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Fractional Order Sliding Mode Control to Mitigate Power Quality Issues using Dynamic Voltage Restorer in Distribution Network

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ABSTRACT

Power quality (PQ) issues lead industrial customers to suffer significant financial losses. These PQ issues are garnering more attention from electricity suppliers and consumers in the modern day. This study addresses prevalent PQ issues, namely voltage sag and swell, stemming from a decrease in RMS voltage within electrical networks, particularly impacting sensitive loads. The solution proposed involves employing a series connected custom power device (CPD) named as dynamic voltage restorer (DVR) with an integrated DC battery for energy storage, to consistently maintain the requisite voltage magnitude. To effectively combat voltage sag and swell, the study introduces a novel control strategy known as fractional order sliding mode control (FOSMC). Noteworthy features of the FOSMC methodology include its capacity to autonomously and dynamically address sag and swell issues. The Simscape toolbox of MATLAB®/Simulink® is used to perform simulations to showcase the efficacy of the FOSMC technique. The results demonstrate that this strategy ensures total harmonic distortion remains below 5% and achieves sag/swell mitigation in less than 2 milliseconds, aligning with SEMI-F-47 and IEEE voltage standard 1159-2019. In summary, the study introduces and validates a robust control strategy implemented in a DVR system to autonomously alleviate voltage sag and swell issues, with simulation results supporting its effectiveness in upholding PQ standards. The FOSMC scheme with DVR is also compared with FOSMC scheme with DSTATCOM as well as with super twisting sliding mode control (STSMC) algorithm and classical sliding mode controller (SMC) to show the effectiveness of the proposed scheme. The FOSMC technique with DVR is more effective in restoring voltage sag/swell and PQ issues.

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1. INTRODUCTION

PQ problems are becoming more and more of a concern for end users and electrical utilities these days since they are costing industrial clients a lot of money. Thus, the main issue facing the distribution system of today is mitigating PQ issues [1]. To ensure end-users receive continuous and reliable power, the power system must be trustworthy. PQ issues like sag/swell primarily from fluctuations in voltage parameters. The accomplishment of clean power becomes challenging in the presence of linear/nonlinear loads. Numerous delicate loads require a dependable supply of clean power, even when the source is consistently available. Despite a steady power supply, the reliability of the distribution system may not always be assured. The escalating concern regarding PQ emanates from the prevalence of sensitive loads and the proliferation of sensitive loads [2]. CPD are also referred to as D-FACTS devices, work similarly to FACTS devices in demand to lessen voltage instabilities in distribution systems. The distribution system can be linked to these D-FACTS devices either in series, parallel, or a mix of the two. The several aspects highlighted in that cause voltage quality problems in the distribution system [3]. It is noted that several equipment, including DVRs, tap changers, UPSs, and static VAR compensators (STATCOM), can be employed to adapt for voltage Sag. It is concluded that the UPS, which oversees handling the entire load without assistance from the grid, is improper after comparing these devices. Because of their size, tap changers are rarely used. STATCOMs are typically used to support systems with poor power factor and insufficient regulation [4]. The literature review focus on the voltage pollutants like voltage sags and swells and their ameliorating D-FACTS devices namely, DVR, DSTATCOM and UPQC in power distribution system. Flexible AC transmission systems (FACTS) were developed in response to transmission system-related PQ issues [5]. While CPD's like distribution-static compensators (DSTATCOMs) address these PQ issues, the effectiveness largely depends on the accompanying controller. Hence, this study suggests implementing a FOSMC for DSTATCOMs to mitigate PQ issues in low-power distribution systems by regulating the injection or absorption of reactive power amidst disturbances [6-7].

Several research-based approaches present in literature demonstrate how Dynamic Voltage Restore (DVR) equipment can control voltage sags and swell events. The combination of PI and PID controllers is extensively used because they provide effective steady-state voltage protection through simple implementation methods. A comparison between an enhanced phase locked loop (EPLL) and a DVR based on a fuzzy logic controller (FLC) is presented in order to increase voltage quality. The study presents a battery-supported DVR to mitigate voltage pollutants such swells, sags, and harmonics [8]. Fuzzy Logic Control (FLC) together with Neural Network-based controllers represent two main AI-based approaches that have been developed to achieve adaptive and intelligent control strategies. The effective handling of diverse grid situations becomes possible with these methods although their live operation capabilities and sophistication require further investigation. The voltage compensation efficiency of DVRs increases through implementation of Space Vector Pulse Width Modulation (SVPWM) control techniques and Hysteresis control methods that decrease harmonic frequency components during switching operations. The implementation of these performance-enhancing techniques for DVRs has led to better results although total parameter optimization alongside real-time system control along with adaptability remains ongoing research challenges [9-10]. The analysis indicates that DVRs are the most cost-effective method of lowering voltage sag in the distribution system. Currently, fluctuations in voltage, arising from the complexities of the grid and unbalanced load conditions, pose significant PQ challenges such as total harmonic distortion (THD) and voltage unbalance factor (VUF) in the grid voltage [11]. These control systems experience difficulties when confronted with dynamic disturbances in addition to needing fine tuning adjustment for best results. Predictive control systems including Model Predictive Control have been applied to DVR applications because they enhance their response quality and operational stability. The predictive control system of MPC achieves quick responses and makes decisions based on forecasting but performs complex calculations that limit real-time application.

The utilization of a resilient control strategy has garnered significant impact across diverse engineering applications. Its effectiveness lies in its ability to effectively manage uncertainties and disturbances within dynamic systems. DVR, a device employed in power systems to alleviate voltage sag/swell can further augment the performance of the power system in terms of voltage regulation and stability when integrated with sliding mode control (SMC) [12]. Sliding Mode Control (SMC) represents a popular control methodology which demonstrates strong resistance to unpredictable system conditions and interference. Voltage compensation through SMC-based DVRs functions with fast accuracy yet causes excessive switching losses and system instability because of high-frequency chattering. Several modified SMC techniques were created to minimize chattering including the robust and smooth control approach known as Super Twisting Sliding Mode Control and Real twisting sliding mode control. A sophisticated hybrid control approach like SMC for DVR is presented in the research [13]. Simulation results demonstrate that the super-twisting sliding mode control (STSMC) may decrease reaction time while maintaining the essential characteristics of conventional SMC. To solve several PQ problems, the author demonstrates a real-twisting RTSMC for DVR to reduce phase deviations, voltage swell, and voltage sag, the voltage source converter (VSC) runs in voltage control mode [14].

Despite twisting algorithms, Fractional Order Sliding Mode Control (FOSMC) has been introduced because it offers superior robustness alongside enhanced dynamic performance with the help of fractional calculus. There are multiple research studies indicating FOSMC provides better transient operation with decreased chattering effects when compared against conventional SMC techniques. The utilization of FOSMC on D-STATCOM equipment leads to better control of system stability and voltage regulation and harmonic suppression across different load scenarios [15]. Modern research demonstrates that D-STATCOM controlled with FOSMC performs better than traditional controllers in two ways: it reduces low-frequency disturbances in power networks and controls non linearity effectively. The implementation of optimization methods such as PSO or ANN with FOSMC allows users to optimize controller parameters thus improving system efficiency. The optimization of computational efficiency alongside hardware implementation for FOSMC requires additional research before becoming suitable for real-time applications. The FOSMC control strategy shows strong potential for D-STATCOM-based power quality enhancement by providing increased stability and flexibility to modern electrical power systems [16].

Recent research demonstrates Fractional Order Sliding Mode Control (FOSMC) benefits from D-STATCOM can be successfully implemented in power quality improvement devices through Dynamic Voltage Restorers (DVRs). The voltage source converter-based device DVR operates similarly to D-STATCOM therefore serves as an excellent device for implementing FOSMC to mitigate voltage sags and swells. The combination with DVR deliver improved voltage compensation along with faster dynamic responses by employing its strong operating characteristics and decreased response oscillations.

The simscape toolbox of MATLAB®/simulink® is used to simulate the DVR applied control scheme. The simulation findings demonstrate the effectiveness of the proposed controller in the DVR system, demonstrating how quickly it can identify and mitigate voltage sag/swell and recompense Power, both active as well as reactive in an astoundingly little amount of time [17]. This time parameter is substantially shorter than the SEMI F-47 Standard's allowable limit, which is less than 20 milliseconds. Additionally, the THD in all simulated scenarios remained comfortably below the allowable threshold of 5% [18-19].

The proposed study used combined strategy of fractional order and sliding mode control (FOSMC) in DVR to mitigate the issue of sag /swell in the electrical System. To assess the effectiveness of the suggested controller, The results will be compared with the traditional SMC, STSMC, FOSMC with DSTATCOM and FOSMC with DVR and a thorough investigation was being carried out.The implementation of Fractional Order Sliding Mode Control (FOSMC) with dynamic voltage Restorer (DVR) aligns with a significant step forward because fractional calculus enables better system stability together with chattering reduction while delivering improved transient alongside steady-state performance compared to conventional SMC and standard controllers.

2. MATHEMATICAL MODELLING OF DVR USING FOSMC

By quickly correcting for voltage sags and surges, the DVR efficiently keeps smooth the voltage magnitude at the load bus while guaranteeing dependable and constant power supply. The DVR greatly enhances PQ by minimizing voltage disturbances, which lowers the possibility of equipment damage or failure brought on by voltage variations. Due to its fast reaction time, the DVR can quickly compensate for voltage fluctuations, offering swift rectification and minimizing interference with delicate machinery and operations.The block diagram of DVR is shown in figure 1.

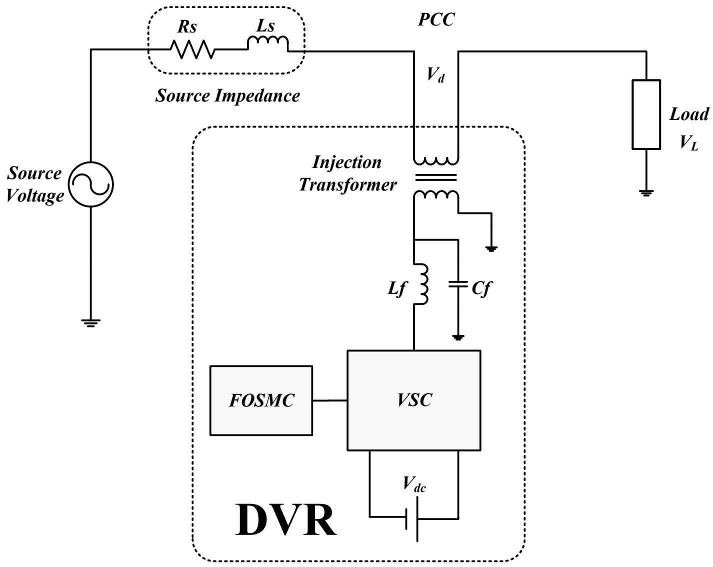

Figure 1. Block diagram of DVR [20]

An analogous Dynamic Voltage Restorer (DVR) coupled in series with a source-and-load distribution system is shown in Figure 2.

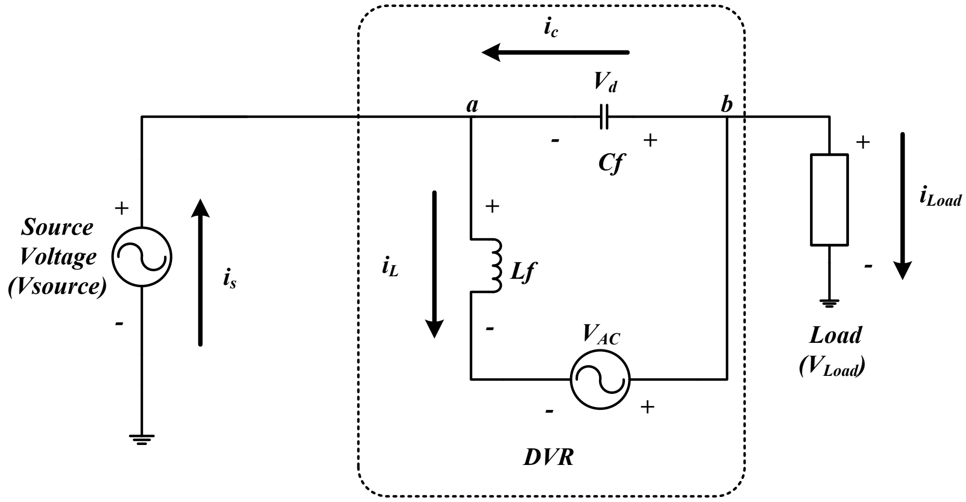

Figure 2: Schematic diagram of DVR [21]

By applying Kirchhoff's voltage law in figure 2 we get equation (1).

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

The AC output of the VSC undergoes filtration to eliminate high-frequency components, a process depicted in Figure 3 through the use of filter parameters C_{FC} and L_{FL}. It's important to note that the current flowing through the filter capacitor is:

$$I_{FC} = C_{FC}\frac{dV_{DVR}}{dt} \tag{2}$$

Applying KCL at node a_1 in figure 2.

$$I_S - I_{FL} + I_{FC} = 0 \tag{3}$$

Where i_s is a source current and I_{FL} is filter inductor current. Put the value of I_{FC} from equation (2) into equation (3).

$$I_S - I_{FL} + C_{FC}\frac{dV_{DVR}}{dt} \tag{4}$$

By simplifying equation (3),

$$\frac{dV_{DVR}}{dt} = \left(\frac{I_{FL} - I_S}{C_{FC}}\right) \tag{5}$$

By applying Kirchhoff's Voltage Law (KVL) to the closed loop in Figure 3, we can establish the second state equation.

$$V_{DVR} + V_{FL} - V_{in} = 0 \tag{6}$$

In Equation (6), V_{in} represents the AC output voltage of the VSC in the DVR, and V_{FL} is the voltage across the filter inductor. This equation can be utilized for computing the voltage across an inductor.

$$V_{FL} = L_{FL}\frac{dI_{FL}}{dt} \tag{7}$$

Put the value of V_{FL} from equation (7) into equation (6) we get equation (8)

$$V_{DVR} + L_{FL}\frac{dI_{FL}}{dt} - V_{in} \tag{8}$$

By simplifying equation (8) we get equation (9).

$$\frac{dI_{FL}}{dt} = \left(\frac{V_{in} - V_{DVR}}{L_F}\right) \tag{9}$$

Thus, the state space model series connected DVR is given in equation (10).

$$\frac{d}{dt}\begin{bmatrix} I_{FL} \\ V_{DVR} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_{FL}} \\ \frac{1}{C_{FC}} & 0 \end{bmatrix}\begin{bmatrix} I_{FL} \\ V_{DVR} \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{L_{FL}} \\ \frac{-1}{C_{FC}} & 0 \end{bmatrix}\begin{bmatrix} I_S \\ V_{in} \end{bmatrix} \tag{10}$$

Where I_{FL} and V_{DVR} are state variables, while i_s and V_{in} are the input variables

This control approach aims to effectively mitigate the issues of voltage sag and swell in the system.

$$V = \begin{bmatrix} V \\ \dot{V} \end{bmatrix} \tag{11}$$

In this context, 'v' represents the state variable, 'v' denotes the state vector, and 'v' signifies the first derivative of the state variable. The output AC voltage of the VSC of DVR is regulated by a sliding surface.

The sliding manifold, depicted by the signal 'S' is constructed based on the anticipated error voltage 'V_{ERROR},' as shown in equation (12).

$$V_{ERR} = V_{REF} - V_{LOAD} \tag{12}$$

The state feedback law presented below is a widely employed approach for the selection of the sliding surface is given in equation (13)

$$S = V_{ERR} + k\frac{d}{dt}V_{ERR} \tag{13}$$

where k is a gain in feedback.

There are two criteria that should meet for reaching to zero of sliding surface are given in equation (14) and (15).

$$S = 0 \tag{14}$$

$$\dot{S} = 0 \tag{15}$$

All state trajectories should be changed to zero origin of sliding surface line in the proposed control system.

$$S\dot{S} = 0 \tag{16}$$

The lyapunov function, as defined in equation (16), guarantees the stability of the system under the following conditions:

The formulation of the switching law is as follows: Here, the switching control variable $x(t)$ is defined, with c representing a constant. The value of control input is chosen within the range of $\pm c$ as shown in equation (17).

$$x(t) = \begin{cases} +1 \ IF \ S > +c \\ -1 \ IF \ S < \ -c \end{cases} \tag{17}$$

However, a common drawback of standard SMC is the occurrence of oscillations. To address this issue, FOSMC is utilized. The diagram below illustrates the modelling of FOSMC.

The following section provides an overview of the fundamental operator in fractional-order proportional-integral-derivative (FOPID) is shown in equation (18) and the block diagram of FOPID is seen in figure 3.

$${}_{\alpha}^{1}D_t^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_{\alpha}^{t}(dt)^{\alpha} & \alpha < 0 \end{cases} \tag{18}$$

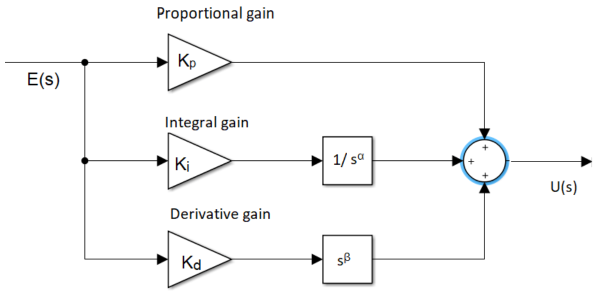

Figure 3. Block diagram of FOPID [22, 23]

The use of FOPID (Fractional Order Proportional-Integral-Derivative) controller in the FOSMC-DVR (Fractional Order Sliding Mode Control with Dynamic Voltage Restorer) strategy significantly enhances power quality improvement in electrical systems, especially in smart grids. Unlike traditional PID controllers, the FOPID controller introduces two additional parameters—λ (lambda) for the integral part and μ (mu) for the derivative part—allowing the controller to operate in a fractional domain. This fractional order approach offers a greater degree of freedom in tuning the system, which improves the dynamic performance, robustness, and control accuracy [24].

When integrated with FOSMC, the FOPID controller enables more precise control of the DVR, a custom power device used to inject compensating voltages during disturbances such as voltage sags or swells. In conventional SMC strategies, the controller typically drives the system states toward a predefined sliding surface and maintains them there. However, by incorporating the FOPID controller, this process becomes smoother and more adaptive, especially in nonlinear and uncertain grid environments. The fractional derivatives and integrals provide memory and hereditary properties, which are crucial in accurately predicting and correcting voltage fluctuations over time. The applications of FOPID with FOSMC-DVR configuration are enhanced transient response, improved robustness against parameter variations and external disturbances, Lower Total Harmonic Distortion (THD), and Faster compensation time [25].
The FO is employed with the super twisting algorithm to the sliding surface to provide the control output "W"', as shown in equation (19) and the test system design parameters is given in table 1.

$$W = -\left[\left(k_1 sgn(S) * \sqrt{|S|}\right) + \left(k_2 * \int \left(sgn(S)ds\right)\right)\right] \quad (19)$$

Table 1. Test System Design Parameters

Serial No.	Components and parameters	Value	Unit
1	Voltage (Vs) Vrms (ph-ph)	400	Volts
2	Frequency	50	Hertz
3	Line impedance	0.8929,16.5e-3	Ohm, Henry
4	Load type	P=10e3, Q=1e3	Watt, VAR
5	Switching constant	0.1	-
6	Energy storage	40	Volts
7	LC Filter, Lc, Cf	1.8e-3,5.5e-6	Henry, Farad
8	Injection transformer rating	100e3	VA
9	Voltage sag/swell mitigation time	1.9 ms	Mili second
10	Control action	FOSMC	-
11	Contant values	+5,-5	-
12	Feedback gain	0.142e-6	-
13	Switching frequency	10e3	Hertz
14	Solver	Ode23tb (stiff/TR-BDF2)	-
15	Sampling time	0.3	Second

3. SIMULATION RESULT AND DISCUSSION

3.1. Case 1: Compensation of 10% voltage sag and 10% voltage swell in supply voltage

The three-phase source voltage waveform under 10% voltage sag and 10% voltage swell caused by load switching is seen in Figure 4. Sag duration is from 0.05 and 0.1 seconds likewise swell duration is from

0.1 to 0.15 seconds in the source voltage. The FOSMC-based controller detects the voltage sag at 0.05 seconds, detect swell at 0.1 seconds and injects the desired compensation voltage with the appropriate magnitude and angle into the distribution system. Three-phase regulated voltages have a THD value of 0.45%, which is less than the acceptable limit of 5% as per IEC standard.

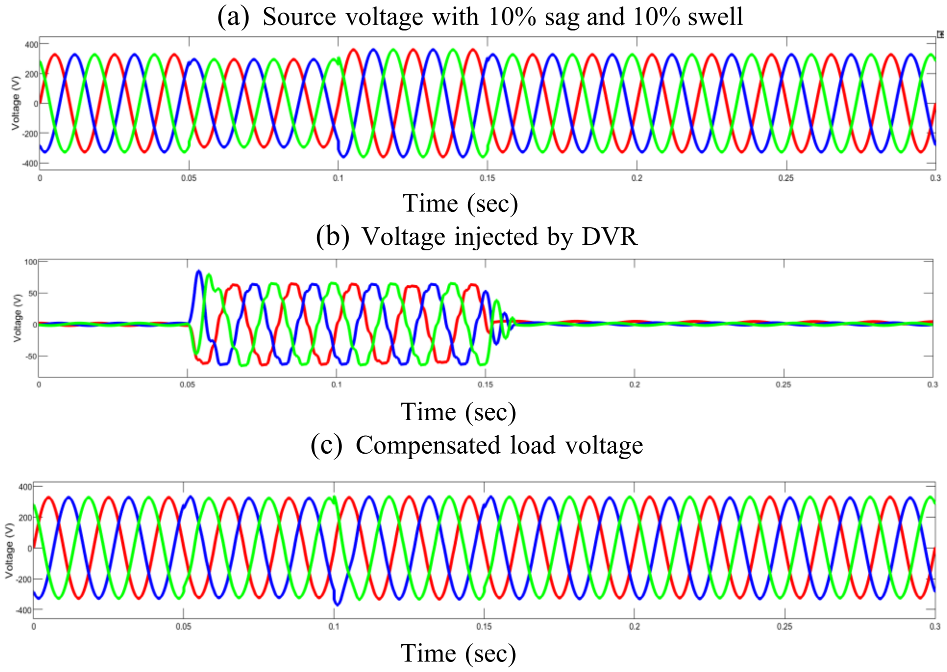

Figure 4. (a) 10% voltage sag and 10% voltage swell in supply voltage (b) DVR-injected voltages with 10% sag and 10% swell with FOSMC control strategy (c) Corrected load voltage with 10% of voltage sag and 10% voltage swell with FOSMC control strategy

3.2 Case 2: Compensation of 30% voltage sag in supply voltages

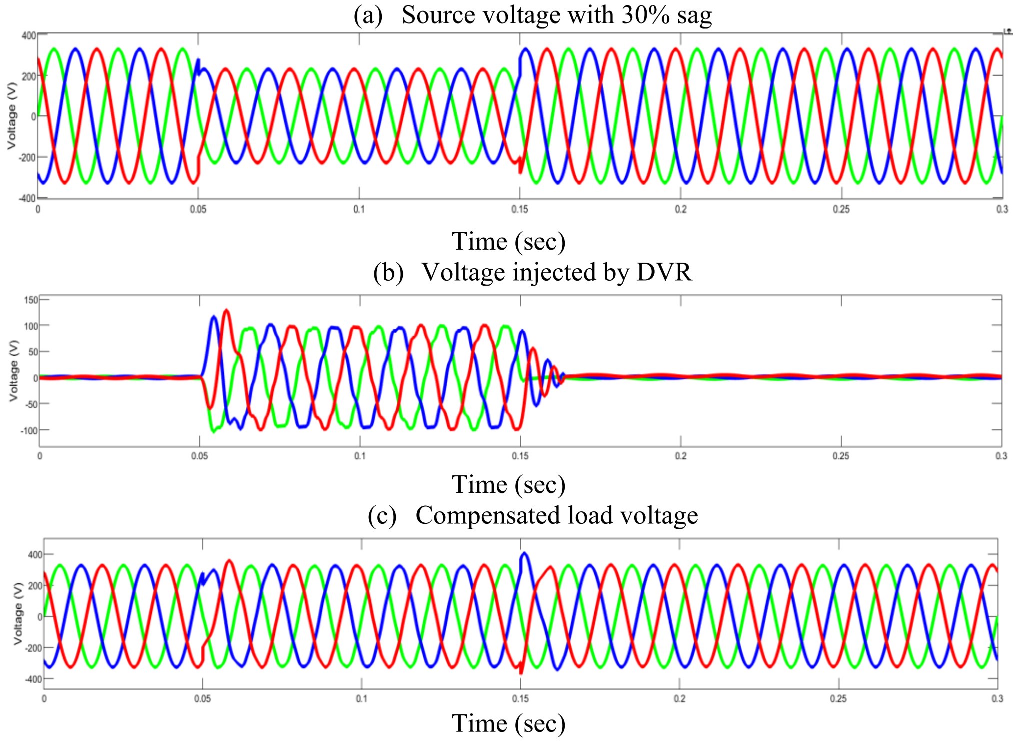

Figure 5. (a) 30% voltage sag in supply voltage (b) DVR-injected voltages with 30% sag with FOSMC control strategy (c) Corrected load voltage with 30% of voltage sag with FOSMC control strategy

The three-phase source voltage waveform under 30% voltage sag caused by load switching is seen in Figure 5. Sag duration is from 0.05 and 0.15 seconds in the source voltage. The FOSMC-based controller detects the voltage sag at 0.05 seconds and injects the desired compensation voltage with the appropriate magnitude and angle into the distribution system. Three-phase regulated voltages have a THD value of 0.45%, which is less than the acceptable limit of 5% as per IEC standard.

3.3 Case 3: Compensation of 30% voltage swell in supply voltages

The three-phase source voltage waveform under 30% voltage swell caused by load switching is seen in Figure 6. Swell duration is from 0.05 and 0.15 seconds in the source voltage. The FOSMC-based controller detects the voltage swell at 0.05 seconds and injects the desired compensation voltage with the appropriate magnitude and angle into the distribution system. Three-phase regulated voltages have a THD value of 0.24%, which is less than the acceptable limit of 5% as per IEC standard.

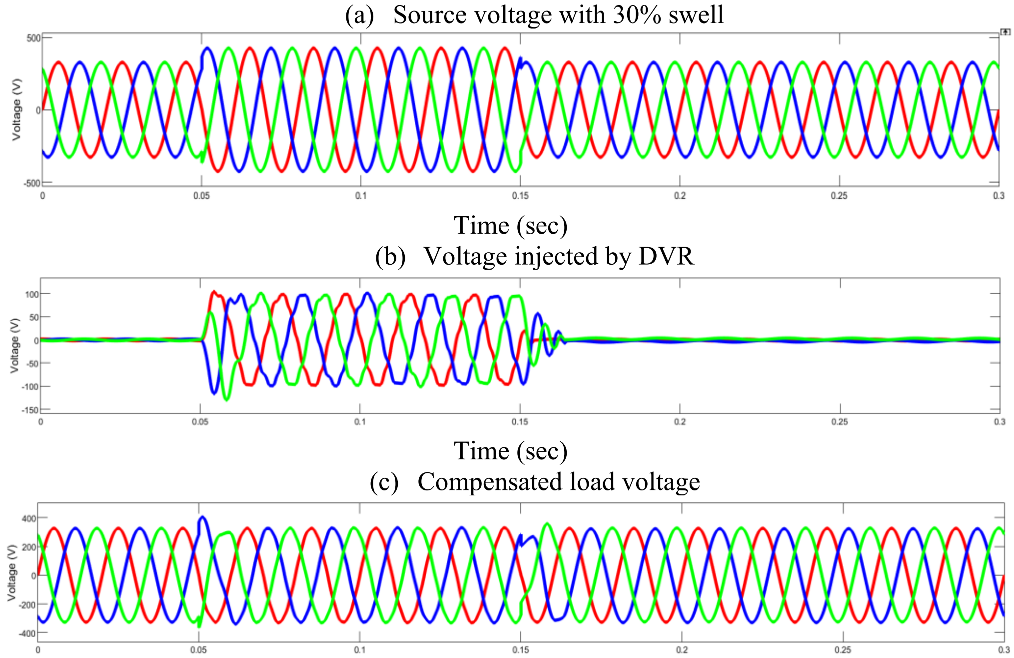

Figure 6. (a) 30% voltage swell in supply voltages (b) DVR-injected voltages with 30% swell with FOSMC control strategy (c) Corrected load voltage with 30% of voltage swell with FOSMC control strategy

3.4 Case 4: Compensation of 40% voltage sag in supply voltages

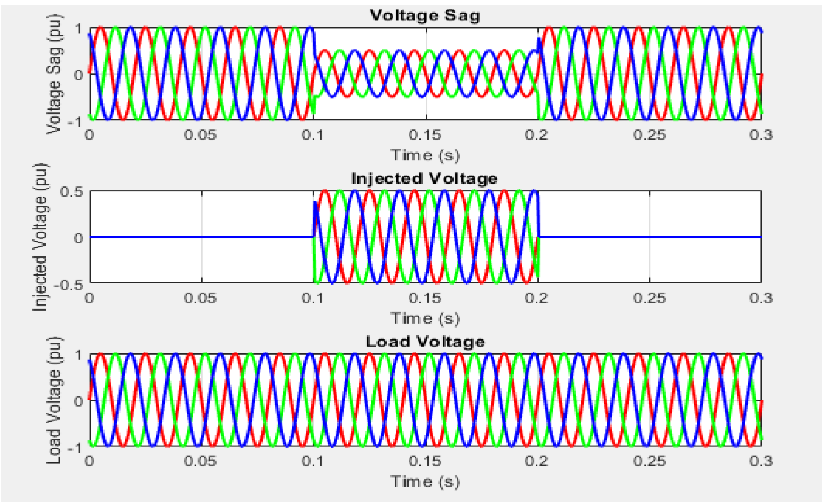

Figure 7. (a) 40% voltage sag in supply voltage (b) DVR-injected voltages with 40% sag with FOSMC control strategy (c) Corrected load voltage with 40% of voltage sag with FOSMC control strategy

The three-phase source voltage waveform under 40% voltage sag caused by load switching is seen in Figure 7. Sag duration is from 0.1 and 0.12 seconds in the source voltage. The FOSMC-based controller detects the voltage sag at 0.1 seconds and injects the desired compensation voltage with the appropriate magnitude and angle into the distribution system. Three-phase regulated voltages have a THD value of 1.40%, which is less than the acceptable limit of 5% as per IEC standard.

3.5 Case 5: Compensation of 40% voltage swell in supply voltages

The three-phase source voltage waveform under 40% voltage swell caused by load switching is seen in Figure 8. Swelling duration is from 0.1 and 0.2 seconds in the source voltage. The FOSMC-based controller detects the voltage swell at 0.1 seconds and injects the desired compensation voltage with the appropriate magnitude and angle into the distribution system. Three-phase regulated voltages have a THD value of 1.98%, which is less than the acceptable limit of 5% as per IEC standard.

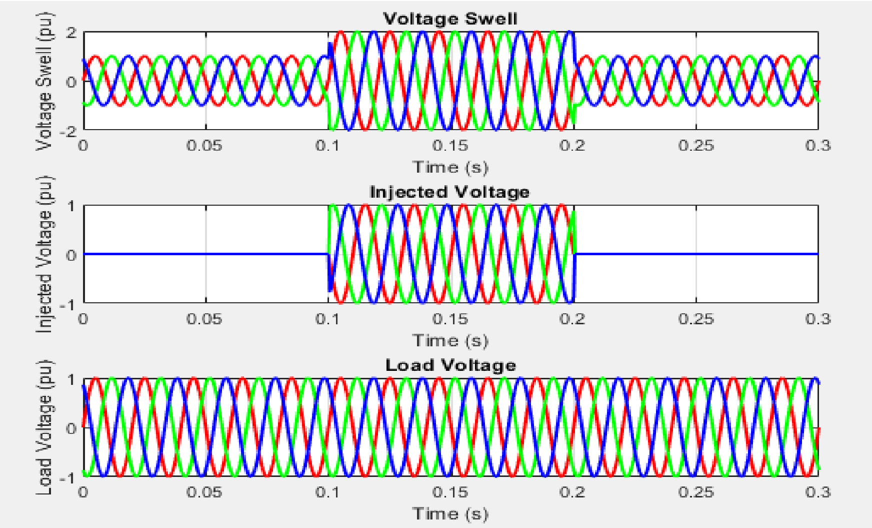

Figure 8. (a) 40% voltage swell in supply voltages (b) DVR-injected voltages with 40% swell with FOSMC control strategy (c) Corrected load voltage with 40% of voltage swell with FOSMC control strategy

3.6 Case 6: Comparison of FOSMC for DVR with other Latest Researches

The comparison of different strategies—FOSMC with DVR, FOSMC with DSTATCOM, ST-SMC with DVR, and SMC with DVR—reveals significant insights into their performance in mitigating power quality issues such as voltage sags, swells, and harmonic distortion.

The proposed Fractional Order Sliding Mode Control (FOSMC) combined with a Dynamic Voltage Restorer (DVR) proves to be the most efficient approach for mitigating power quality issues such as voltage sags and swells. By integrating the principles of fractional calculus with the traditional Sliding Mode Control (SMC), this method allows for the design of a more flexible and robust sliding surface. As a result, the system's state variable is effectively and quickly restored to its desired position. This strategy stands out for its exceptional robustness and fast dynamic response, achieving a response time of just 1.9 milliseconds for both sag and swell mitigation. Moreover, it offers superior power quality performance, as indicated by its remarkably low Total Harmonic Distortion (THD), which ranges from only 0.24% to 2.2%, as shown in Table 2. These characteristics make FOSMC with DVR the most reliable and high-performing method among the four compared approaches.

The FOSMC strategy with DSTATCOM also employs fractional-order control with the SMC algorithm, and while it shares a similar working principle with the DVR-based approach, it performs slightly lower in voltage mitigation and robustness. It offers good performance in sag/swell mitigation, with a response time of 2.2 ms and 2.3 ms respectively, and THD between 0.52% to 2.9%—still better than most but not as refined as the DVR-integrated FOSMC [26].

The ST-SMC (Super Twisting Sliding Mode Control) with DVR makes use of the ST algorithm for sliding surface selection. While it successfully returns the state variable to its origin, its voltage mitigation is only decent, with a slower response of 2.5 ms for both sag and swell, and higher THD levels between 2.8% and 4.6%. The robustness here is rated as merely good, showing some decline in performance compared to the previous two strategies [27].

The conventional SMC strategy with DVR, which does not incorporate fractional order or ST algorithms, ranks the lowest in performance. Although it follows the standard SMC approach for sliding surface selection and stabilization, its response time is the slowest, taking 4 ms for both sag and swell mitigation. Its robustness is fair, and THD is the highest, between 4.2% to 8%, making it the least favorable method among the compared strategies [28].

Overall, the FOSMC with DVR is clearly superior in terms of fast response, voltage quality, and robustness, proving its effectiveness for power quality improvement in smart grid systems.

Table 2. Comparison of the results of FOSMC strategy with DVR, FOSMC strategy with DSTATCOM, ST-SMC Strategy with DVR and SMC strategy with DVR.

Parameters	FOSMC with DVR	FOSMC with DSTATCOM [26]	ST-SMC with DVR [27]	SMC with DVR [28]
Working principle	Using the fractional order with the conventional SMC algorithm to choose a sliding surface, and bringing the state variable back to its origin.	Using the fractional order with the conventional SMC algorithm to choose a sliding surface, and bringing the state variable back to its origin.	Utilizing the ST algorithm to select a sliding surface, return the state variable to its origin.	Utilizing the SMC algorithm to select a sliding surface, return the state variable to its origin.
Voltage sag and swell mitigation	Exceptional	Good	Decent	Appropriate
Robustness	Best	Better	Good	Fair
Mitigating time sag	1.9 ms	2.2 ms	2.5 ms	4 ms
Mitigating time swell	1.9 ms	2.3 ms	2.5 ms	4 ms
THD	0.24-2.2%	0.52-2.9%	2.8-4.6%	4.2-08%

4. CONCLUSION

This study offered a novel voltage control mode-based DVR control strategy to offset distribution network voltage sag/swell. The FOSMC is the foundation of DVR control technique. The suggested control approach offers quicker reaction times, finite time convergence, and resilience against voltage disturbances. According to the ITIC curve and SEMI-F-47 standard for sensitive loads, simulation findings demonstrate that the FOSMC for DVR can correct voltage sag/swell and power within 2 millisecond with less than 5% THD. In the case of a sensitive load, the suggested control approach can offer a faster reaction time, and better voltage compensation. A comparison of the FOSMC with DVR, FOSMC with DSTATCOM, STSMC with DVR and a classical SMC with DVR is presented. The FOSMC with DVR method shows excellent performance over the other schemes.

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