All Sciences Proceedings
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1st International Conference on Modern and Advanced Research
July 29-31, 2023: Konya, Turkey

ICMAR
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Dynamic Voltage Restorer with a Novel Robust control strategy to improve Power Quality issues in Distribution Network

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Abstract – The incorporation of renewable energy sources into the electrical system has resulted in power quality (PQ) concerns like voltage sag and voltage swell. These issues affect sensitive loads and pose challenges in power distribution networks. To address these challenges, a recently introduced device called the Dynamic Voltage Restorer (DVR) offers a unique solution. This research focuses on mitigating voltage sag and voltage swell using a DVR and a sliding mode controller based on a rotating sliding surface. The DVR, incorporating energy storage similar to a DC battery, plays a vital role in averting voltage sags and swells by injecting high voltage for a brief period. When the DVR is connected between the voltage source and the load through an injection transformer, it effectively enhances the load voltage within the power distribution system. In contrast to conventional methods that rely on the grid, this suggested approach enables the system to independently address PQ issues like voltage sag and swell. Through simulated investigations using MATLAB/Simulink R2018a, the effectiveness of the proposed technique is demonstrated. The solution exhibits a mitigation time of 2 milliseconds and maintains total harmonic distortion below 5%, meeting IEEE criteria. As a result, the proposed solution is proven to be more efficient, straightforward, dependable, and adaptable.

Keywords –Dynamic Voltage Restorer (DVR), Rotating Sliding Surface (RSS), Sliding Mode Controller (SMC), Power Quality Problems, And Voltage Sag.

I. INTRODUCTION

Power quality (PQ) plays a vital role in the functionality of an electrical distribution system. The presence of sensitive and nonlinear loads within the electrical distribution network greatly affects power quality (PQ). The characteristics of electric loads have undergone substantial changes with the introduction of power electronics devices such as adjustable speed drives (ASD), programmable logic controllers (PLC), and energy-efficient lighting. These power electronics devices are responsible for introducing nonlinear loads, which are a prevalent cause of power quality problems [1].

For clients to receive constant, uninterrupted power, the power system must be dependable. Changes in the magnitude of the voltage, the frequency, and the level of harmonic distortion are the root causes of power quality issues. Clean power is not achievable since non-linear loads exist. There are numerous delicate loads that require clean power that is reliable [2]. The distribution supply may not always be dependable, even if the power supply is consistent. People are becoming more concerned about power quality due to power electronics, variable speed drives (VSD), programmable logic controllers (PLCs), and other nonlinear loads [3].

Voltage transients, prolonged voltage shifts, brief voltage variations, voltage imbalances, waveform distortions, and voltage flicker are the primary contributors to inadequate power quality [4]. To ensure uniform power quality standards, the Institute of Electrical and Electronics Engineers (IEEE) and the International Electromechanical Commission (IEC) have established comprehensive guidelines. According to these guidelines, a sag is defined as a reduction in the root mean square (rms) voltage or current that persists from 0.5 cycles to 1 minute [3], and the power frequency during a sag range between 0.1 and 0.9 pu. On the other hand, a swell is characterized by an increase in rms voltage or current lasting from 0.5 cycles to 1 minute [4], with the power frequency ranging between 1.1 and 1.8 pu. Voltage fluctuations lasting less than a minute encompass voltage sags, swells, and interruptions, as depicted in Figure 1 [5]-[6].

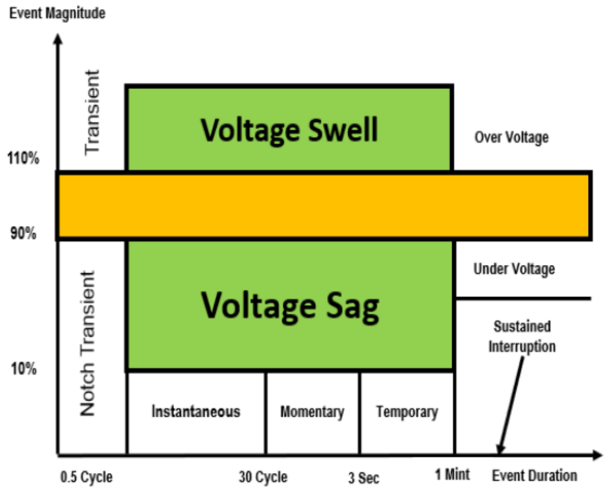


Fig 1: IEEE Std. 1159-1995 Standard for Voltage Reduction [5].

The power quality (PQ) issues mentioned above pose a greater risk to the distribution system (DS), which is considered the most vulnerable component within the power system. The distribution system experiences challenges due to its susceptibility to failures, varying load conditions, and the presence of interconnected or radial configurations. In comparison to power generation and transmission, the distribution system operates at a considerably lower voltage profile [6], [7].

Using tap changers, capacitor banks, uninterruptible power supply (UPS), and adding more parallel feeders to existing lines are a few of the traditional techniques for enhancing the voltage profile of a power system [8]. However, due to unpredictable compensated reactive power and expensive equipment costs, these solutions are unable to fully address power quality concerns. UPS is also ineffective since it consumes the full load without passing it along to the utility. The tap changer's hefty construction prevents usage [9].

Devices for flexible AC transmission systems that are frequently modified for use in electrical distribution systems include Static synchronous compensators (STATCOM), Active filters (AF), Unified power quality conditioners, DVR, Distribution static synchronous compensators, and Unified power flow controllers (UPFC). Due to its superior performance over other devices, among these alternatives, the DVR stands out as the most favourable solution for mitigating power quality (PQ) issues. This rapid, dynamic, and effective approach is employed to significantly reduce voltage magnitude [10].

Numerous control schemes have been studied and explored to attain a pure AC waveform at the output of voltage source converters (VSCs) in dynamic voltage restorer (DVR) systems. These control schemes include state feedback, self-tuning, and instantaneous reactive power theory. Each of these control methods has its own advantages and limitations [8]-[11]. Indeed, the mentioned control approaches heavily depend on accurate and linearized mathematical models of the system to achieve effective performance under certain operating conditions. However, when the system characteristics undergo changes, these control methods may not deliver optimal performance. This highlights the necessity for a dependable and efficient control system capable of operating with high precision and stability in dynamic scenarios. Such a control system would be able to adapt to varying conditions and maintain its effectiveness across different operating scenarios.

Sliding mode control (SMC) has emerged as a highly effective solution in this regard. Unlike traditional control methods, SMC does not heavily rely on detailed mathematical models of the system and exhibits reduced sensitivity to changes in system characteristics.

However, a common issue with traditional SMC is the occurrence of chattering, which can affect control performance [12]. To tackle this challenge, a range of algorithms has been employed to mitigate chattering effects, including real-twisting, super-twisting, smooth-super twisting, optimum, suboptimal, global, integral, and state-observer algorithms [4], [13]-[15]. These algorithms aim to reduce or eliminate the oscillations and rapid changes in control signals that can occur in certain control systems, helping to achieve more stable and efficient performance. These algorithms enhance the performance of SMC and mitigate the chattering phenomenon, resulting in improved control stability and accuracy.

Out of the various algorithms mentioned, the rotating sliding surface (RSS) method distinguishes itself with its notable characteristics of stability, robustness, accurate tracking, and minimal chattering effect. The proposed Sliding Mode Control (SMC) approach, utilizing the RSS algorithm, proves to be effective in mitigating voltage sags, swells, and reducing chattering in DVR systems. By leveraging the RSS method, the control system can maintain stability and accuracy while efficiently addressing power quality issues in dynamic scenarios. This approach leverages the voltage source converter (VSC) within the DVR system and utilizes the RSS algorithm. Simulation studies using the MATLAB/SIMULINK software platform demonstrate the effectiveness of the RSS-SMC and DVR combination in reducing total harmonic distortion (THD) and voltage disruptions [16].

In conclusion, this paper presents an improved control method for the Dynamic Voltage Restorer (DVR) system, utilizing the RSS algorithm. The proposed approach effectively addresses voltage sag and swell issues while minimizing chattering effects. By employing the RSS method, the control system demonstrates enhanced performance in mitigating power quality problems, making it a promising solution for dynamic voltage regulation in electrical power systems.

II. DYNAMIC VOLTAGE RESTORER STRUCTURE

The dynamic voltage restorer (DVR) is an electrical power quality device utilized for voltage control and restoration in electrical power systems. Its purpose is to compensate for voltage fluctuations that can occur due to various factors such as faults, lightning strikes, or sudden changes in load. By continuously monitoring the incoming voltage waveform, the DVR injects the appropriate amount of voltage into the system to maintain stable and regulated voltage on the load side. Typically, the DVR comprises a voltage source converter (VSC) with power electronics, an energy storage device (such as batteries or capacitors), and control algorithms.

When a voltage sag or swell is discovered, the DVR reacts quickly by injecting a voltage that is in the opposite phase as the disturbance. This successfully cancels out the deviation and keeps the voltage level at the load close to constant. The DVR's energy storage mechanism provides the energy required for adjustment, enabling quick and flawless voltage regulation.

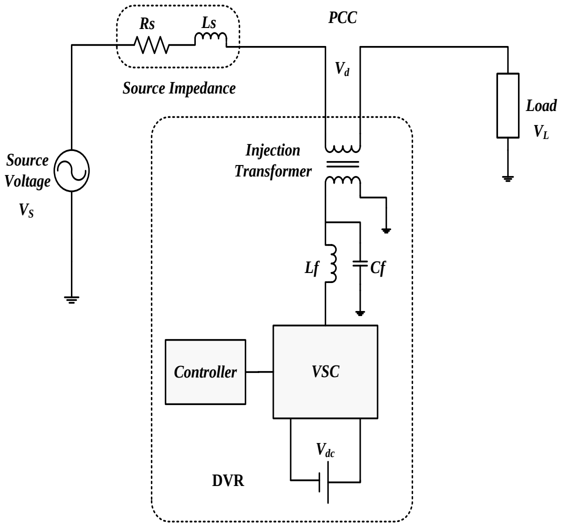


Fig 2: DVR Structure and its connection with Distribution Network

The DVR consists of a DC storage source, voltage source converter (VSC), filter, boosting transformer, and most importantly a precise and accurate control strategy for switching of VSC. DVR is shown in Fig 2. DVR performance is mainly dependent upon the control strategy for switching of VSC.

The main components of a DVR typically include:

A. Voltage Sensor

The DVR features voltage sensors built in to track the system voltage's magnitude and phase angle over time. These sensors give the DVR's control system feedback.

B. Control System

Monitoring voltage changes and producing control signals based on detected voltage levels are the responsibilities of the control system. It finds the proper compensatory voltage required to restore the system voltage by analyzing the input from the voltage sensors.

C. Energy Storage System

During voltage sag or swell events, the DVR uses an energy storage system to store and supply energy. This energy storage device typically relies on batteries or capacitors to supply the reactive power required to counteract voltage fluctuations.

D. Power Electronics Converter

The power electronics converter is a key component of the DVR that converts the stored energy from the energy storage system into a form suitable for injecting into the power system. It is usually based on insulated gate bipolar transistors (IGBTs) or other high-power semiconductor devices.

E. Voltage Source Inverter (VSI)

The power electronics converter known as the VSI is utilised in DVRs to produce the compensating voltage. With the proper magnitude, frequency, and phase angle, it transforms the DC voltage from the energy storage system into an AC voltage. By carefully switching the power electrical components, the VSI runs.

F. Injection Transformer

The DVR's output voltage is connected to the power system through the injection transformer. It enables the injection of the compensatory voltage produced by the VSI into the system and raises the point of common coupling (PCC) voltage to the appropriate level.

Key features and benefits of DVRs include:

G. Voltage Regulation

DVRs can quickly mitigate voltage sags, swells, and interruptions, ensuring a stable and regulated voltage supply to sensitive loads.

H. Fast Response Time

DVRs can respond within milliseconds to voltage disturbances, minimizing the impact on connected equipment and preventing downtime.

I. Customized Compensation

The control algorithms in DVRs can be tailored to specific load requirements, allowing for precise and efficient voltage restoration.

J. Voltage Support for Critical Loads

DVRs are commonly used in applications where uninterrupted power supply is essential, such as hospitals, data centers, manufacturing facilities, and sensitive industrial processes.

K. Power Quality Improvement

By compensating for voltage variations, DVRs enhance the overall power quality of the electrical grid, reducing the risk of equipment damage and improving system reliability.

DVRs are typically installed at critical points in the distribution network, close to sensitive loads or equipment that require high-quality power. They are considered an effective solution for voltage-related power quality issues and have gained significant prominence in modern power systems [17].

III. MATHEMATICAL MODELLING OF VOLTAGE SAG

According to IEEE 1152-1995, voltage sag (VS) is the rapid decrease in root mean square (RMS) value of the alternating current (AC) voltage over the course of a half-cycle to a minute, ranging from 0.1 to 0.9 p. u. Equation 1 uses a specified function by parts to describe VS.

$$V_i(t) = \begin{cases} V_p Sin(\omega t), \ if\ t < t_1, \\ V_{p_{sag}} V_p(\omega t + \phi), \ if\ t_1 < t < t_2, \\ V_p Sin(\omega t), \ if\ t > t_2, \end{cases} \quad (1)$$

Where, V_P = Pre fault voltage of peak

V_{pSag} = Peak faulty voltage sag

ϕ = Phase angle,

t_1 =Sag beginning time,

t_2 = Recovery of voltage to nominal value,

ω = Angular frequency.

Below Fig 4.1 shows that, VS determined by the Voltage Division Method [1]. Equation 2 is given to calculate the VS in distribution system.

$$V_{sag} = \frac{Z_L + Z_f}{Z_s + Z_L + Z_f} V_s, \qquad (2)$$

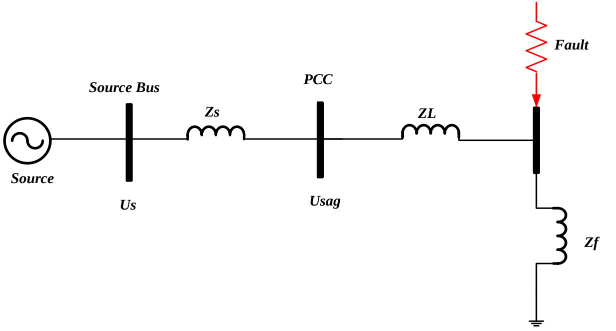


Fig 3. Voltage sag model in radial distribution network

IV. MATHEMATICAL MODELLING OF VOLTAGE SWELL

Voltage swell is an increase in rated voltage brought on by a sudden load disengagement or by a highly capacitive load between 1.1 and 1.8 p.u. during 0.5 to 1 min. How to compute the VS magnitude is shown in Fig. 4 [1].

Equivalent impendence Z_{eq} show that Z_{L2} is connected to PCC bus along with Z_{L1} as shown in equation (3)

$$Z_{eq} = Z_{L1} + Z_{L2}. \qquad (3)$$

Normal Voltage V_{Normal} at PCC when Z_{L2} relates to Z_{L1} is shown in equation (4)

$$V_{Normal} = \frac{Z_{eq}}{Z_s + Z_{eq}} V_s. \qquad (4)$$

Equation (5) shows that when ZL2 load is abruptly severed from the load bus by the circuit breaker, a voltage swell (VSwell) results from the removal of the heavy load.

$$V_{Swell} = \frac{(Z_{eq} - Z_{L2})}{Z_s + (Z_{eq} - Z_{L2})} V_s. \qquad (4.5)$$

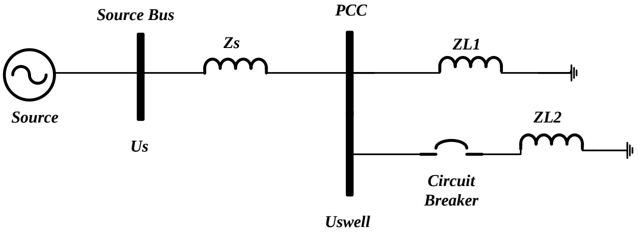


Fig 4. Voltage swell model in radial distribution network

V. MATHEMATICAL MODELLING OF DVR

To inject the desired regulated voltage, a DVR, a power electronics switching device, is connected in series with the distribution line. The generalised DVR model and its connection to the grid are shown in Fig. 5. DVR primarily comprises of a control system, a voltage source converter (VSC), and a boosting injection transformer connected in series with the grid.

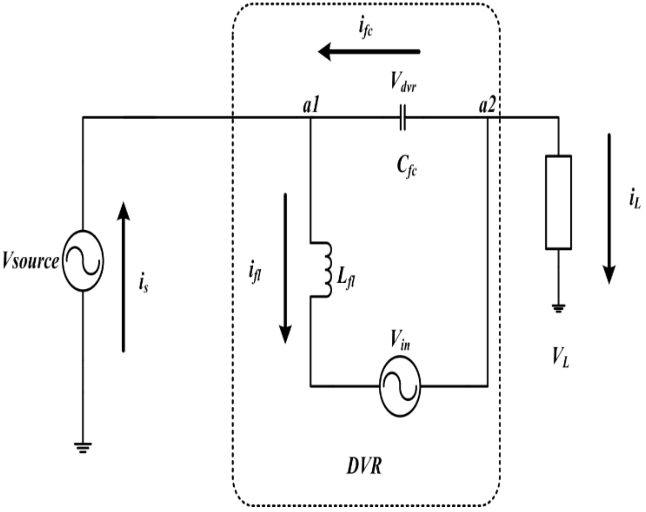


Fig 5: Equivalent schematic diagram of DVR connected in series with distribution system

The comparable schematic representation of a DVR coupled in series with a source-and-load distribution system is shown in Fig. 5. According to equation (6), the load voltage VL is equal to the source voltage Vsource and the voltage injected by the DVR Vdvr.

$$V_L = V_{source} + V_{dvr} \qquad (6)$$

The high frequency components of the AC output of VSC are filtered out using the filter parameters Cfc and Lfl as illustrated in fig. 5. It is said that the filter capacitor current is;

$$i_{fc} = C_{fc}\frac{dV_{dvr}}{dt} \qquad (7)$$

Applying KCL at node *a1* in fig 5 we get.

$$i_s - i_{fl} + i_{fc} = 0 \qquad (8)$$

Where i_s is source current and i_{fl} is filter indictor current. Put the value of i_{fc} from equation (7) into equation (8). We get;

$$i_s - i_{fl} + C_{fc}\frac{dV_{dvr}}{dt} = 0 \qquad (9)$$

By simplifying equation (9), we get;

$$\frac{dV_{dvr}}{dt} = \frac{\left(i_{fl} - i_s\right)}{C_{fc}} \qquad (10)$$

The initial state equation for the DVR in the distribution system is equation (10). Applying KVL to the closed loop in Fig. 5 allows us to determine the second state equation. We get;

$$V_{dvr} + V_L - V_{in} = 0 \qquad (11)$$

where Vin is the AC output voltage of the DVR's VSC and Vfl is the voltage across the filter inductor. Equation (12) may be used to calculate the voltage across an inductor;

$$V_{fl} = L_{fl}\frac{di_{fl}}{dt} \qquad (12)$$

Put the value of V_{fl} into equation (11);

$$V_{dvr} + L_{fl}\frac{di_{fl}}{dt} - V_{in} = 0 \qquad (13)$$

By simplifying equation (13), we get;

$$\frac{di_{fl}}{dt} = \frac{(V_{in} - V_{dvr})}{L_f} \qquad (14)$$

Thus, the state space model series connected DVR is;

$$\frac{d}{dt}\begin{bmatrix} i_{fl} \\ V_{dvr} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_{fl}} \\ \frac{1}{C_{fc}} & 0 \end{bmatrix}\begin{bmatrix} i_{lf} \\ V_{dvr} \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{L_{fl}} \\ \frac{-1}{C_{fc}} & 0 \end{bmatrix}\begin{bmatrix} i_s \\ V_{in} \end{bmatrix} \qquad (15)$$

Where i_{lf} and V_{dvr} are state variables, while i_s and V_{in} are the input variables.

VI. MATHEMATICAL MODELLING OF RSS-SMC

To mitigate voltage sag, a sliding surface specific to the dynamic voltage restorer (DVR) is employed to regulate the voltage output of the voltage source converter (VSC). In the first equation of Vdvr, the first derivative of Vdvr is computed since Vin is not considered a control input.

The implementation of sliding mode control (SMC) involves three essential steps: selecting the sliding surface, ensuring its reachability, and determining the switching control rule. The sliding surface is chosen in such a way that it keeps the system's state trajectory on the desired sliding manifold or line. The reachability condition assesses the system's ability to reach and remain on the chosen sliding surface within a specified timeframe, thereby achieving the intended DVR performance. Once the existence of the sliding mode condition is confirmed, the switching law is applied.

A. Selection Of Sliding Manifold

A state vector is formulated to develop a control strategy for the dynamic voltage restorer (DVR) that is independent of system parameters and load conditions. This control strategy aims to effectively mitigate voltage sag and swell issues in the system.

$$V = \begin{bmatrix} v \\ \dot{v} \end{bmatrix} \qquad (16)$$

Where v is the state variable, v is the state vector, and v is the state variable's first derivative. The output AC voltage of the DVR's VSC is controlled via a sliding surface.

The difference between the reference voltage and the load voltage is the sliding surface S for the suggested technique. The estimated error voltage Vdiff, as shown in (17), serves as the foundation for the sliding manifold shown by signal S in Figure 6. Equation (18) served as the design basis for this sliding surface.

$$V_{err} = V_{ref} - V_{Load} \qquad (17)$$

To effectively control the output voltage of the voltage source converter (VSC), it is crucial to determine an appropriate sliding surface that is directly influenced by the switching law. In practical terms, the sliding surface represents a state trajectory that guides the system towards a stable state. Hence, the equation of the sliding surface needs to exhibit dynamic stability. A commonly used format for selecting the sliding surface is through the following state feedback law:

$$S = V_{err} + k\frac{d}{dt}V_{err} \qquad (19)$$

where k is a gain in feedback.

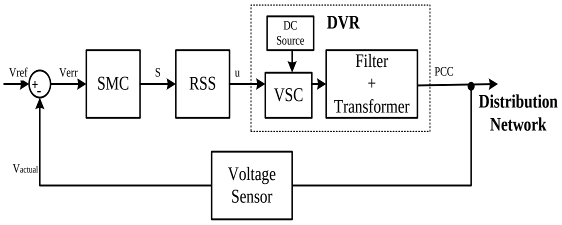


Fig. 6. Diagram of RSS-SMC model

B. Reaching Criteria

There are two criteria that should meet for reaching to zero of sliding surface are;

$$S = 0 \qquad (20)$$

$$\dot{S} = 0 \qquad (21)$$

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

$$S\dot{S} = 0 \qquad (22)$$

The Lyapunov function in equation (22) maintains the stability of the system because:

- If and, then S will drop towards zero.
- If and, then S will grow until it reaches zero.

The existence of the sliding mode indicates that there will be no gap between the system states and the sliding surface.

C. Determining Control Law

The switching law can be formulated as;

$$x(t) = \begin{cases} +1 if\ S > +c \\ -1 if\ S < -c \end{cases} \qquad (23)$$

If the value of x(t) is +1, switches Sw1 and Sw2 are turned on. On the other hand, switches Sw3 and Sw4 are activated when x(t) equals -1. In the ideal sliding mode control (SMC), the state trajectories align with the direction of the sliding surface at an infinite switching frequency. However, practical power inverters are incapable of achieving an infinite switching frequency. Consequently, the state trajectories deviate from the origin and traverse the discontinuity surface, resulting in undesirable oscillations known as Chattering. These oscillations can excite system dynamics that have not been accounted for in the model. To address this issue and mitigate Chattering, the rotating sliding surface (RSS) is employed for practical implementation. By utilizing the RSS, the undesired oscillations are effectively suppressed, providing a more stable control performance.

A DVR controller's fundamental duties include the following:

- The detection of sags and swells in voltage.
- Voltage compensation for sag and swell.
- Creation of the sinusoidal PWM converter from trigger pulses.
- High frequency components from injected voltage are filtered
- Stopping of trigger pulses following sag/swell

In SMC, there is no exact 1:1 correspondence between the system and the controller. According to the switching control law, if the state trajectories are above the switching surface, one value is assigned to control, and if they are below the switching surface, a different value is assigned to control. The state trajectories must be brought onto the manifold in the ideal situation for the state to glide across the line. When a manifold's state trajectories change continuously, it is said to be chattering. Chattering is brought on by ordinary SMC, which is a disadvantage.

Although sliding mode control has been shown to be extremely precise, effective, and shock-resistant in dynamic systems, it has a downside known as the "chattering effect" that limits its efficacy. It is possible to think of the chattering effect as high-frequency oscillations of a dynamic system that must be controlled. People have evolved a variety of tactics to counteract the impact. Using higher order sliding mode control (HOSMC) is one way to lessen chattering. Due to this HOSMC, the standard sliding mode only uses higher-order derivatives.

By doing this, chattering is eliminated, and the system is made more effective. To minimize the chattering along this discontinuity surface, HOSMC regulates the movement of a dynamic system. HOSMC is superior to regular SMC for the following primary reasons [18]:

- Avoid chattering,
- Improve accuracy,
- Maintain convergence of finite time under uncertainty

Real-time use of the typical sliding mode results in oscillations along the line when switching at infinite frequency. It's possible that adding techniques to lessen chattering close to a discontinuity surface will have its own swift dynamics. HOSMC will appear as a result of the increase in relative degree.

In this study, a control strategy for the DVR's VSC is created using a PWM-based second order SSTSMC. PQ issues in the distribution network, such as voltage sag and increase, can be addressed by doing this. Discontinuous control functionalities for the DVR are created using an SSTSMC technique. The operation of a DVR in RSS-SMC is depicted in a diagram in Fig 7.

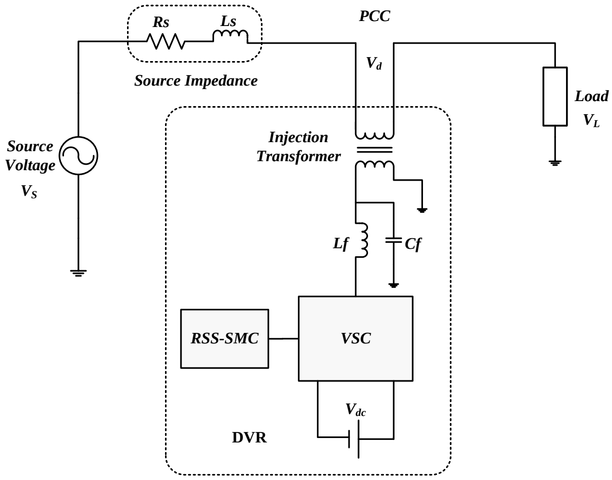


Fig 7: Single Line Diagram of DVR with RSS-SMC

Sliding mode controllers have certain advantages, such as being simple to implement and not being sensitive to the settings. SMC is a type of variable structure control that strengthens the system's stability and resistance to external changes and disruptions. In order to get the desired result, an SMC will be used in the voltage control loop of the VSC.

D. Rotating Sliding Surface

However, chattering is one issue with standard SMC, hence RSS-SMC was utilized to eliminate the chattering. Below is a diagram of the RSS-SMC modelling.

The RSS is applied via the switching rule as depicted in (24):

$$W = -S * Sgn(S) - \int Sgn(S)dS \qquad (24)$$

VII. SIMULATION RESULTS AND DISCUSSION

Figure 8 illustrates the proposed configuration of the test system, designed specifically for transient modeling and simulation of the dynamic voltage restorer (DVR) along with its associated control techniques. The simulation duration spans a total of 0.30 seconds. The distribution model comprises several components, including a three-phase 10kVA injection transformer with voltage ratings of 40-400V, a 400V, 50Hz supply system featuring a source resistance of 1.57 ohms and a source inductance of 15.70 millihenries. Additionally, the model includes a three-phase linear load with an active power (P) of 10kW and a reactive power (Q) of 1kvar, as well as a DVR with a 40V DC energy storage unit equipped with a capacitance of 55mF and an inductive filter with an inductance of 1.8mH.

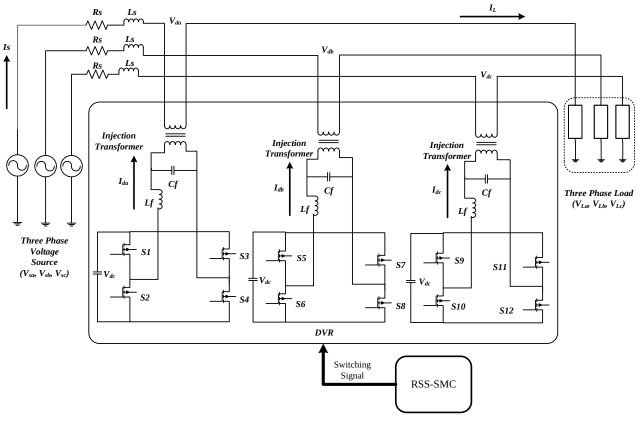


FIG 8: DVR IS CONNECTED WITH DISTRIBUTION SYSTEM

A. Compensation of Voltage Dip

Fig 9 shows the three phase waveform of source voltage under voltage sag of 30% due to switching of linear load. The voltage sag is produced from 0.1 sec to 0.2 sec. At 0.1 sec, the RSS-SMC based controller detect the voltage sag and inject the desire compensation voltage with proper magnitude and angle into distribution system as shown in fig 9 (b). This controller mitigate the VS in 2 msec which is lower than the tolerable limit of less than 20 msec according to voltage standards. The corrected load voltage is shown in fig 9 (c), of almost 1 p. u. The THD value of all phases of compensated voltage is 1.13, 4.62 and 4.05 respectively, which is lower than tolerable limit of 5% as shown Fig 10 (a-c).

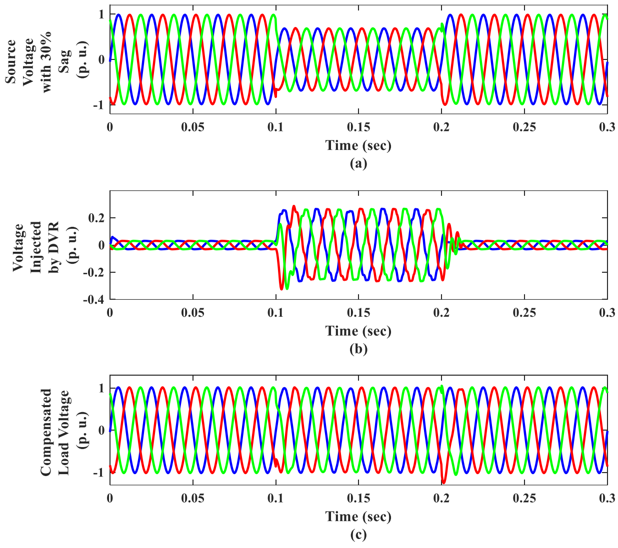
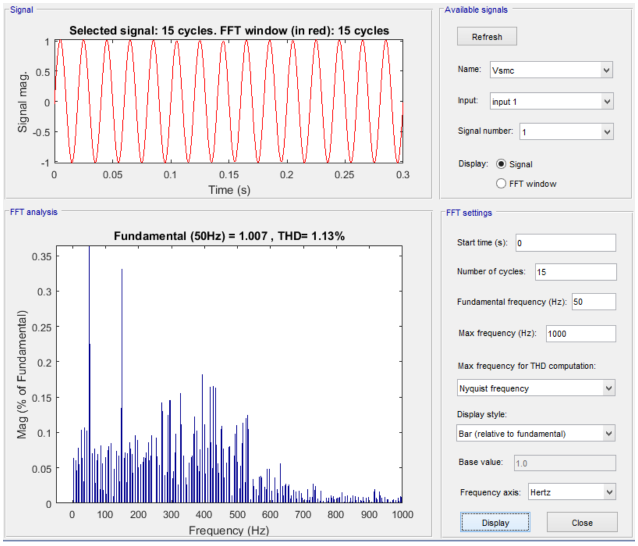


Fig 9: 30% Voltage Sag with RSS-SMC Controller (a) V_{source} with dip of 30% (b) DVR Voltage injected to mitigate 30% dip and (c) Corrected Voltage across the load with 30% dip

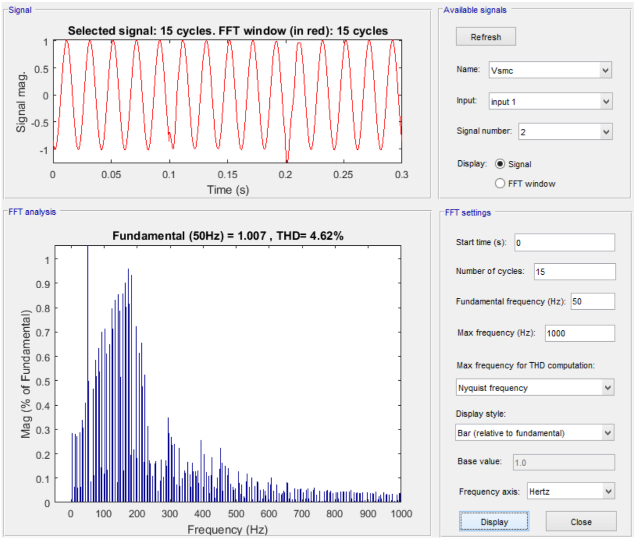


Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.007 , THD= 1.13%

Name: Vsmc
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 10 (a): Corrected Load Voltage THD analysis under Sag of 30% (Phase A)

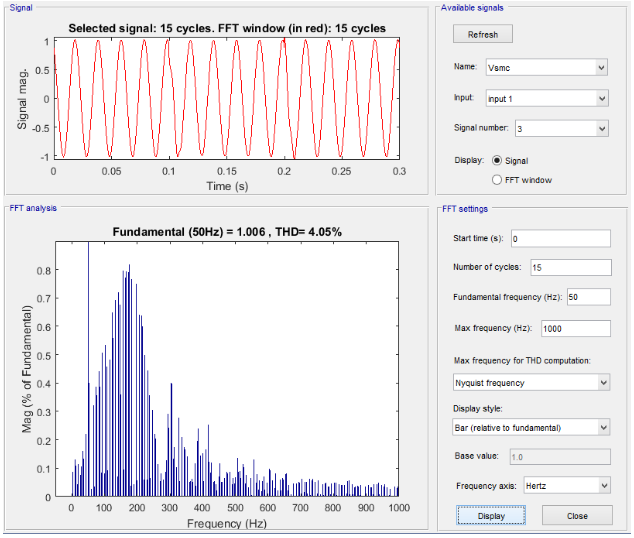


Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.007 , THD= 4.62%

Name: Vsmc
Input: input 1
Signal number: 2
Display: ● Signal ○ FFT window
Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 10 (b): Corrected Load Voltage THD analysis under Sag of 30% (Phase B)



Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.006 , THD= 4.05%

Name: Vsmc
Input: input 1
Signal number: 3
Display: ● Signal ○ FFT window
Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 10 (c): Corrected Load Voltage THD analysis under Sag of 30% (Phase C)

B. Compensation of Voltage Swell

Fig 11 shows the waveform of three phase source voltage under VS of 30% due to switching of linear load. The voltage sag is produced from 0.10 sec to 0.20 sec. At 0.10 sec, the RSS-SMC based controller detect the voltage sag and inject the desire compensation voltage with proper magnitude and angle into distribution network as dipected in fig 11 (b). The controller mitigate VS in 2 msec which is lower than the tolerable limit of less than 20 msec according to voltage standards like (SEMI F-47) for sensitive loads. The corrected load voltage is shown in fig 11 (c), with peak of almost 1 p. u. The THD value of all phases of compensated voltage is 1.83, 4.91 and 4.51

respectively, which is lower than tolerable limit of 5% as shown Fig 12 (a-c).

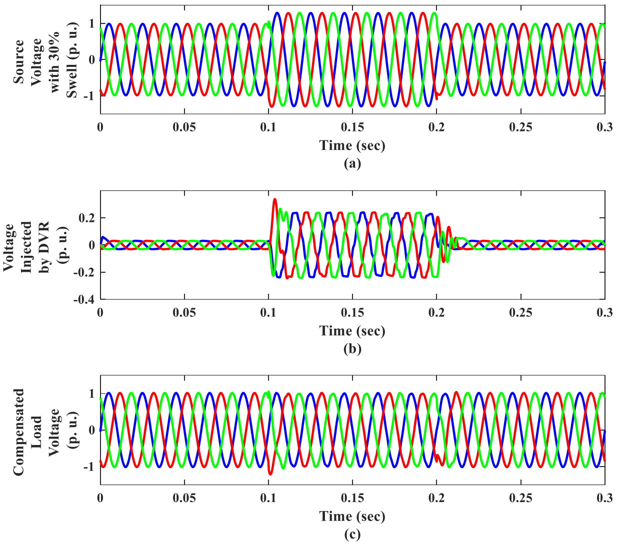
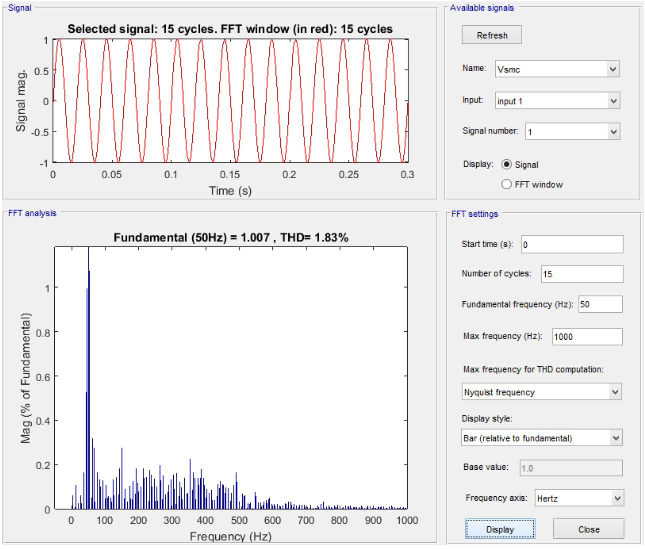


Fig 11: 30% Voltage Swell with RSS-SMC Controller (a) V_{source} with Swell of 30% (b) DVR Voltage injected to mitigate 30% Swell and (c) Corrected Voltage across the load with 30% Swell



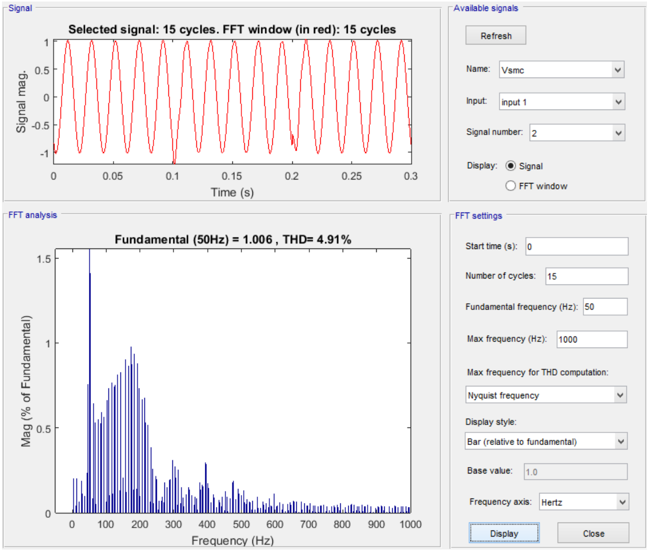
Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.007 , THD= 1.83%

Name: Vsmc
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 12 (a): Compensated Load Voltage THD under 30% Swell (Phase A)



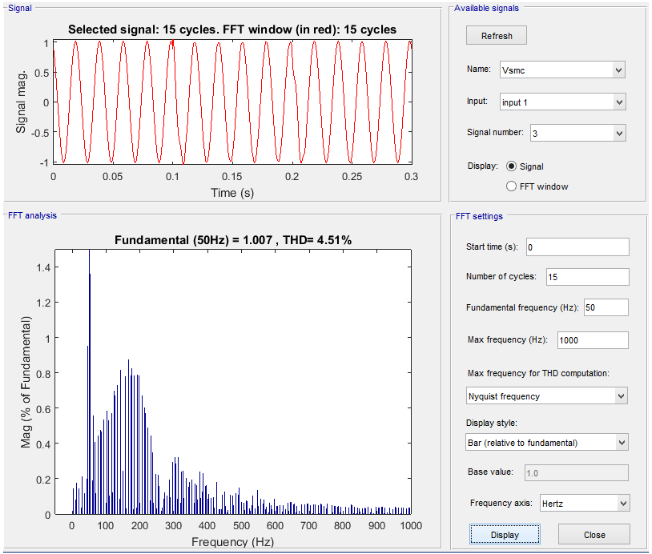
Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.006 , THD= 4.91%

Name: Vsmc
Input: input 1
Signal number: 2
Display: ● Signal ○ FFT window

Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 12 (b): THD of Compensated Load Voltage under 30% Swell (Phase B)



Selected signal: 15 cycles. FFT window (in red): 15 cycles

Fundamental (50Hz) = 1.007 , THD= 4.51%

Name: Vsmc
Input: input 1
Signal number: 3
Display: ● Signal ○ FFT window

Start time (s): 0
Number of cycles: 15
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 12 (c): THD of Compensated Load Voltage under 30% Swell (Phase C)

VIII. CONCLUSION

This study introduces a three-phase dynamic voltage restorer (DVR) incorporating a rotating sliding surface (RSS)-based sliding mode control (SMC). The proposed control strategy effectively eliminates chattering and maintains a consistent switching frequency. When employed in DVR operations, the RSS generates a continuous control input that can be compared to a triangular carrier signal to generate pulse width modulation signals. The performance of the recommended control mechanism is evaluated using the MATLAB/Simulink SimPower System. Simulation results based on the Information Technology Industry Council curve and the SEMI-

F-47 standard demonstrate the efficacy of the developed RSS-SMC control for DVR. The control mechanism efficiently regulates voltage sags and swells, achieving the desired power adjustment in under 2 milliseconds, while maintaining total harmonic distortion (THD) below 5%. The proposed control approach enables faster response times, reduces disruptions, and improves voltage sag and swell correction.

ACKNOWLEDGMENT

I appreciate the guidance and assistance that my MS supervisor, Dr. AJMAL FAROOQ, continues to provide. Without their amazing support and encouragement, I would never have been able to finish my research.

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