Terminal Sliding Mode Control for Dynamic Voltage Restorer

Jeevan J. Inamdar* and K. Iyswarya Annapoorani

Centre for Automation and School of Electrical Engineering, Vellore Institute of Technology, Chennai, India
E-mail: jeevan.jagannath2016@vitstudent.ac.in
**Corresponding Author*

Received 20 July 2021; Accepted 04 December 2021;
Publication 18 February 2022

Abstract

Day by day the increment in non-linear load has deteriorated the Voltage Quality of power supply system. The crucial concerns originated are Voltage Sag and Voltage Harmonics. These power quality problems cause a lot of losses in the power system which results in commercial losses as well. The moderation of these issues within the permissible limits is much needed. Among, the several methods and devices that exist, the Dynamic Voltage Restorers (DVR) are often used. This paper focuses on mitigation of Voltage Sag and Voltage Harmonics. In the development phase of DVR, the design of controller is an important phase to be considered. The nonlinear control approach of design is superior to linear control. In this paper the Terminal Sliding Mode Control is used for designing the controller for DVR. To improve accuracy and robustness, an additional nonlinear quantity has been introduced to the equation of traditional Sliding Mode control. The Dynamic Voltage Restorer is modelled using MATLAB/Simulink and used

Distributed Generation & Alternative Energy Journal, Vol. 37_3, 771–792.
doi: 10.13052/dgaej2156-3306.37318

for studies. The simulation results presented validates effectiveness of the proposed control approach.

Keywords: Voltage quality, voltage harmonics, dynamic voltage restorer, sliding mode control.

1 Introduction

The power supply with high quality is produced at power stations and distributed to the consumers. This power supply gets deteriorated due to frequent usage of power electronic-based non-linear devices and various faults occurring at the supply system. Thus study of power quality has got admiration from customers and suppliers. The consumer demands for a supply with acceptable power quality, as defined by IEEE 519 [1], in order to preserve production continuity. To meet these requirements, disturbances in the supply system must be removed. There are various Power Quality (PQ) issues reported in [2]. Among these, Voltage Sag is considered as most severe because it causes other issues. These issues affect the performance of sensitive loads since they are very susceptible to changes in the Voltage. There is a wide range of equipment which got problems due to these problems [2]. The extent of the remaining Voltage affects the system more than the duration of the Sags. There are worst effects of Voltage Sags on the industry which results in increased expenditure. Short circuits, motor starting, and transformer energising are some of the causes of voltage sags. The Voltage correction system may be the only economic alternative available for some end customers of delicate equipment. There are various ways in which Voltage dips can be reduced. A Voltage Source Inverter is usually connected in series with the power supply and a sensitive load. This kind of device is frequently called a Dynamic Voltage Restorer which is able to bring back any deviations in the load Voltage to normal operating range. The key advantage of DVR is that consumers are able to manufacture continuously with a high quality constant Voltage. The DVR is a quick, flexible and effective solution to mitigate Voltage Sag issues. The load Voltage restoration time is in a few milliseconds and therefore can mitigate any power disturbance. The authors in [4] have suggested theory of variable structure to carry out design analysis of Harmonic Series Compensators. The control technique implemented is based on measurement of the harmonic source current by using the Instantaneous Reactive Power Theory. It has been observed that for compensating the Current Harmonics caused by rapidly changing loads results in increment in converter ratings. The Sliding Mode Control with Current Control Mode of DVR including PI based feed- forward control is summarised in [5]. The drawback observed is that the controller fails to judge the inductance effect caused by harmonic current which results in poorer quality of compensation and Voltage regulation. Authors in [6], has discussed a DVR using Sliding Mode Control for minimum energy injection in order to maintain the angle between load and source voltage to a minimum value. The system analyses only linear kind of loads. A three phase UPQC with constant frequency Sliding Mode Controlled DVR is analysed by [7]. The satisfactory Voltage regulation is achieved at the load end. The waveform of compensated load Voltage shows presence of transients. Researchers from [8, 9], have designed and developed a single phase DVR with sliding mode control. The control technique adopted is based on load Voltage detection. Though it is said that DVR is multifunctional but results shown does not include all Voltage related Power Quality issues. Authors in [10] illustrated a Phase-Locked Loop approach with Synchronous Reference Frame and Sliding Mode Control to design the controller for DVR. The results reveal that fast and robust detection of the Phase and the Frequency of System Voltage is possible. The results obtained by authors are not clear enough to show effectiveness of proposed controller. The Sliding Mode Control combined with Proportional- Integral for generation of reference signal for DVR is proposed by [11]. The results obtained are only for Voltage Sag mitigation and do not give idea about other power quality issues. A twelve-switch three-phase Voltage Source Converter [12] with Sliding Mode Control technique, Double-Band Hysteresis Control [13], and an Adaptive Notch Filter [14] minimize the Voltage variations at the load terminals. The Authors of [15], analyzed the performance of DVR by optimizing the PI gains by the GAVS-LMS algorithm to address voltage sag, swell, unbalance and distortions. In [16], an experimental study is carried out utilizing a dual slope delta modulation technique to reduce Voltage Sag problems in power systems by controlling a DVR. A single-phase DVR with Brockett oscillator based frequency locked loop with Super Twisting Sliding Mode Control is developed by authors in [17]. A Sliding Mode Observer with optimization based PI tuning has been developed for a DVR that compensates for voltage related power quality problems (18). Authors in [19] claimed optimal parameter setting of PI controller for DVR using Harris Hawks Optimization (HHO) and results are verified in Matlab Simulink environment.

The stated control strategies so far have numerous benefits and shortcomings related to Steady-State Error, Dynamic Response, Robustness, Control

Circuit Complexity and Switching Frequency. But the controller presented in literature studied so far does not put focus on dynamic nonlinear load conditions. Because of its Fast Dynamic Response and ability to be very resilient to parameter alterations, the Sliding Mode Control technique has gained favour. In this paper Terminal Sliding Mode Control method is used to develop the control algorithm for DVR. Further, the results obtained are compared with the results claimed by authors in [23], to prove the effectiveness of proposed methodology.

2 Dynamic Voltage Restorer Model

The Dynamic Voltage Restorer (DVR) can act as power conditioner if an appropriate control strategy is adopted. The main parts of DVR are energy storage device, frequency converter, controller, and passive LC filter. It is connected in series configuration to the power supply through a coupling transformer [18]. In Figure 1, the DVR is connected in series with both source and load through a coupling transformer. A LC filter is installed at the inverter output to eliminate high frequency components occurring as a result of switching of the power electronics.

In DVR a controller provides control signals to Voltage Source Inverters (VSIs). The controller detects the source current and generates the voltage proportional to that current. There are three main strategies to generate a reference voltage. First, the controller detects the current source and generates a voltage proportional to the current source. The controller detects the voltage of the load, and to generate the voltage, the DVR produces voltage with the same harmonic content, but opposite phase compared to the voltage of the

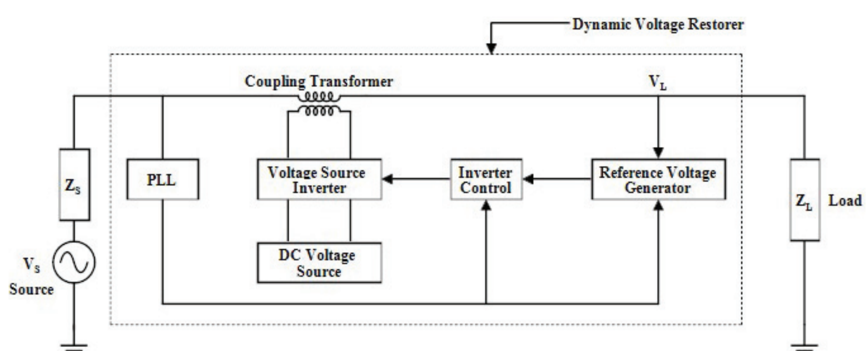

Figure 1 Block diagram of dynamic voltage restorer [18].

load. Thirdly, the method detects both source and load currents and DVR generates a voltage using a combination of the first two.

2.1 Average Model of Dynamic Voltage Restorer

The mathematical model of controller for DVR is derived by using average model described in [20]. This device compensates the load Voltage Harmonics by generating compensating Voltages *Vcomp* for each phase. For carrying out average modelling the electrical equations are obtained for system under consideration. The model is designed by using various state variables available at the controller side. To make control design more suited, a vector transform matrix is employed to reduce system order. This is carried out by transforming all state variables into synchronously rotating frame (d, q, 0). The entire average model is thus obtained by averaging the inverter legs with consideration that the transformation ratio is 1:1.

The lossless inductors are taken so that resistance effect will be neglected. In the Figure 2, *Lf* is filter inductance, *Cf* is filter capacitance, $V_{comp}d$ and $V_{comp}q$ are d-q components of output of three phase series compensator Voltage, *Id and Iq* are d-q components of three phase source current. The Series Voltage Controller is dynamically modeled by adopting synchronous

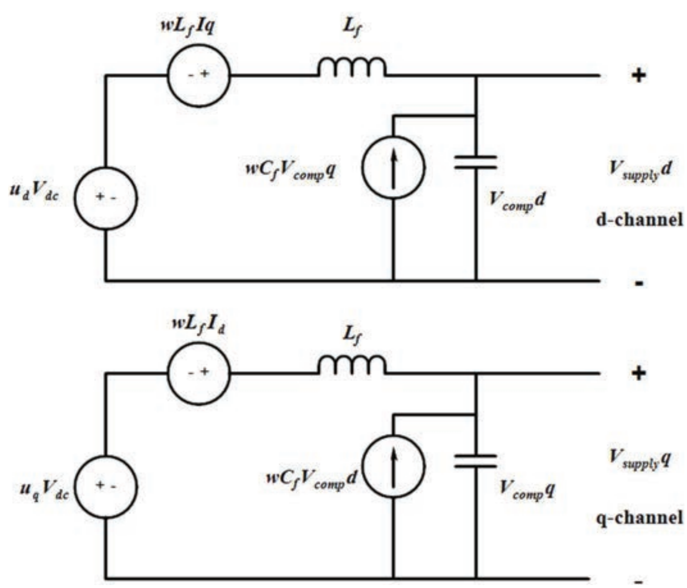

Figure 2 Average model of inverter leg.

reference frame based differential equations.

$$\frac{di_{comp}d}{dt} = \frac{V_{comp}d}{Lf} + \omega i_{comp}q - \frac{\mu_d V_{dc}}{Lf} \quad (1)$$

$$\frac{di_{comp}q}{dt} = \frac{V_{comp}q}{Lf} - \omega i_{comp}d - \frac{\mu_q V_{dc}}{Lf} \quad (2)$$

$$\frac{dV_{comp}d}{dt} = \omega V_{comp}q - \frac{i_{comp}d}{Cf} + \frac{i_{supply}d}{Cf} \quad (3)$$

$$\frac{dV_{comp}q}{dt} = -\omega V_{comp}d - \frac{i_{comp}q}{Cf} + \frac{i_{supply}q}{Cf} \quad (4)$$

Where, $V_{comp}d$ and $V_{comp}q$ are the *d-q* axis compensating voltages, μd and μq are the *d-q* axis duty ratio, and ω is the angular frequency.

Following state equation are used for controller design.

$$\left.\begin{aligned} \dot{x} &= f(x) + g(x)\mu \\ y &= h(x) \end{aligned}\right\} \quad (5)$$

The state vector is, $x = [i_{comp}d,\ i_{comp}q,\ V_{comp}d,\ V_{comp}q]^T$, the vector $u = [ud, uq]^T$ is vector of control variables, and output vector is, $y = [y1, y2]^T = [V_{comp}d,\ V_{comp}q]^T$. As the state variables are multiplied to the control variables, the non-linearity of the system is observed. The nonlinear behavior is precisely linearized using a sliding-mode controller.

3 Sliding-Mode Controller Design for Dynamic Voltage Restorer

3.1 Reference Voltage Generation

The control approach adopted in this paper is based on detection of source current [21]. Figure 3 shows equivalent diagram of Series Voltage Controller with non-linear load.

In the Figure 3, *Vsf* is the fundamental and *Vsh* is harmonic component of source Voltage, *Vpf* is shunt passive filter Voltage *Ish* is the harmonic and *Isf* is the fundamental component of source current *Is*, the fundamental component of load voltage is *VLf*, while the harmonic component is *VLh*. The compensating Voltage *Vc* is produced by the Series Voltage Controller which behaves as a Controlled Voltage Source.

$$V_c = KI_{sh} \quad (6)$$

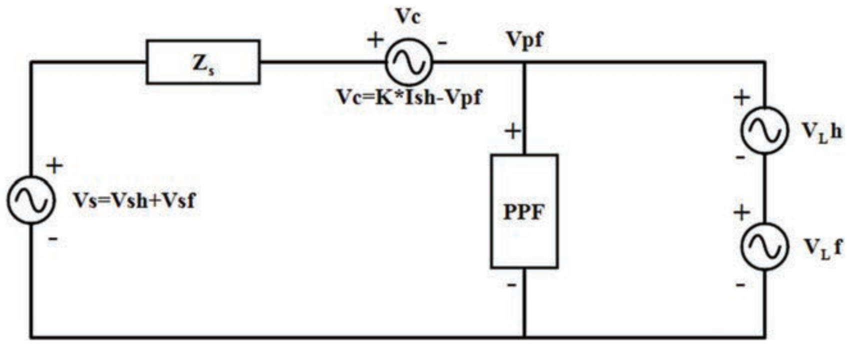

Figure 3 Equivalent diagram of series voltage controller.

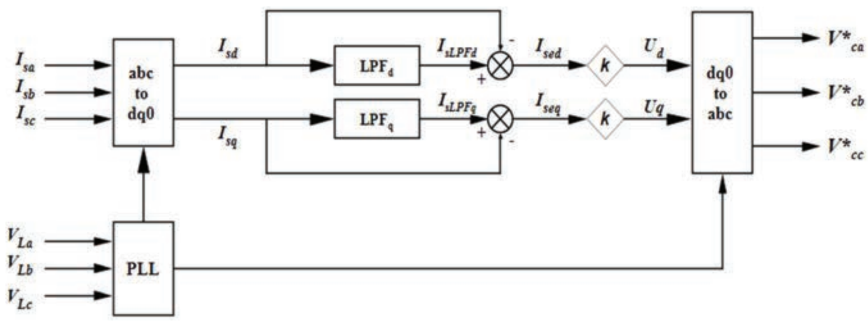

Figure 4 Reference generation scheme realization.

By applying ohm's law

$$I_{sh} = \frac{V_{sh-}V_{Lh}}{Z_s + K} \tag{7}$$

The value of I_{sh} depends on control gain K.

Based on the synchronous reference frame method, the reference compensating signal Vc* is obtained as follows:

$$u_d = kI_d \tag{8}$$

$$u_q = kI_q \tag{9}$$

V*c formation is shown in Figure 4.

The reference signal realised is then used as an input for the controller to generate pulses for VSI. The control flow chart to generate pulses is shown in Figure 5.

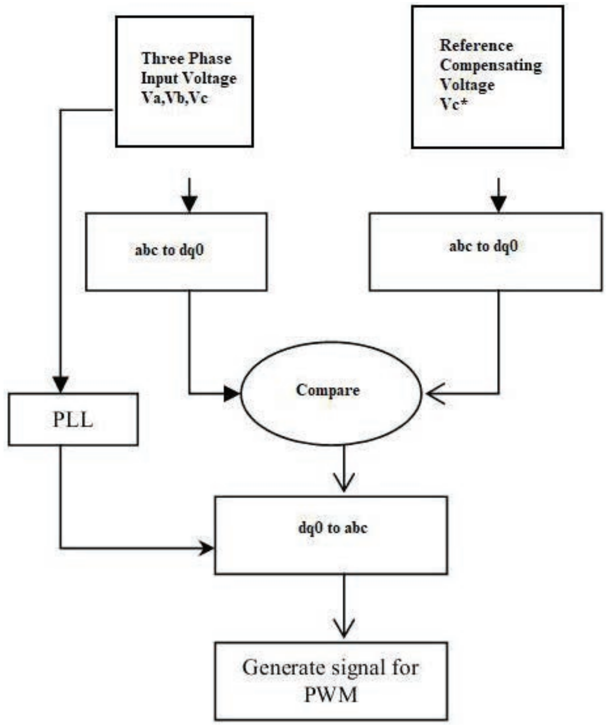

Figure 5 Control flow chart of DVR.

3.2 Sliding Mode Controller Design

The design of Sliding Mode Controller is synthesized by referring average model derived earlier. The compensating Voltages are differentiated w.r.t. time until the control variable ud and uq appear separately which results in the following equations:

$$\frac{d^2 V_{comp}d}{dt} = -\omega^2 V_{comp}d - \omega\frac{i_{comp}q}{Cf} + \omega\frac{i_{supply}q}{Cf} - \frac{V_{comp}d}{LfCf} - \omega\frac{i_{comp}q}{cf} - \frac{u_{dV_{dc}}}{LfCf} + \frac{di_{supply}d}{dt}\cdot\frac{1}{Cf} \tag{10}$$

$$\frac{d^2 V_{comp}q}{dt} = -\omega^2 V_{comp}q - \omega\frac{i_{comp}d}{Cf} + \omega\frac{i_{supply}d}{Cf} - \frac{V_{comp}q}{LfCf} - \omega\frac{i_{comp}d}{Cf} - \frac{u_{qV_{dc}}}{LfCf} + \frac{di_{supply}q}{dt}\cdot\frac{1}{Cf} \tag{11}$$

From Equations (10) and (11) it is clear that the control variables *ud* and *uq* are obtained after double derivate of compensating voltage. Therefore the system has relative degree of “2”. To design the sliding-mode controller, the linearized model in Equation (5) is referred. The series controller should drive the compensating voltages to achieve the control objective. The sliding surface is defined by following equations.

$$\overline{S} = S + \gamma \dot{S} \tag{12}$$

$$\overline{S_d} = S_d + \gamma \dot{S}_d \tag{13}$$

$$\overline{S_q} = S_q + \gamma \dot{S}_q \tag{14}$$

Where, γ is positive constant.

The sliding mode controller is designed by using following equations.

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

$$\dot{\overline{S_d}} = 0 \tag{16}$$

$$\dot{\overline{S_q}} = 0 \tag{17}$$

The sliding surfaces are defined as

$$S_d = V_{comp}d - V_{comp}d^* \tag{18}$$

$$S_q = V_{comp}q - V_{comp}q^* \tag{19}$$

The equivalent control law in d and q domain is obtained by substituting the output Equations (3) and (4) with value from Equations (16), (17), (18), (19).

$$\begin{aligned} u_{dequivalent} = & -(\dot{V}_{comp}d^* + \ddot{V}_{comp}d^*) \\ & + \frac{Lf}{V_{dc}}(cf\omega V_{comp}d - i_{comp}d + i_{supply}d) \\ & + \frac{\gamma Lf}{V_{dc}}\bigg(- cf\omega^2 V_{comp}d - \omega i_{comp}q + \omega i_{supply}q - \frac{v_{comp}d}{Lf} \\ & - \omega i_{comp}q + i_{supply}d\bigg) \end{aligned} \tag{20}$$

$$\begin{aligned} u_{qequivalent} = & -(\dot{V}_{comp}q^{*} + \ddot{V}_{comp}q^{*}) \\ & + \frac{Lf}{V_{dc}}(cf\omega V_{comp}q - i_{comp}q + i_{supply}q) \\ & + \frac{\gamma Lf}{V_{dc}}\Bigg(- cf\omega^{2}V_{comp}q - \omega i_{comp}d \; + \; \omega i_{supply}d - \frac{v_{comp}q}{Lf} \\ & - \omega i_{comp}d + i_{supply}q\Bigg) \end{aligned} \tag{21}$$

Equations below are used to derive a non-linear control law

$$U = u_{euivalent} + u_{switching} \tag{22}$$

$$Ud = u_{deuivalent} + u_{switching} \tag{23}$$

$$Uq = u_{qeuivalent} + u_{switching} \tag{24}$$

When Equations (20) and (21) are incorporated into Equations (23) and (24), the nonlinear control law is obtained in the d-q domain.

$$\begin{aligned} u_{d} = & -(\dot{V}_{comp}d^{*} + \ddot{V}_{comp}d^{*}) + \frac{Lf}{V_{dc}}(cf\omega V_{comp}d - i_{comp}d + i_{supply}d) \\ & + \frac{\gamma Lf}{V_{dc}}\Bigg(- cf\omega^{2}V_{comp}d - \omega i_{comp}q + \omega i_{supply}q - \frac{v_{comp}d}{Lf} \\ & - \omega i_{comp}q + i_{supply}d\Bigg) - \varepsilon_{11}signal(S_{d}) - \varepsilon_{12}signal(\dot{S}_{d}) \end{aligned} \tag{25}$$

$$\begin{aligned} u_{q} = & -(\dot{V}_{comp}q^{*} + \ddot{V}_{comp}q^{*}) + \frac{Lf}{V_{dc}}(cf\omega V_{comp}q - i_{comp}q + i_{supply}q) \\ & + \frac{\gamma Lf}{V_{dc}}\Bigg(- cf\omega^{2}V_{comp}q - \omega i_{comp}d + \omega i_{supply}d - \frac{v_{comp}q}{Lf} \\ & - \omega i_{comp}d + i_{supply}q\Bigg) - \varepsilon_{21}signal(S_{q}) - \varepsilon_{22}signal(\dot{S}_{q}) \end{aligned} \tag{26}$$

The block illustration of the Sliding Mode Control approach is depicted in Figure 6.

This controller has the following control function: $U_{\text{eq}} = U_{\text{switching}}$

$$U_{eq} = \begin{cases} +1, & \text{when } S > 0 \\ -1, & \text{when } S < 0 \end{cases} \tag{27}$$

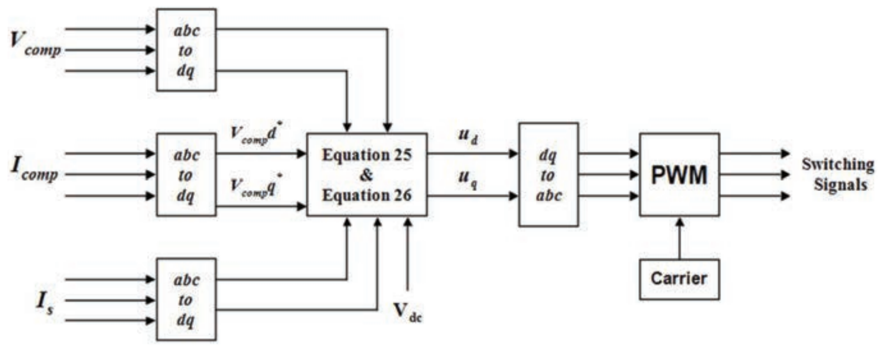

Figure 6 Block diagram of Sliding Mode Control approach.

3.3 Terminal Sliding Mode Control

The Equation (28) illustrates a nonlinear sliding surface,

$$S = \dot{x}_1 + \gamma x_1^{k1/k2} \tag{28}$$

Where, γ, $k1$ and $k2$ are positive odd integers, $k2 > k1$. The system dynamics is observed by establishing sliding mode equilibrium $(S = 0)$ for finite time *tr*,

$$0 = \dot{x}_1 + \gamma x_1^{k1/k2} \quad \text{i.e. } \dot{x}_1 = -\gamma x_1^{k1/k2} \tag{29}$$

For, $k2 = k1$, the equation of system looks like as conventional sliding mode, i.e. $\dot{x}_1 = -\gamma x_1^1$.

After solving this differential equation we get,

$$x_1(t) = x_1(t_r)e^{-i\gamma}$$

From above equation it is clear that, the value of x_1 approaches to *zero* with increase in γ when time is varied from 0 to ∞.

If, $k2 > k1$, the finite time required to attain equilibrium condition is given by

$$t_s^{TSMC} = \frac{k_2}{\gamma(k2 - k1)}|x_1(t_r)|^{1-k1/k2} \tag{30}$$

As the system attains equilibrium in finite time it is called as "terminal" [22]. The extra non-linear term added makes the convergence rate of system to attain equilibrium faster than that of system with linear term.

4 Simulation Results and Analysis

This simulation study compares the behaviour of series voltage control when the various control schemes discussed previously are used. The assessment is made by estimating the reduction of source Voltage Harmonics and the capacity of DVR to restore Voltage Sag. To make comparative analysis the system parameters used for simulation are considered from [23].

Figure 7 depicts the top level of MATLAB/Simulink model developed. The model is simulated for 0.2 seconds using fixed step solver ode45 with a 1μs sampling time. The load considered here consists of linear three phase R-L load and non-linear rectifier load. The analysis is carried out for three phase LLL-G fault with star connected load. The transmission line consists of two

Table 1 Parameters used for Simulation

Sr. No.	Parameter	Value
1	Rating of Source Voltage	11 kV
2	Ratio of Source Impedance (X/R)	7
3	Source Frequency	50 Hz
4	Short Circuit Power	100 MVA
5	Three Phase Fault Resistance	1 Ω
6	Linear Load	5 kVA
7	Controllable Load	10 kVA, Power Factor = 0.9
8	Rectifier load (R-C, R-L)	R = 100 Ω, C = 100 mF, L = 1 mH
9	Passive Filter Inductance	7 mH
10	Switching Frequency	2 kHz

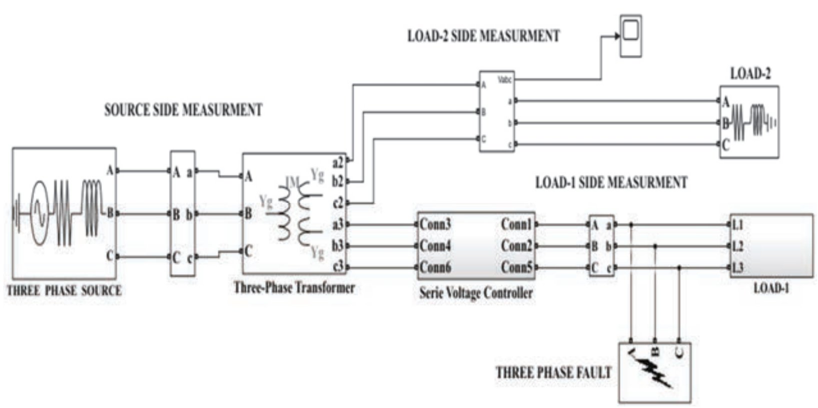

Figure 7 Overall simulink scheme of dynamic voltage restorer.

feeders with load 1 and load 2. There is three phase fault on feeder 1. The DVR should maintain the Voltage at feeder 2 when there is fault at feeder 1.

The results shown in subsequent figures are interpreted for conventional as well as algorithms discussed in earlier sections. Firstly the simulation is carried out with a conventional control algorithm as described in [23]. In this paper the simulation in [23] is modified by introducing one extra feeder at source side and incorporating proposed control approach. The analysis is carried out by observing the Voltage at feeder-2 when there is fault on feeder-1. Figure 8(a) and 8(b) shows Voltage at feeder-1 and feeder-2 respectively while Figure 8(c) shows Total Harmonic Distortion (THD) Level of Voltage at feeder-2. It is clear that with conventional algorithm DVR fails to maintain the Voltage at feeder-2 with higher percentage of Harmonics.

A Sliding-Mode Control algorithm is used to correct the variations in load voltage in the second simulation. Figure 9(a) and 9(b) shows Load Voltages at feeder-1 and feeder-2 respectively. Figure 9(c) illustrates the level of Total Harmonic Distortion (THD) at the feeder-2 load voltage. The results indicate that with Sliding Mode Control technique the Series Voltage Controller maintains the Voltage at value of 0.9015 p.u. of the feeder-2 which is within permissible the limits prescribed by IEEE. It is observed that the reduction in Harmonics is from 62.87% to 4.46%. But this is reduction is not within the IEEE limits.

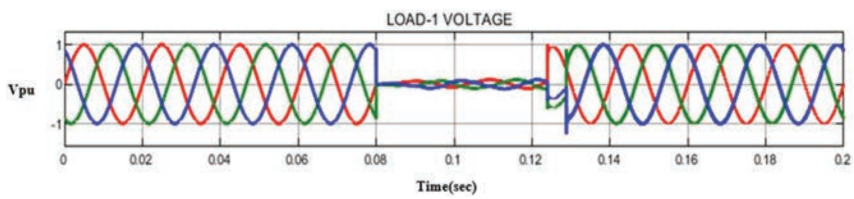

Figure 8(a) Feeder-1 Load Voltage with conventional method.

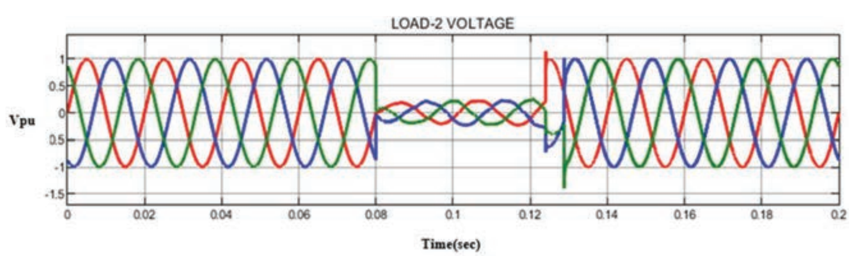

Figure 8(b) Feeder-2 Load Voltage with conventional method.

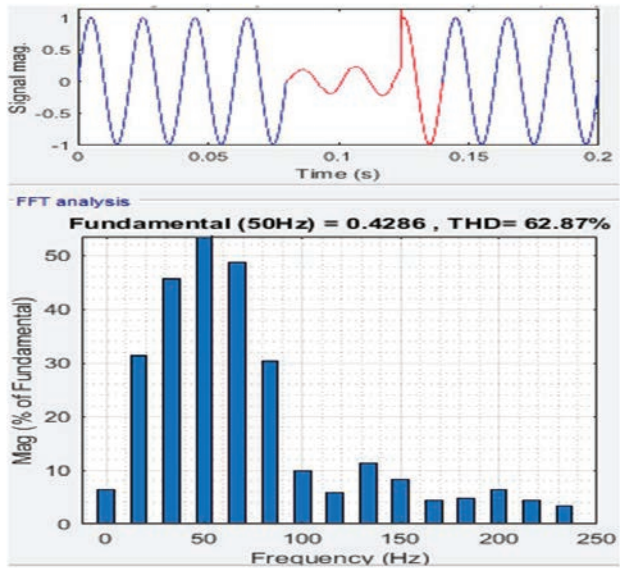

Figure 8(c) Feeder-2 Load Voltage THD with conventional method.

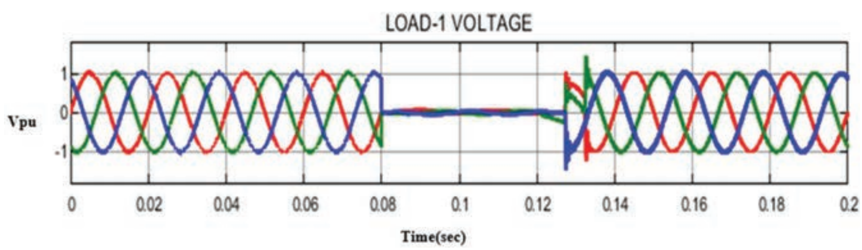

Figure 9(a) Feeder-1 load voltage with sliding mode control technique.

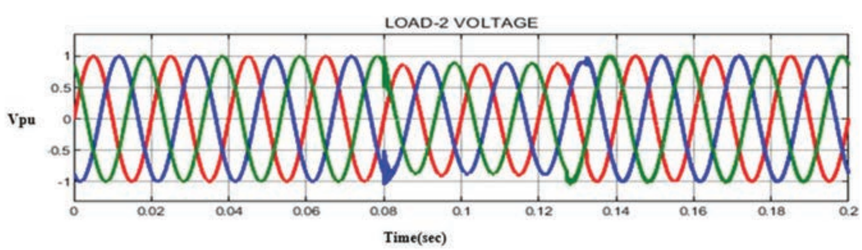

Figure 9(b) Feeder-2 load voltage with sliding mode control technique.

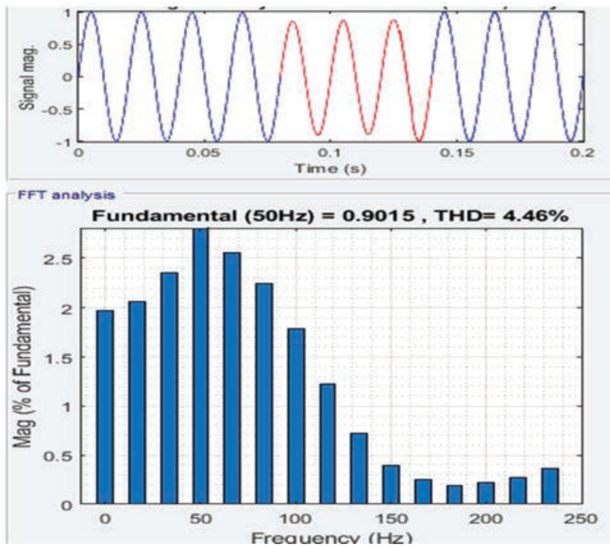

Figure 9(c) Feeder-2 load voltage THD with sliding mode control technique.

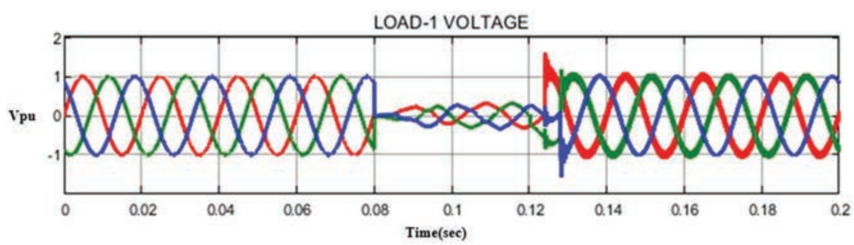

Figure 10(a) Feeder-1 load voltage with terminal sliding mode control technique.

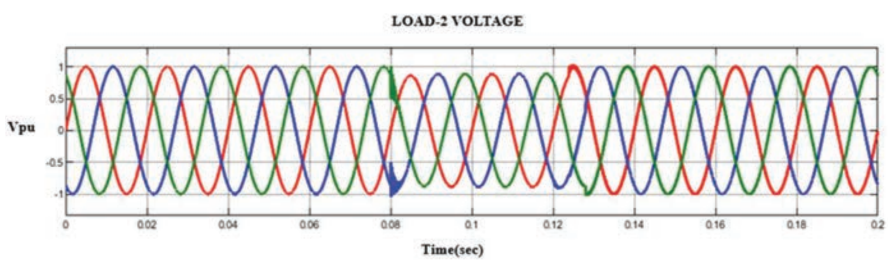

Figure 10(b) Feeder-2 load voltage with terminal sliding mode control technique.

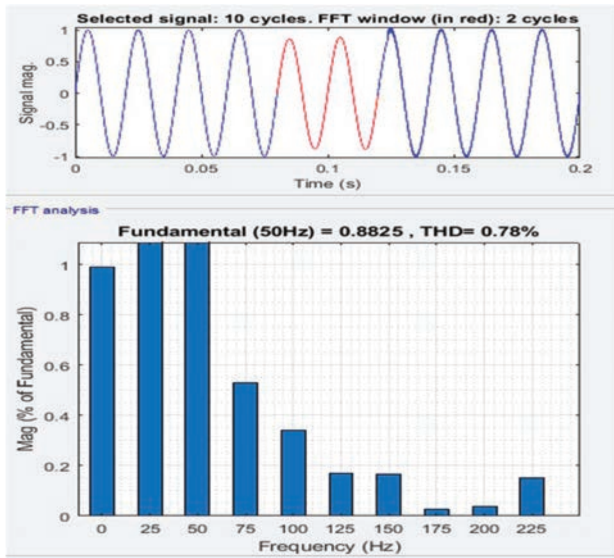

Figure 10(c) Feeder-2 load voltage THD with terminal sliding mode control technique.

Table 2 Performance analysis at Feeder 2

Parameter	Conventional DVR	Sliding Mode Controlled DVR	Terminal Sliding Mode Controlled DVR
% Voltage THD	62.87	4.46	0.78
Fundamental Voltage (pu)	0.4286	0.9015	0.8825

To reduce harmonic content further and to improve Voltage profile further, the simulation is carried out with Terminal Sliding Mode Control Algorithm. The sliding surface described in Equation (28) is designed with the values of γ is taken equal to 1 while the ratio $k1/k2$ is selected as 0.6. Figure 9(a) to 9(c) shows the results obtained with proposed controller.

4.1 Result Analysis

Thus results obtained are more satisfactory than conventional sliding mode control technique. Table 2 presents the numerical analysis to for validating performance of proposed DVR at Feeder 2.

The harmonic level is reduced from 62.87% to 4.46% and further to 0.78% which is well below IEEE limit. Also it is observed that per unit Voltage level is improved from 0.4286 to 0.9015. Thus, the proposed technique proves superior to conventional approach.

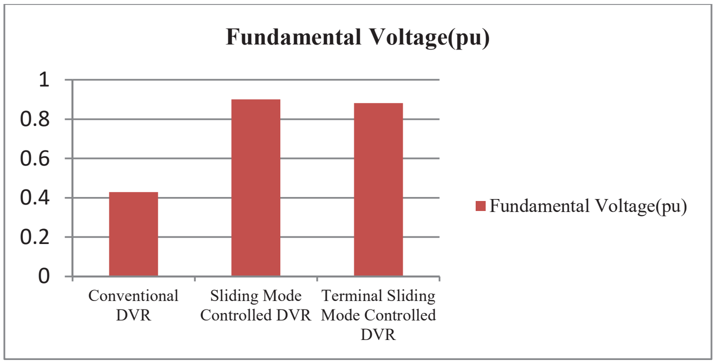

Figure 11(a) Plot of fundamental voltage.

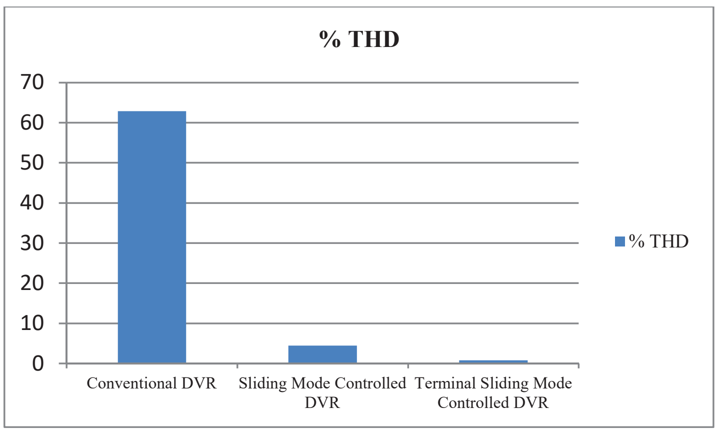

Figure 11(b) Plot of % THD.

Table 3 Performance analysis of DVR at Feeder 2 (Rectifier with R-L load)

Parameter	Conventional DVR	Sliding Mode Controlled DVR	Terminal Sliding Mode Controlled DVR
% Voltage THD	52.64	3.48	0.24
Fundamental Voltage(pu)	0.6214	0.8827	0.8932

Furthermore, for more clarification on performance of DVR, the load connected at Feeder 1 is varied. A Controllable load of rating 10 kVA, power factor of 0.9 and Rectifier with R-L load is connected at Feeder 1 and simulations are carried out with same conditions as before. The results obtained at Feeder 2 are summarised in Tables 3 and 4.

Table 4 Performance analysis of DVR at Feeder 2 (Controllable Load)

Parameter	Conventional DVR	Sliding Mode Controlled DVR	Terminal Sliding Mode Controlled DVR
% Voltage THD	48.52	3.44	0.24
Fundamental Voltage(pu)	0.7423	0.8712	0.8927

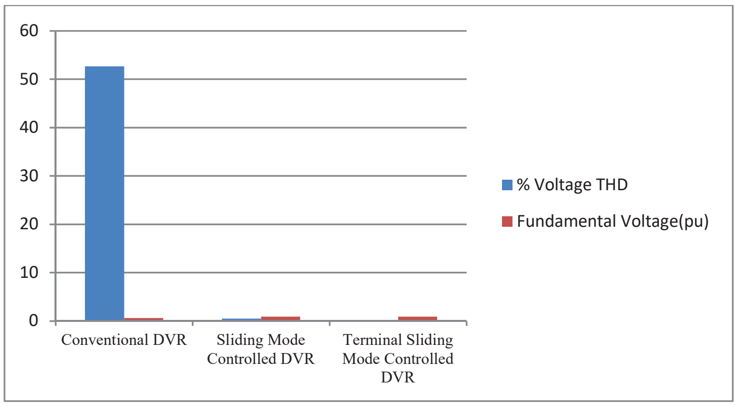

Figure 12(a) Plot of performance analysis of DVR (Rectifier with R-L load).

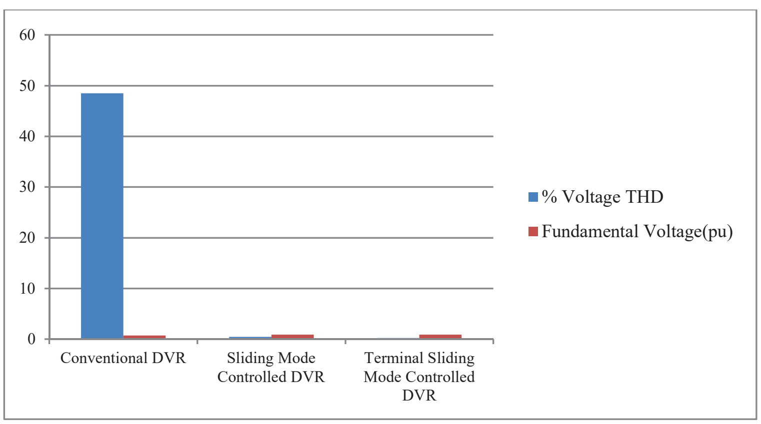

Figure 12(b) Plot of performance analysis of DVR (Controllable Load).

Figure 12(a) and 12(b), shows the pictorial bar chart view of performance analysis with changing load conditions.

From the results obtained and plots shown, it is clear that the proposed Terminal Sliding Mode Controlled Dynamic Voltage Restorer demonstrates satisfactory results for changing load conditions. It has been observed that with TSMC DVR the percentage voltage THD levels are reduced to levels within IEEE levels.

5 Conclusion

Dynamic Voltage Restorer has been shown to reduce voltage sag and voltage harmonics at supply side using voltage restoration. The methodology proposed applies classical concept and Terminal Mode control concept of Sliding Mode for designing non-linear controller of the DVR. The simulation results obtained with the proposed controller depicts the DVR can be considered as a multi-functional series compensator. Based on the per-cent harmonic distortion and the changes per unit change, three control algorithms have been studied and compared. Quantifiable results obtained from the experiment indicate a decrease in Total Voltage Harmonic Distortion as well as an increase in per unit change in the source voltage. The simulation results evidenced the productivity of the mitigation technique purposed. In terms of improving power quality, it has been demonstrated that the proposed strategy is superior to the standard approach by compensating a number of power quality issues, such as voltage sag and voltage harmonics.

References

[1] IEEE Standard 519-1992, IEEE recommended practices and requirements for harmonic control in electrical power systems, 1992.
[2] Bollen, M. H. J., 'Understanding power quality problems Voltage Sags and interruptions', NewYork, USA: IEEE Press, 2000
[3] Slotin, J. E., and Li, W. Applied Non-Linear Control, Englewood Cliffs, New Jersey: Prentice Hall Inc., 1991
[4] Hernán De Battistaand Ricardo J. Mantz, 'Harmonic Series Compensators in Power Systems: Their Control via Sliding Mode', IEEE Transactions on Control Systems Technology, Vol. 8, No. 6, November 2000.
[5] Ruilin, P., and Yuegen, Z. 'Sliding mode control strategy of dynamic Voltage restorer', IEEE International Conference on Industrial Electronics and Control Applications, pp. 1–3, 2005.
[6] Piatek, K., 'Sliding mode control of DVR with minimized energy injection', IEEE European Conference on Power Electronics and Applications, 2005.

[7] Kolhatkar, Y. Y., Errabelli, R. R., and Das, S. P., ‘A sliding mode controller based optimum UPQC with minimum VA loading’, IEEE Power Engineering Society General Meeting, 2005, 1, 871–875.

[8] Errabelli, R. R., Kolhatkar, Y. Y., and Das, S. P. ‘Experimental investigation of DVR with slidingmode control’, IEEE Power India Conference, pp. 5, 2006.

[9] Nagesh Kumar, G. V., and Chowdary, D. D., ‘DVR with sliding mode control to alleviate Voltage Sags on a distribution system for three phase short circuit fault’, 2008 IEEE Region 10 and the Third international Conference on Industrial and Information Systems, pp. 1–4, 2008

[10] Pires, V. F., Marques, G. D., and Sousa, D., ‘Phase-locked loop topology based on a synchronous reference frame and sliding mode approach for DVR applications’, IEEE International Conference on Computer as a Tool (EUROCON), pp. 1–4, 2011

[11] Mahalakshmi, M., Latha, S., and Ranjithpandi, S., ‘Sliding mode control for PMSG Based Dynamic Voltage Restorer’, IEEE International Conference on Energy Efficient Technologies for Sustainability (ICEETS), pp. 1320–1323, 2013.

[12] Biricik, S., Komurcugil, H., and Basu, M., ‘Sliding mode control strategy for three-phase DVR employing twelve-switch Voltage source converter’, 41st Annual Conference of the IEEE on Industrial Electronics Society, pp. 921–926, 2015.

[13] Biricik, S., and Komurcugil, H., ‘Optimized Sliding Mode Control to Maximize Existence Region for Single Phase Dynamic Voltage Restorers’, IEEE Transactions on Industrial Informatics, 12(4), 1486–1497, 2016.

[14] Samet Biricik, Hasan Komurcugil, Nguyen Duc Tuyen, Malabika Basu, ‘Protection of Sensitive Loads Using Sliding Mode Controlled Three-Phase DVR With Adaptive Notch Filter’, IEEE Transactions on Industrial Electronics, Volume: 66, Issue: 7, 5465–5475, 2019.

[15] Talada Appala Naidu, et.al., “Performance of DVR Using Optimized PI Controller Based Gradient Adaptive Variable Step LMS Control Algorithm”, IEEE Journal of Emerging And Selected Topics In Industrial Electronics, Vol. 2, No. 2, April 2021.

[16] Sumaiya Hasan, et al., “A Novel Dual Slope Delta Modulation Technique for a Current Source Inverter based Dynamic Voltage Restorer for Mitigation of Voltage Sags”, IEEE Transactions on Industry Applications (Volume: 57, Issue: 5, Sept.–Oct. 2021).

[17] Samet Biricik, et al., "Super Twisting Sliding Mode Control of DVR with Frequency-Adaptive Brockett Oscillator", IEEE Transactions on Industrial Electronics (Volume: 68, Issue: 11, Nov. 2021).
[18] Talada Appala Naidu, et al., "Compensation of voltage-based power quality problems using sliding mode observer with optimised PI controller gains", IET Generation, Transmission & Distribution, 2020, Volume 14 Issue 14, pp. 2656–2665.
[19] Zeinab Elkady, et al., "Enhanced DVR Control System based on the Harris Hawks Optimization Algorithm", September 2020, IEEE Access, Volume: 8, pp. 1–17.
[20] S. Rahmani, K. Al-Haddad, and H. Y. Kanaan, 'Average modelling and hybrid control of a three-phase series hybrid power filter', in Proceedings of IEEE International Symposium on Industrial Electronics, vol. 2, pp. 919–924, 2006.
[21] Sushree Diptimayee Swain, Pravat Kumar Ray, 'Harmonic current and Voltage compensation using HSAPF based on hybrid control approach for synchronous reference frame method', Electrical Power and Energy Systems 75, 83–90, 2016.
[22] H. Komurcugil, 'Fast Terminal Sliding Mode Control for Single-Phase UPS inverters', 2011 IEEE International Symposium on Industrial Electronics, Gdansk, pp. 277–282, 2011.
[23] Jeevan Inamdar, K. Iyswarya Annapoorani, "A Modified Series Voltage Controller for Power Conditioning", International Journal of Recent Technology and Engineering, Volume-8 Issue-4, November 2019.

Biographies

Jeevan J. Inamdar has received his M.Tech (Electrical Power System) from Bharati Vidyapeeth Deemed University, Pune, India in the year of 2015. Currently he is full time PhD scholar at VIT University, Chennai, India. His area of research is Power Quality Analysis and Mitigation Techniques.

K. Iyswarya Annapoorani received B.E., M.E. and Doctorate in Electrical Engineering from Anna University in the field of High Voltage Engineering. Currently she is an Associate Professor in the School of Electrical Engineering at VIT University, Chennai, India. She has total 15 years of teaching experience. Her research interest includes Soft Computing Techniques, High Voltage Engineering, Renewable Energy Systems and Power Quality.