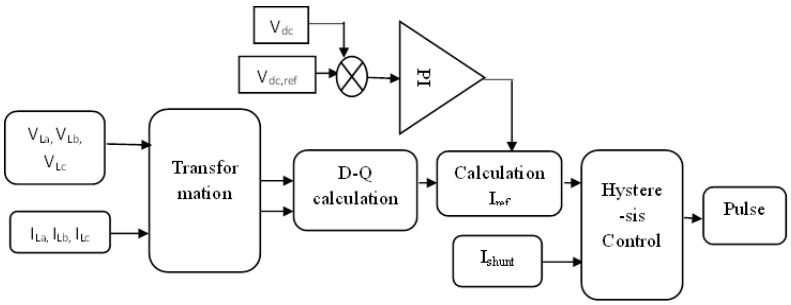

Figure 3. Block diagram of hysteresis control

2.4. PLL with PI control

Three basic easy to understand PLL connected to the voltage source Vsabc make up the PI controller. Given the voltage load abc VLabc, the direct quadrature transform transforms it to the direct quadrature domain. Once more, the signal transforms from the direct quadrature-abc domain, and the selection is used for extracting the signals to PI at constant values. Here, the PWM generator controls the signals and, in the end, supplies the series APF compensator with a pulse. Figure 4 explains a PI control.

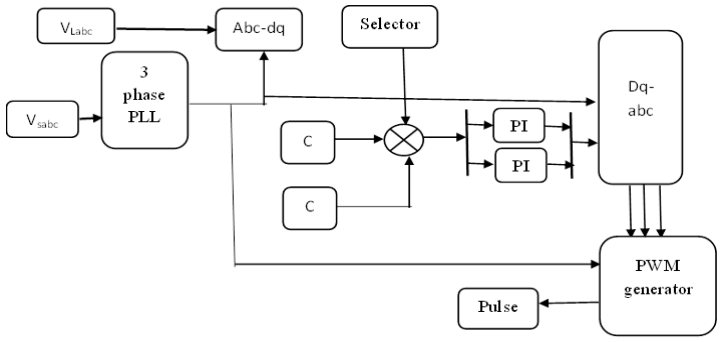

Figure 4. PI control

2.5. ZSI

A power inverter, typically described as a ZSI. Due to its distinctive circuit design acts as a buck-boost inverter without using a DC-DC converter bridge. The impedance source inverter's storage of energy and filtration part is a combined networking circuit. One feature that is provided by an impedance source inverter is the second-order filter. When it comes to reducing voltage and current ripples, this approach performs better. Another distinction is that the inductor and capacitor requirements should be lesser than of a conventional inverter.

3. SIMULATION AND RESULTS

The IDVR system's thorough simulation comprises multiple feeders with parameters that must be performed using MATLAB/Simulink. MATLAB provides great performance for the simulation, an interactive system shown in Figure 5. A comprehensive simulation of a basic IDVR system consisting of two 11 KV voltage lines was performed. Two lines supply 230 VA loads with a unity power factor.

The two line supplies are three-phase sources with 50 Hz, 3-phase short circuit level at base voltage is 100 mVA, 25 MVrms, and X/R ratio is 10. Then the sources are connected to the DVR, implemented through the linear windings transformer with the nominal power and frequency of 4 KV and 50 Hz. The series RC elements are implemented in the range of 1 Ω and 100 µF. The transformer is linked to the three-phase LC circuit to filter purposes with the content of 100 mH and 250 F. Then the line is connected to the series VSI, which is linked with the common DC link voltage. The fault is produced in line two, and the fault circuit breaker is used to diagnose the fault. As well as the breaker should select the external switching time of fault duration [0.2 0.35]. Likewise, a three-phase parallel LC branch with 370 mH and 0.19 F injects the voltage and current compensation of the power quality issues. Figure 6 illustrates the proposed system's source voltage (Vs) and source current (Is). The Vs and Is are 400 V and 4 A, respectively. Figure 7 represents the interlined first line's load voltage (VL1) and load current (IL1), which are not faulted. This first DVR dynamically replenishes the energy in the common DC link. The IDVR's performance and restoration capacity were evaluated using MATLAB/Simulink simulation.

The system was exposed to 100% sag, shown in Figure 8. The transient performance at the sagging front and recovery were studied during simulations. The performance was also analyzed when the DC voltage dropped during a long sag. However, DVR's energy storage capabilities are limited, typically comprised of capacitors. Figure 9 shows the injected voltage and current second IDVR. The voltage should be injected from 800 V to 600 V during 0.2s to 0.35s to mitigate the voltage sag in IDVR. Then the current is injected to 1.5 A from 0.2s to 0.35s.

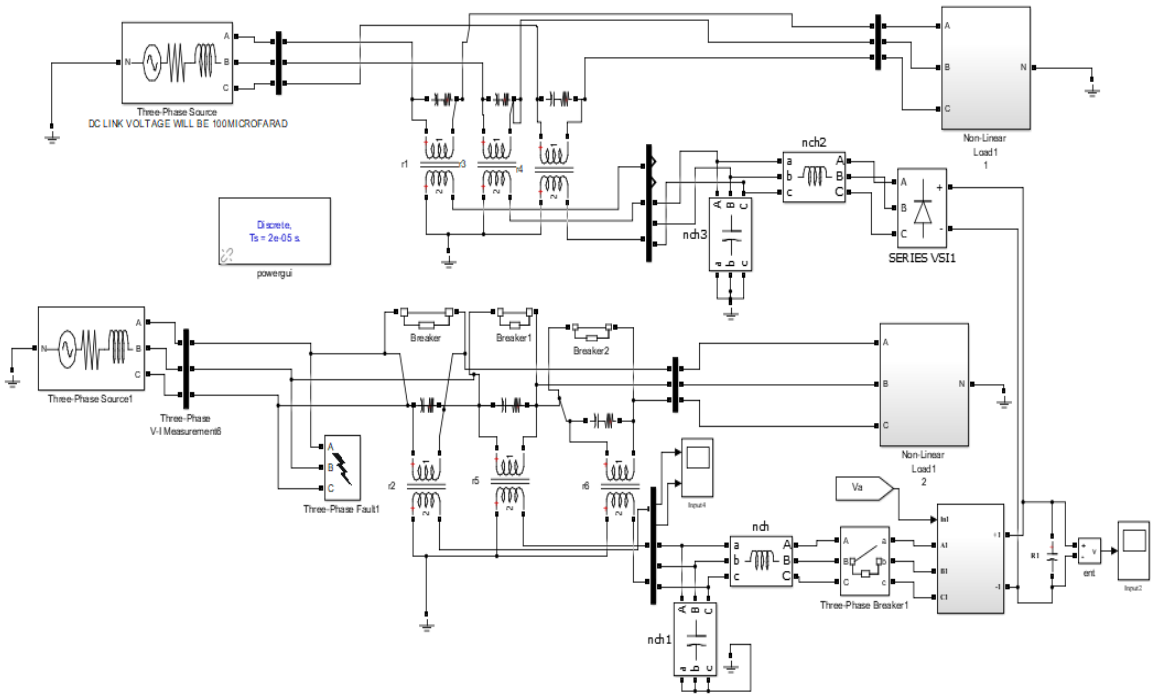

Figure 5. Simulation circuit of the proposed IDVR

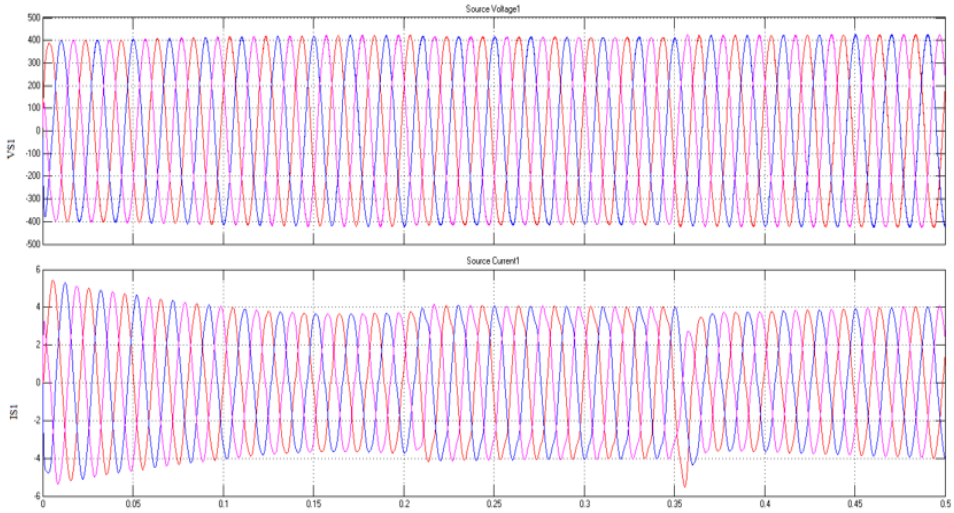

Figure 6. Source voltage and current of the interlined IDVR system

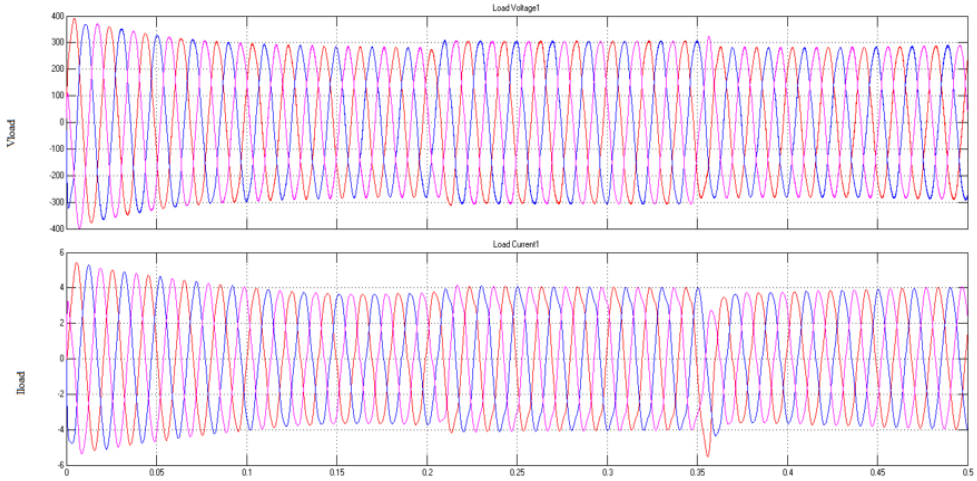

Figure 7. Load voltage and load current of the first line interlined IDVR system

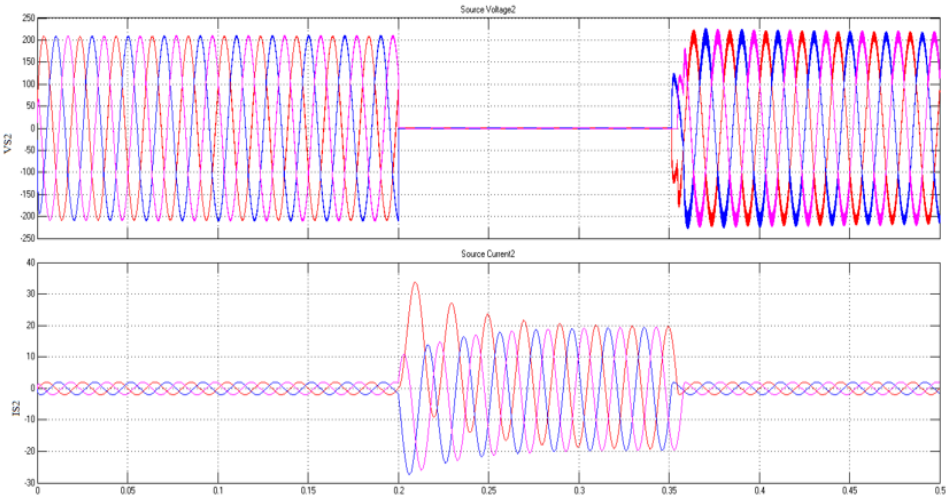

Figure 8. Vs2 and Is2 of without compensation

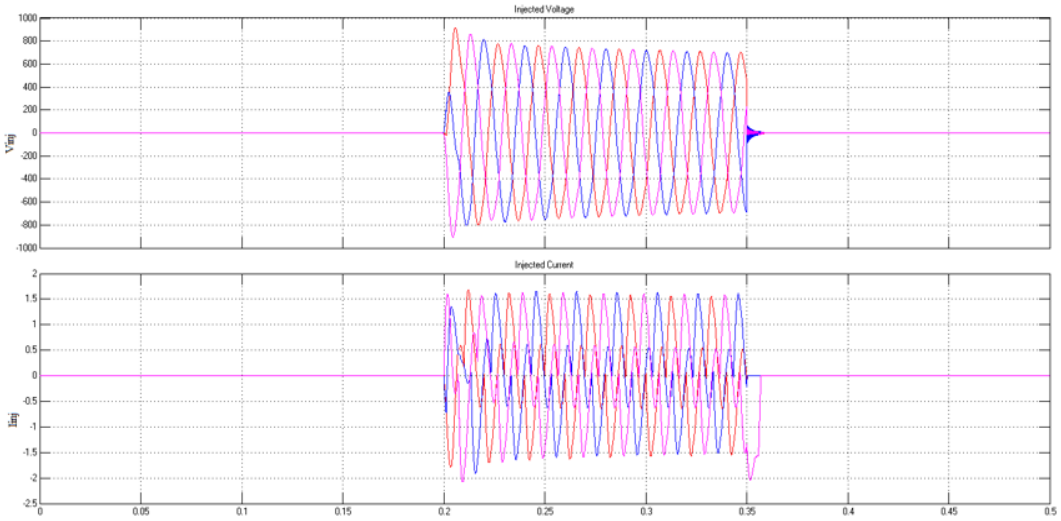

Figure 9. Injected voltage and current

As a result, it must be studied how to limit injection energy while keeping the load voltage near the pre-fault value. When operational, the DVR's architecture permits P and Q to be provided or absorbed. If a minor defect develops on the protected system, the DVR can rectify it using just internal Q. The DVR may be necessary to create P to restore significant defects. An energy storage device is required to enable the development of P; the DVR design currently employs a capacitor bank. Figure 10 illustrates the voltage and current compensation of the IDVR system using the MSRF control technique. The compensated voltage is 200b V, and 2 A is supplied to the non-linear loads.

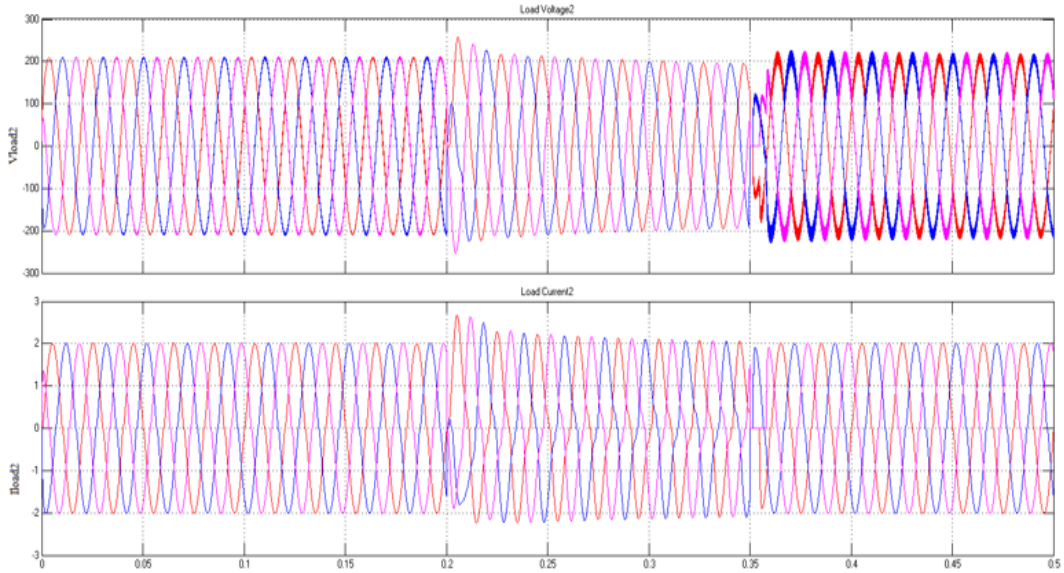

Figure 10. Compensated voltage and current

Figure 10 demonstrates the simulated voltage waveforms across loads 1 and 2 with IDVR employing a hysteresis controller system and a shared DC link voltage. It also indicates utilizing the inverter's buck-boost capability. The IDVR operating ZSI may store energy in the common DC link during the voltage compensation process. Figure 11 represents the compensated voltage and current using hysteresis control and Figure 12 demonstrates the compensated voltage and current using PI controlling the IDVR system. This compensation is slightly different than using the proposed controlling technique.

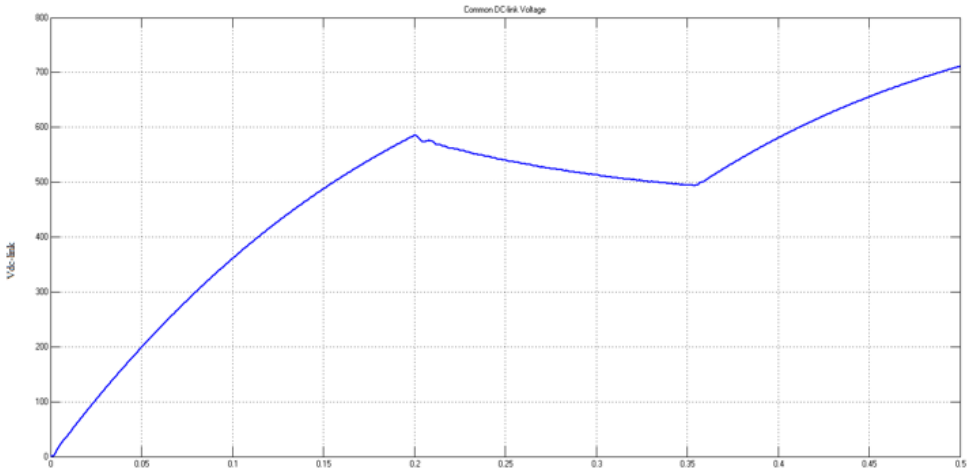

Figure 11. DC link voltage

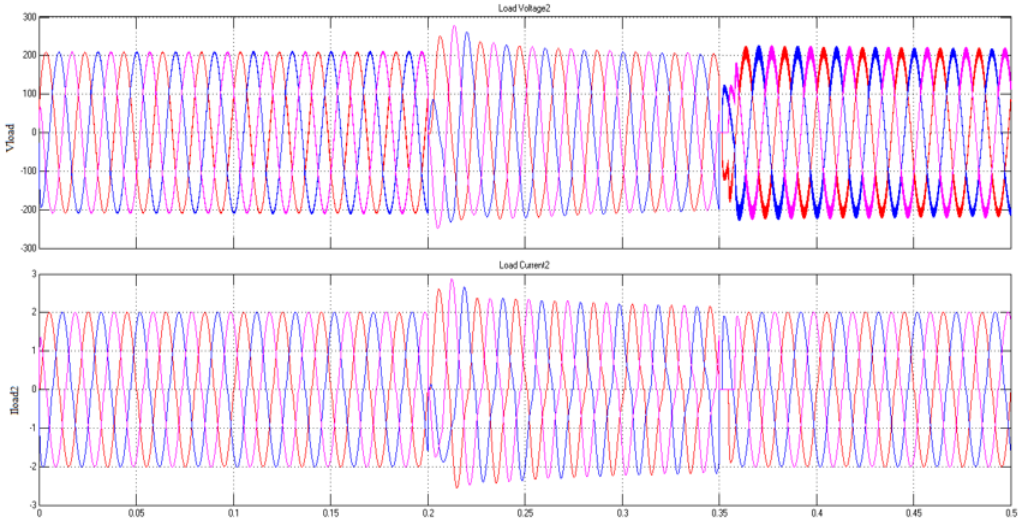

Figure 12. Compensated voltage and current using hysteresis control in the IDVR system

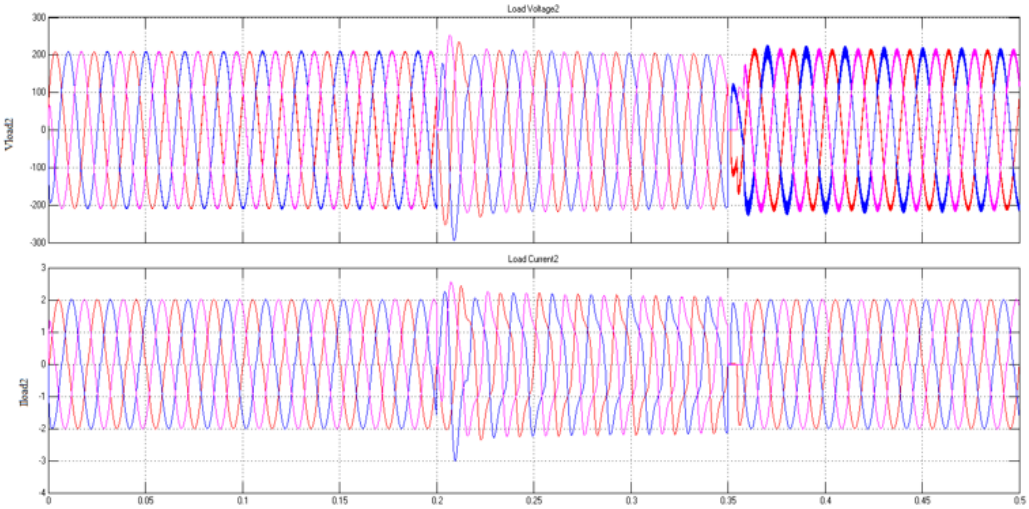

Figure 13. Compensated voltage and current using PI control in IDVR system

The IDVR in a distributed system using various control techniques has been used to analyze the THD. THD is often created by non-linear loads employed by end consumers of electricity. Non-linear loads, which are power electronic loads, draw current in a non-sinusoidal mode. This comparative analysis shows that the MSRF/ direct quadrature theory is better than hysteresis and PI control. Table 1 explains the THD analysis of controlling techniques. This table presents ZSI and VSI. In ZSI compared to load 1 and load 2, MSRF, hysteresis, and PI control are higher. Also, in VSI, load 2 is higher than load 1.

Table 1. THD analysis of controlling techniques

Methods	ZSI		VSI	
	Load 1	Load 2	Load 1	Load 2
MSRF/direct quadrature	3.45%	4.34%	3.47%	4.52%
Hysteresis control	3.45%	4.60%	3.70%	4.37%
PI control	4%	4.14%	4.10%	4.68%

4. CONCLUSION

This IDVR is used to improve the multiline power quality and is economical. This proposed IDVR system uses several DVRs commonly connected DC links. The proposed IDVR system has two interlined DVR and the IDVR's control strategy utilizes a multi-loop feedback control mechanism that is identical for voltage compensation and P regulation. The designed IDVR system and its PI and hysteresis controller were evaluated using MATLAB/Simulink simulations. It was discovered that the IDVR efficiently adjusts for sag disruptions while fully utilizing the common DC-link via the ZSI's buck-boost capabilities via the MRSF controller. The proposed IDVR system's limiting factor is that the amount of power that can transmit from on line to the DC-link power storage depends on the load power factor. According to the simulation, a two-line IDVR system may minimize voltage sag with a longer duration emerging in one line. IDVR modeling research for distribution line power flow control and voltage stabilization. The simulation results demonstrate the IDVR's unique capacity to rectify power imbalance in a distribution network with more than two lines and receive end voltage stability of a line at the sub-station utilizing ZSI for MRSF/direct quadrature, hysteresis and PI controller.

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