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Distribution Network Voltage Improvement using Dynamic Voltage Restorer with Smooth Super Twisting Sliding Mode Control

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Abstract – Sensitive industrial customers need higher Power Quality (PQ). End-users and electrical utility firms are both paying more attention to PQ problems as a result of massive financial losses caused by PQ problems to sensitive industrial loads. The most important and frequently recurring PQ problems in a secondary distribution system are voltage sags and swells. A rapid, adaptable, dynamic Custom Power Device called the Dynamic Voltage Restorer can be utilized to reduce voltage sags and swells. The control approach selected for switching Voltage Source Converters (VSCs) largely determines its performance. By using the Sliding Mode Control (SMC) with Smooth Super Twisting Algorithm (SSTA), this research successfully removes the effects of voltage sags and swells on the VSC of DVR. When SSTA is used in conjunction with conventional SMC, chattering, a downside of SMC, is reduced while keeping other advantages including robustness, shorter response times, and insensitivity to changings in the load. The efficiency of this technique is evaluated using the MATLAB/Simulink SimPower System toolbox. The simulation's findings demonstrate that the Smooth Super Twisting Sliding Mode Controller (SSTSMC) for DVR device can identify and compensate the voltage sags/swells in less than 2 milliseconds (ms), which is significantly less time than the 20 milliseconds allowed limit of SEMI F-47 standard for sensitive loads and the values of Total Harmonics Distortion (THD) is less than 5%. The comparative study also performed between Real Twisting Algorithm (RTA) and proposed technique Smooth Super Twisting Algorithm (SSTA), which shows that performance of proposed SSTSMC is much better than RTA.

Keywords – Dynamic Voltage Restorer, Sliding Mode Control, Voltage Sag, Voltage Swell, Smooth Super Twisting Algorithm

I. Introduction

A major issue with today's power systems is Power Quality (PQ), which has the potential to affect utilities and sensitive loads [1]-[2]. Many industrial equipment are often made up of electronic components that are extremely sensitive to changes like voltage sags/swells and harmonics [3]. These PQ issues have a greater effect on the Distribution System (DS), which is power system weakest link [4]-[5]. Some of the most often used Custom Power Devices (CPDs) to resolve these problems such as Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC), and the Active Filter (AF) [6]. Due to improved performance of DVR, it is thought to be the most effective way to reduce PQ problems. It uses a quick, flexible, and effective method to efficiently reduce voltage magnitudes [7]. In terms of producing a pure AC waveform at the output of voltage source converters of DVR, state feedback, self-tuning, instantaneous reactive power theory, and many more control schemes have benefits and drawbacks [8]-[11]. They are made to create a mathematical model of the system that is precise, linearized, and effective under operating conditions. Yet, as the system's characteristics change, these control methods are unable to deliver the best performance. A reliable and efficient control system that can operate with high precision and stability in dynamic situations is therefore required. The DVR with SMC can function extremely effectively. It does not require a thorough mathematical model of the system and it is not sensitive to changes in system characteristics. However, the traditional SMC has the drawback of chattering [12]. Some algorithms, including real-twisting, super-twisting, smooth-super twisting, optimum, suboptimal, global, integral, and state-observer algorithms, have been utilized in literature to prevent the chattering effect [4], [13]–[15].

II. MATERIALS AND METHOD

The smooth-super twisting method has an advantage over the others because of its stability, robustness, excellent tracking accuracy, and minor chattering effect. The proposed SMC control approach can mitigate the effects of voltage sags and swells in successfully and can reduce the chattering. It is DVR's VSC's based SST algorithm. [16] states that by employing the MATLAB/ SIMULINK software platform, SSTSMC and DVRs may successfully reduce the THD value and disruptions in the voltage.

III. MATHEMATICAL MODELLING

DVR is a power electronic series connected device with the line that is used to alleviate a line's voltage problem. DVR is made up of an energy storage unit, a control unit, voltage source converters, and an injection transformer that injects voltage into the line. Fig 1 presents the DVR model connected to the grid.

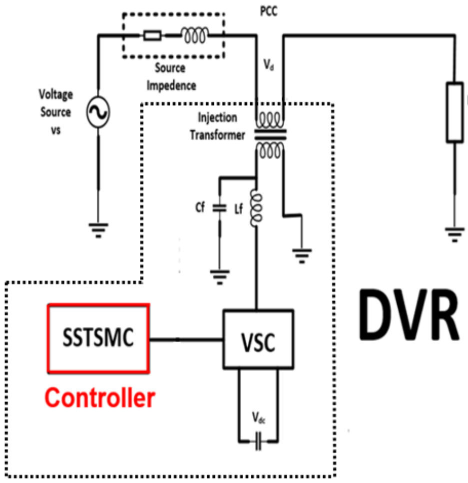


Fig 1: DVR and distribution system are connected in series in the one-line diagram..

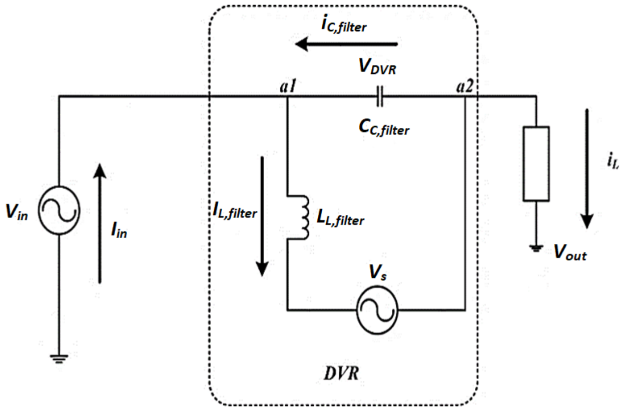


Fig 2: Equivalent schematic diagram of DVR connected in series with distribution system.

The equivalent schematic diagram of DVR connected in series with distribution system having source and load is shown in Fig 2. The load voltage V_{out} is equal to source voltage V_{in} and voltage injected by DVR V_{DVR} as shown in (1).

$$V_{out} = V_{in} + V_{DVR} \quad (1)$$

Filter parameter i.e., C_{filter} and L_{filter} are used to filter out the high frequency components from AC output of VSC. The filter capacitor current $I_{C,filter}$ is described in (2):

$$I_{C,filter} = C_{filter} \frac{dV_{DVR}}{dt} \quad (2)$$

Applying KCL at node *a1*, we get the equation as given in (3):

$$I_{in} - I_{L,filter} + I_{C,filter} = 0 \quad (3)$$

where I_{in} is source current and $I_{L,filter}$ is filter inductor current. Put the value of $I_{C,filtert}$ from (2) into (3). We get:

$$I_{in} - I_{L,filter} + C_{C,filter}\frac{dV_{DVR}}{dt} = 0 \quad (4)$$

By simplifying (3), the following equation can be obtained:

$$\frac{dV_{DVR}}{dt} = \frac{\left(I_{L,filter} - I_{in}\right)}{C_{filter}} \quad (5)$$

Equation (5) is the first state equation of DVR in distribution system. To find the second state equation, we apply KVL at the closed loop in Fig 2:

$$V_{DVR} + V_{L,filter} - V_s = 0 \quad (6)$$

where $V_{L,filter}$ is voltage across filter inductor and V_s is AC output voltage of VSC of DVR. The voltage across inductor can be determined by (7):

$$V_{L,filter} = L_{filter}\frac{dI_{L,filter}}{dt} \quad (7)$$

Put the value of $V_{L,filter}$ from (7) into (6):

$$V_{DVR} + L_{L,filter}\frac{dI_{L,filter}}{dt} - V_S = 0 \quad (8)$$

By simplifying (8), we get:

$$\frac{dI_{L,filter}}{dt} = \frac{(V_s - V_{DVR})}{L_{filter}} \quad (9)$$

Thus, the series linked DVR's state space model is presentede in (10):

where

$$\frac{d}{dt}\begin{bmatrix} I_{L,filter} \\ V_{DVR} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_{filter}} \\ \frac{1}{C_{filter}} & 0 \end{bmatrix}\begin{bmatrix} I_{L,filter} \\ V_{DVR} \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{L_{filter}} \\ \frac{-1}{C_{filter}} & 0 \end{bmatrix}\begin{bmatrix} I_{in} \\ V_s \end{bmatrix} \quad (10)$$

$I_{L,filter}$, V_{DVR}: state variables

I_{in} and V_s: input variables

IV. MATHEMATICAL MODELLING OF SSTSMC FOR DVR

A DVR sliding surface that can adjust the output of VSC is used in order to reduce voltage sag. Firstly, we determine the derivative of V_{DVR} since the control input *Vs* is absent from the first equation of V_{DVR}.

SMC installation requires the completion of three phases. The first step is choosing the sliding surface, the second is defining its reachability, and the third is choosing the switching control rule. The sliding surface is chosen in a way that maintains the state trajectory on the intended sliding manifold or line. Reachability condition refers to the system's ability to forcibly reach and remain on a chosen sliding surface in a certain amount of time in order to achieve the intended DVR performance. The switching law is provided after confirming the existence of sliding mode conditions.

A. Choosing a Sliding Surface

The following state vector is built to develop a DVR control approach that is independent of parameters of system and load in order to reduce voltage sag/swell.

$$V = \begin{bmatrix} v \\ \dot{v} \end{bmatrix} \quad (11)$$

where state vector is V, state variable is v and first derivative of state variable is is $\dot{v}$. control the output AC voltage of voltage source converter of DVR, asliding surface is selected.

The sliding surface S is shown in Fig. 3. Error in the voltage V_{ERROR} is shown in (12). Sliding surface is designed based on (13). Difference of V_{out} and V_{REF} and the sliding surface is composed of their derivatives.

The sliding surface is composed of V_{out}, V_{REF}, and their derivatives.

$$V_{ERROR} = V_{REF} - V_{out} \quad (12)$$

It is necessary to identify a suitable sliding surface that is directly impacted by the switching law in order to manage the output of VSC. In reality, a sliding surface is one on which the state trajectories are situated in order to reach a stable condition. The sliding surface equation ought to be dynamically stable as a result. The following state feedback law is common for selecting this surface:

$$S = V_{ERROR} + k\frac{d}{dt}V_{ERROR} \quad (13)$$

where k represents the feedback gain. Then, S is subjected to a comparator with $\pm c$ serving as the reference quantity. To apply switching law on a single signal, a multiplexer is used to transmit the resulting value through. The sliding surface is subject to the super-twisting control law. The switching control rule provides the changed input of "*W*" as illustrated below in by applying SSTSMC to a sliding surface (18).

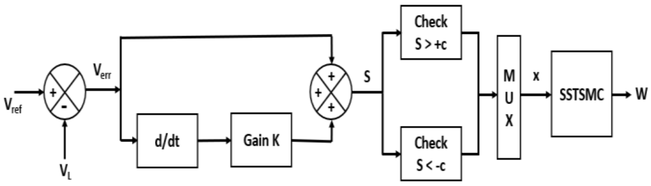


Fig. 3. Block diagram of SMC

A. Reachability Conditions

The below two requirements must be met in order to guarantee operation and bring the state variables to a sliding surface.

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

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

The suggested control scheme should transform all state trajectories to a sliding surface of *S=0* over a finite duration. As a result, the switching law should guarantee the system's stability in the SMC. The existence criterion for the sliding mode is as follows:

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

Equation (16) is the Lyapunov function that ensures the system stability condition.

B. Determination of Control Law

The switching law can be formulated as;

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

Where c is a constant, x(t) is a switching control variable, and u is value is chosen based on c. Sw1 and Sw2 switches are on if *x(t) = +1*. Sw3 and SW4 switches are on if *x(t) = -1*. The smooth super twisting algorithm is employed to implement practically and to remove chattering. The switching rule applies the Smooth Super Twisting Algorithm (SSTA) to the sliding manifold to deliver the updated input of control "W" as indicated in (18):

$$W = n_1 + n_2 = -[(k_1 sat(S)\sqrt{|S|}) + (k_2 \int (sat(S) ds))] \tag{18}$$

Two tuning constants (k_1 and k_2) in the SSTA control law are utilized to filter out undesirable switching components. If the *S* is greater than 0, the sliding manifold's saturation function *sat(S)* outputs +1; if it is less than 0, it outputs -1. Equation illustrates that the modified control input *m* comprises of two control inputs (n_1 and n_2) mentioned in (18). The continuous function of sliding surface *S* is n_1 and its discrete time differential function is n_2, are used as the control inputs. The multiplier output that makes up the first component of the control signal *W* is modified by constant parameter k_1. The inputs of the multiplexer are the modulus of the sliding manifold and *sat(S).* High frequency components are removed using an integrated block in the second section of the control input n_2. The constant parameter k_2 further fine-tunes the filtered output of n_2. The sliding manifold's modulus and *sat(S)* terms decrease the frequency of the switching components, extending the switches life. In the second section, the integral term represents a low pass filter. Faster response times, a reduction in chattering, and robustness are all effects of SSTA on SMC. Block schematic of the smooth super twisting-based SMC switching law is shown in Fig 3 above.

V. CASE STUDY

A test system is created to evaluate the effectiveness of the SSTSMC for DVR in Matlab/Simulink. Table 1 contains information about the parameters. Fig 4 depicts the prescribed distribution system that was used to simulate and model the DVR using the SSTSMC.

The test system of distribution system experiences voltage sags and swells caused by the three-phase programming source, which are then compensated by the DVR. The performance of the suggested control technique is assessed by the analysis that follows.

- Reduction in the total harmonic distortion
- Reduction of voltage sag/swell.

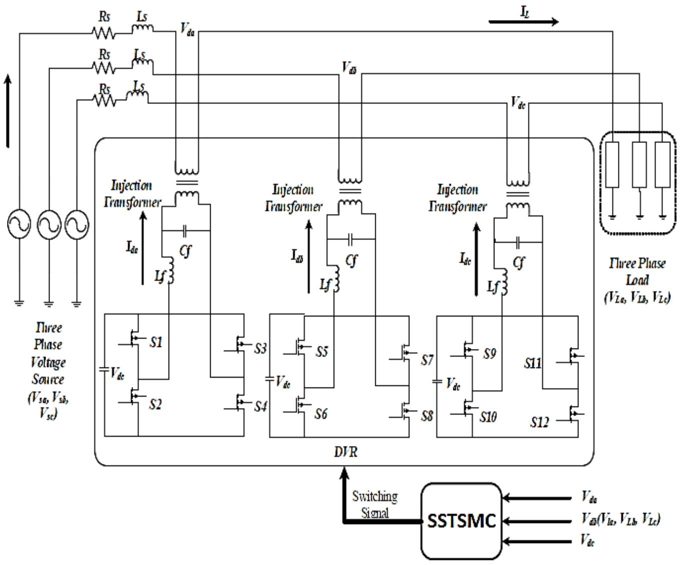


Fig 4: DVR is connected with 3-phase system.

When there is no fault in the system voltage, the SSTSMC does not sends a signal to operate the DVR (normal state). The controller starts to work when the system voltage varies outside of the acceptable range. The way SSTSMC runs is as follows:

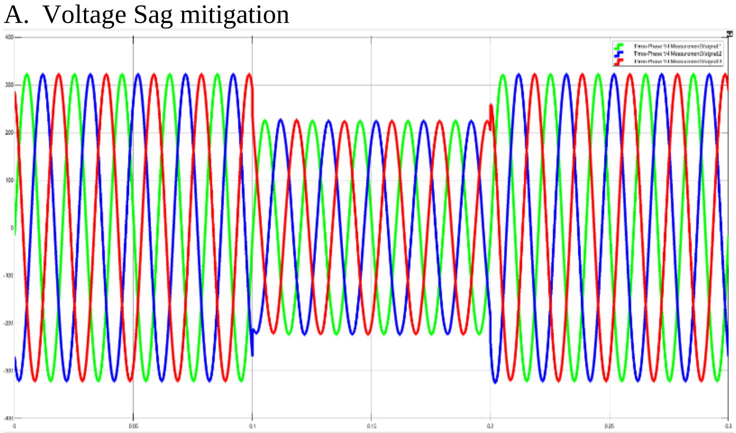
i) Look for voltage sags or surges.
ii) Calculate the voltage dips and peaks (percentage).
iii) Determine the switching control signal.
iv) Create the pulse width modulation switching signal for voltage source converters.
v) Create the necessary switching signal continuously to make sure voltage issues are corrected.
vi) Stop the switching of converters once the fault has been corrected.

Table 1: Distribution test system parameters.

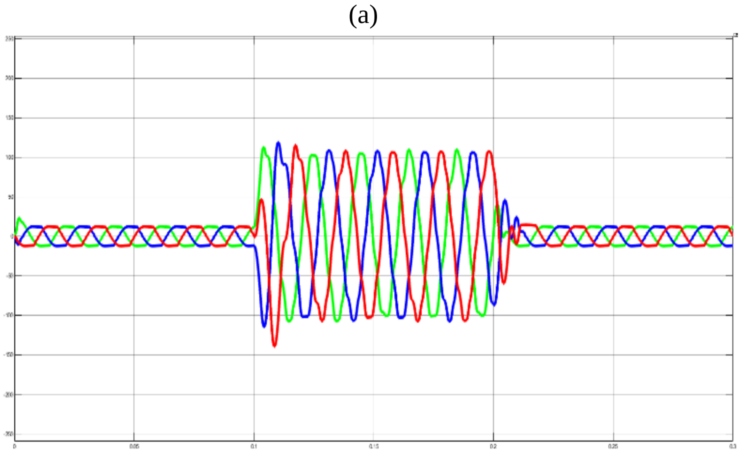
Description of Parameters	**Values**
Phase to phase Voltage of Grid	400V
System Frequency (f_0)	50Hz
Line Impedance (Ls, Rs)	0.8929Ω, 16.58mH
Rating of Three Phase Load	Active Power=10kW, Reactive Power=1kvar
Switching Constant (±c)	0.1
DC Battery Storage	40V
Constants of Switching	1.8mH, 9μF
Coupling Transformer Power Rating	100kVA
Control Algorithm	SSTSMC
Sliding Mode Control Gain (γ)	0.142μ
Frequency of Switching (Fs)	10kHz
Simulation Solver	Ode23tb (Stiff/TR-BDF2)
Time of Sampling	5μsec
Cutt-off Frequency of Filter	405Hz
Tuning Gains of SSTSMC (n1, n2)	0.5, 0.5

VI. RESULTS AND DISCUSSION

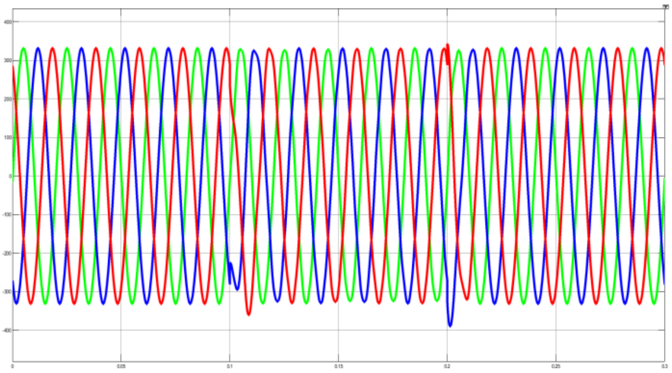
A. Voltage Sag mitigation



(a)



(b)



(c)

Fig 5: Voltage before and after sag adjustment: (a) 30% sag of input voltage. (b) Compensated voltage provided by DVR (c) Voltage sag mitigated by DVR

In Fig 5, a 30% drop in three-phase voltage happens as a result of the supply-side sensitive load being abruptly switched ON. This sag, which begins at 0.1 seconds and finishes at 0.2 seconds. The disturbance is corrected using the controller. If there is no sag in the input voltage signal, no voltage is generated by DVR. The controller will identify a fault (voltage sag) and then DVR will inject the voltage of same magnitude as error in the input voltage.

Compared to the 20ms IEEE standard permitted limit, the defect (voltage sag) is mitigated in a very quick period (2ms). The input voltage in Fig 5(a) has a 30% sag. Fig 5(b) demonstrates how DVR uses a low pass filter to only inject the voltage in order to remove the extra high frequency component. Fig 5 (c) displays the sag-free corrected system voltage.

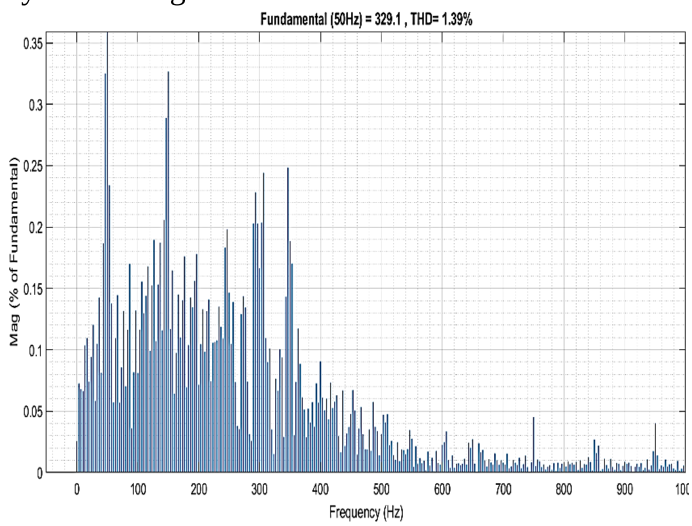
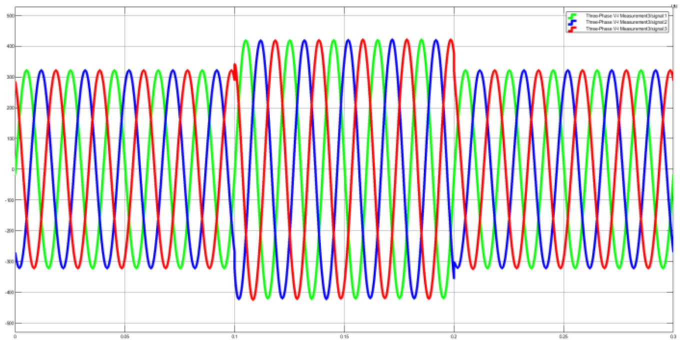


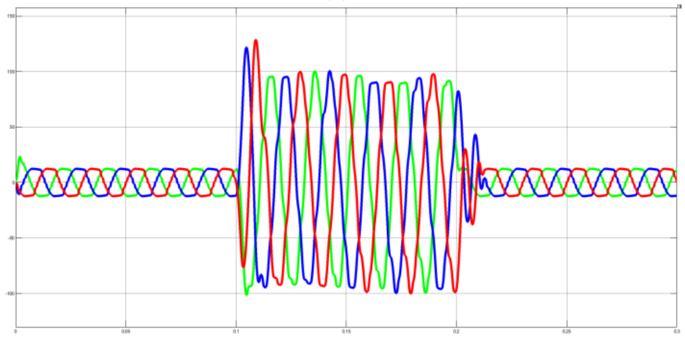
Fig 6: THD value of 30% voltage sag mitigated at three phases.

Fig 6 displays the THD value of the compensated voltage for three phases. THD value for three phases at the load side is 1.39% which is less than 5% as per IEEE 1159-1995.

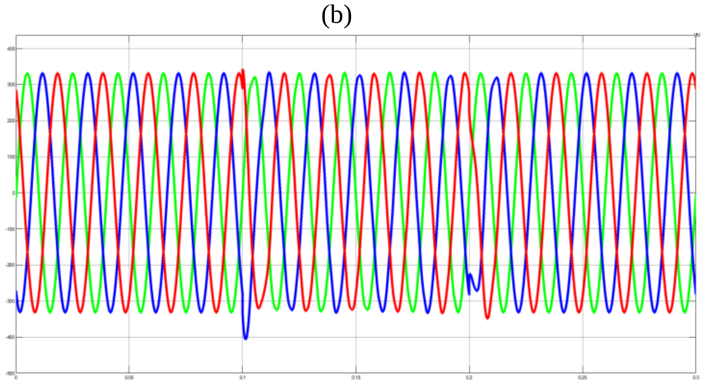
B. Voltage Swell mitigation



(a)



(b)



(c)

Fig 7: Voltage before and after swell adjustment: (a) Input voltage with 30% swell. (b) Compensated voltage provided by DVR. (c) Voltage swell mitigated by DVR.

Fig7(a) illustrates the 30% swell in the three-phase source voltage caused by the sensitive load being switched off, which occurs between 0.1 and 0.2 seconds. The simulation's output demonstrates that the sliding mode's good and quick feedback maintains the sensitive load's load voltage in accordance with ITIC standards. The supply side distortion is brought on by the voltage swell. As seen in Fig 7(b), in 2.5ms, voltage is adjusted, a very brief period of time. Fig 7(c) depicts the system voltage after adjustment, with a magnitude of 1pu.

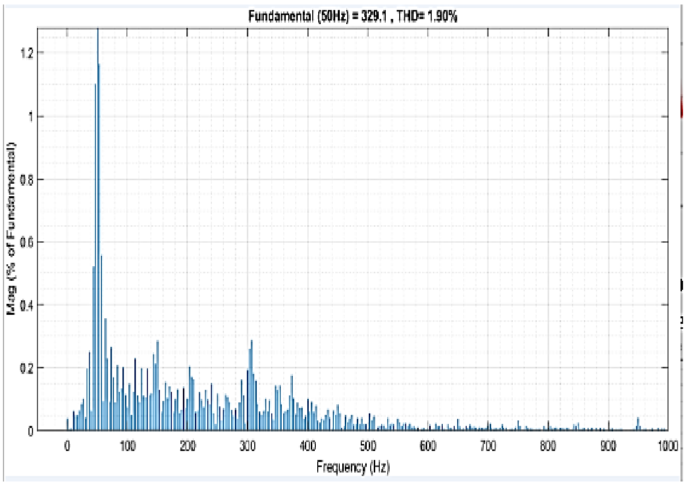


Fig 8: THD value of 30% voltage swell mitigated at three phases.

In the above Fig 8, the compensated voltage THD value is displayed. The percentage of THD at compensated 30% voltage sag is 1.90%. This value is lower than standard value of IEEE i.e., less than 5%.

Table 2: THD values at different voltage sag and swell levels:

Sr. No	Disturbances	T.H.D Value
1	40% sag	2.07%
2	40% swell	3.05%
3	50% sag	2.79%
4	50% swell	3.72%

In above Table 2, THD values are taken from FFT analysis of Matlab/Simulink, when voltage sag is 40%, then THD value of voltage is 2.07% and when voltage sag is 50%, the THD value is 2.79%. Similarly, when voltage swell is 40%, the THD value is 3.05% and when voltage swell is 50%, the THD value is 3.72%. All above THD values are less than 5% as per IEEE 1159-1995.

VII. CONCLUSION

This research presents a three phase DVR SMC approach based on SSTA. The recommended control system achieves consistent switching frequency while eliminating chattering. When SSTA is used to operate a DVR, a continuous control input is produced. To create pulse width modulation signals, this continuous control input can be compared with the triangular carrier signal. The proposed control strategy's effectiveness is evaluated using the MATLAB/Simulink SimPower System. Using the Information Technology Industry Council (ITIC) curve and the SEMI-F-47 standard, the simulation's findings indicates that the developed SSTSMC for DVR efficiently compensates voltage sags/swells and provides the necessary power within 2ms with THD less than 5%. The suggested control strategy enables faster reaction, reduced disruptions, and better voltage sag/swell adjustment. Output results are compared with the Real Twisting Sliding Mode Control (RTSMC), it is clear that performance of SSTSMC is much better than the RTSMC.

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