Power Quality Enhancement using Sliding-Mode Controlled DVR

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***Abstract* - Dynamic voltage restorer (DVR) is one of the important custom power devices used to mitigate voltage sags. voltage sags are vital to power quality issue which causes a bad economic effect on utilities and customers.in this paper classical control algorithm used for DVR based on Park's transformation is modified by using sliding mode control. The sliding mode control strategy is proposed to make the system stable and robust. The proposed control strategy is verified through a simulation study and the results obtained are analyzed.**

***Index Terms* - DVR, sliding mode controller, voltage sag.**

I.INTRODUCTION

Over the past few years, increased use of power electronic devices causes many power electronic problems such as high current harmonics voltage distortion voltage sag, voltage swells etc on the electric grid. [1] Conventionally to eliminate line current harmonics passive LC filters are used but there are some limitations such as problems with resonance, bulky, fixed compensations. to solve these problems active filters were used. [2] But APF too has some limitations like it cannot compensate current harmonics more than 25th order. The use of hybrid APF that is the combination of APF and LC filter overcomes the limitations of both the filters. It provides better performance and cost-effective solutions.

A compensation method for mitigation of voltage related power quality problems with the use of a series voltage regulator is known as Hybrid series active power filter or Dynamic voltage regulator (DVR). DVR has excellent dynamic capabilities, and it is helpful to protect critical loads from short time voltage dips or swells [3].

The control strategy is essential to improve the performance of the DVR or HSAPF. The conventional solution for controller requirement is based on classical theory or modern control theory or modern control theory. [4] Classical control theory-based designs are mainly of PID family controllers which needs an accurate mathematical model. Modern control theory-based controllers are state feedback controllers, modern reference adaptive controllers etc. These controllers also need accurate mathematical models and are sensitive to parameter variations [4-5]. Therefore, to eliminate this need for accurate mathematical models sliding mode control is introduced [5]. The SMC is known as an accurate control technique for controlling a non-linear system with uncertain dynamics and disturbances because of its order reduction property, plant parameter variations etc. SMC is nothing but variable structured control is suggested in this paper to improve the dynamic performance of the DVR and to overcome the limitations of HSAPF.

II.DVR'S AVERAGED MODELLING

The schematic block diagram of a conventional DVR is shown in fig 1. It consists of a DC voltage source, voltage source converter, LC filter & isolation transformer. As shown in the figure DVR is connected in series with both source and load through a coupling transformer. Controller provides control signal to a VSI by using three strategies which are used to get the reference signal. First approach is to detect the source current which is used to generate a voltage proportional to source current harmonics at the output of DVR. Second approach is to detect a load voltage and DVR generates the voltage with the same harmonic content but with opposite phase as that of load voltage and the third approach is hybrid of first and second in which detects source as well as load voltage and DVR generates a voltage

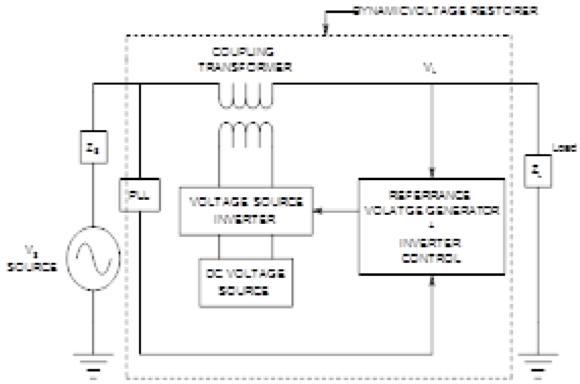

Fig. 1: Schematic Diagram of Conventional DVR

Inverter legs are averaged to obtain the whole averaged model of a three-phase inverter as shown in Fig.2.by using this diagram the dynamic model of HSAPF or DVR under synchronous reference frame can be expressed by using the differential equations which are,

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

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

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

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

Where, $V_{comp}d$ & $V_{comp}q$ are DQ-axis compensating voltages, μ_d & μ_q are DQ-axis duty ratio,ω is the angular frequency of the source voltage. [8] To facilitate the controller, design the HSAPF system model can be defined as

$$\begin{cases} \dot{x} = f(x) + g(x)\mu \\ y = h(x) \end{cases} \quad (5)$$

Where,

x= $[Vcomp\ d, Vcomp\ q, icomp\ d\ , icomp\ q\ , Vdc]^T$ is defined as a state vector, $\mu\ = [\mu d\ , \mu q\ ]^T$ is control variables$y\ = [y1\ , y2\ ]^T$ are system outputs.

It must be noticed that the state variable is combined and the system is non-linear because of multiplication terms of state variables and control variables. These two difficulties are accurately controlled with the help of a sliding mode controller [8].

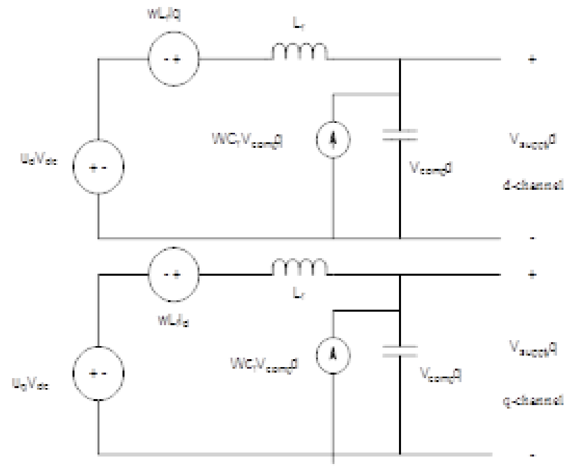

Fig 2: Averaged equivalent circuit in three phase stationary frame of HSAPF

III.CONTROL SYSTEM DEVELOPMENT

A. Control configuration of DVR (control approach based on synchronous reference frame method (SRF))

The reference compensation voltage of DVR using control approach based on SRF method is expressed as

$$V_C{}^* = KI_{sh} \quad (6)$$

The harmonic components of source current can be obtained from source current I_s by using the control approach in which by using the Park's transformation the desired value of load voltage is obtained at the output of VSI. For generating a unit sinusoidal wave in phase with load voltage the PLL circuit is used. The DQ transformation and the phase information of load voltages are used to convert source current to DQ domain currents $i_c d i_c q$and. These currents are further passed through a low pass filter to generate reference control signal currents $i_{comp} d i_{comp}\ q$and. These control signals are used for the generation of reference compensating signal V_c^* using SRF control approach as follows,

$$\mu_{d=KI_{comp}d} \quad (7)$$

$$\mu_{q=KI_{comp}q} \quad (8)$$

The generation of the reference control signal $i_{comp}d\ and i_{comp}q$ using Parks Transformation is shown in following figure 3.

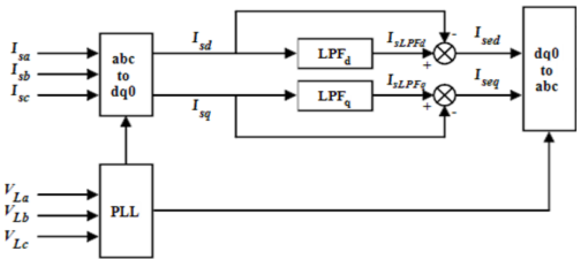

Fig 3: Control approach based on Park's transformation

The reference control signals $i_{comp}d$ and $i_{comp}q$ are given by the following equations

$$I_{comp}\, d = i_{sLPF}d - i_c d \quad (9)$$

$$I_{comp}\, q = i_{sLPF}q - i_c q \quad (10)$$

Sliding mode controller design for DVR

Sliding mode controller design based on the averaged model of DVR is described in this section. It is seen from the differential equations that first-time derivatives of output $\frac{dV_{cd}}{dt}$ *and* $\frac{dV_{cq}}{dt}$ does not explicitly contain control variables μ_d and μ_q.thus we differentiate the compensating voltages concerning the time until the control variables appear explicitly which leads us to follow equations such as,

$$\frac{d^2V_{comp}d}{dt} = -\omega^2 V_{comp}d - \omega\frac{i_{comp}q}{cf} + \omega\frac{i_{supply}q}{cf} - \frac{V_{comp}d}{Lfcf} - \omega\frac{i_{comp}q}{cf} - \frac{\mu_d V_{dc}}{Lfcf} + \frac{di_{supply}d}{dt}\cdot\frac{1}{cf} \quad (11)$$

$$\frac{d^2V_{comp}q}{dt} = -\omega^2 V_{comp}q - \omega\frac{i_{comp}d}{cf} + \omega\frac{i_{supply}d}{cf} - \frac{V_{comp}q}{Lfcf} - \omega\frac{i_{comp}d}{cf} - \frac{\mu_q V_{dc}}{Lfcf} + \frac{di_{supply}q}{dt}\cdot\frac{1}{cf} \quad (12)$$

The equations (11-12) shows that the 2^{nd} derivative of the output depends on control inputs μ_d and μ_q. No further time derivative is needed. Using equation (5) sliding mode controller is designed. To force the compensating voltages $V_{comp}d$ $V_{comp}q$ and is nothing but the control objective of the DVR system. Sliding surface mathematical expressions is as follows:

$$\bar{S} = \begin{bmatrix}\overline{S_d}\\ \overline{S_q}\end{bmatrix} \quad (13)$$

$$\bar{S} = S + \gamma\dot{S} \quad (14)$$

$$\overline{S_d} = S_d + \dot{S_d} \quad (15)$$

$$\overline{S_q} = S_q + \dot{S_q} \quad (16)$$

Substituting values of $V_{comp}d$ and V_{comp}q in equations (15) and (16) and using the design procedure of sliding mode controller which is depicted as,

$$\dot{\bar{S}} = 0 \quad (17)$$

Similarly,

$$\dot{\overline{S_d}} = 0 \quad (18)$$

$$\dot{\overline{S_q}} = 0 \quad (19)$$

Using the equations (18) and (19) and substituting appropriate values from output equations the equivalent control law in d and q domain is obtained as

$$\frac{Lf}{V_{dc}}\left(cf\omega V_{comp}d - i_{comp}d + i_{supply}d\right) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{comp}d - \omega i_{comp}q + \omega i_{supply}q - \frac{v_{comp}d}{Lf} - \omega i_{comp}q + i_{supply}d\right) \quad (20)$$

$$\mu_{qequivalent} = -\left(V_{comp}\dot{}q^* + V_{comp}\ddot{}q^*\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{comp}q - i_{comp}q + i_{supply}q\right) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{comp}q - \omega i_{comp}d + \omega i_{supply}d - \frac{v_{comp}q}{Lf} - \omega i_{comp}d + i_{supply}q\right) \quad (21)$$

The non-linear control law is obtained using the following equations

$$U = \mu_{euivalent} + \mu_{switching} \quad (22)$$

Putting the values of $\mu_{dequivalent}$ and $\mu_{qequivalent}$ the non linear control law in d-q domain is as follows

$$\mu_d = -\left(V_{comp}\dot{}d^* + V_{comp}\ddot{}d^*\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{comp}d - i_{comp}d + i_{supply}d\right) + \frac{\gamma Lf}{V_{dc}}\Big(-cf\omega^2 V_{comp}d - \omega i_{comp}q + \omega i_{supply}q - \frac{v_{comp}d}{Lf} - \omega i_{comp}q + i_{supply}d\Big) - \varepsilon_{11}signal(S_d) - \varepsilon_{12}signal(\dot{S_d}) \quad (23)$$

$$\mu_q = -\left(V_{comp}\dot{}q^* + V_{comp}\ddot{}q^*\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{comp}q - i_{comp}q + i_{supply}q\right) + \frac{\gamma Lf}{V_{dc}}\Big(-cf\omega^2 V_{comp}q - \omega i_{comp}d + \omega i_{supply}d - \frac{v_{comp}q}{Lf} - \omega i_{comp}d + i_{supply}q\Big) - \varepsilon_{21}signal\left(S_q\right) - \varepsilon_{22}signal(\dot{S_q}) \quad (24)$$

The control block diagram of control strategy is shown in the following figure.

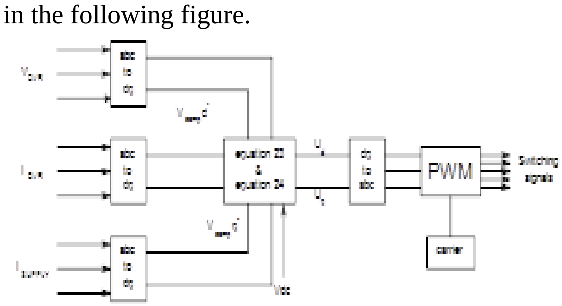

Fig. 4: Sliding Mode Control Strategy for DVR

Switching law for the controller can be shown as

$$\mu_{euivalent} = \mu_{switching}$$

$$\mu_{euivalent} = \begin{cases} +1, when\ S > 0 \\ -1, when\ S < 0 \end{cases} \quad (25)$$

C. Robustness

As sliding surface and switching does not depend on system operating point, load circuit parameters and on power supply converter dynamics operating in sliding mode is robust [1].

IV.SIMULATION RESULTS

The simulation study shows the comparative analysis of the system with DVR but without sliding mode controller and simulation results with sliding mode-controlled DVR. The comparison is done by observing a reduction of supply voltage harmonics and voltage sag restoration capability. The simulation parameters are shown in the following table 1

SR. NO.	Parameter	Rating
1.	Source Voltage (Vrms)	400V
2.	Fundamental frequency	50 Hz
3.	Three phase Fault Resistance	1Ω
4.	source impedance (X/R) ratio	7
5	Passive filter inductance	1.35mH
6	Passive filter capacitance	60μF
7	Series filter indcuctance	1.35mH
8	Series filter capacitancde	60μF
9	Carrier switching frequency	2kHz

Table 1: Simulation Parameters

A Matlab Simulink model is designed with the above parameters. The simulation is carried out in variable step solver (Dormand – Prince) with the tolerance of 1 msec and using a non-adaptive algorithm.

For comparative analysis, two cases are considered .one being without sliding mode control DVR and the second case will be the system with sliding mode-controlled DVR. The load voltage, injected voltage by DVR and supply voltage restored are shown in figure 5a, figure 5b and figure 5c respectively.

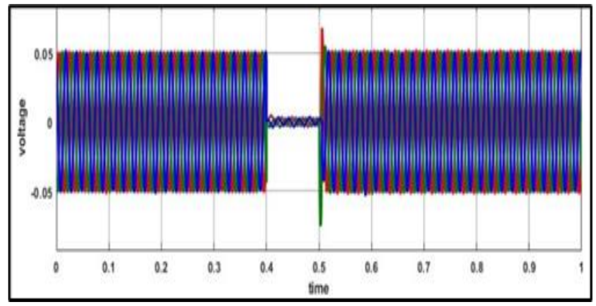

Fig. 5(a): Load Voltage due to Fault on Load Side

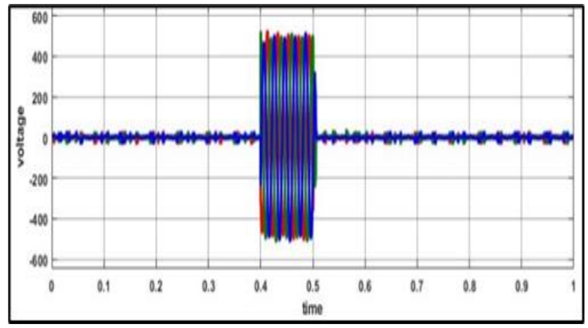

Fig. 5(b): Injected Voltage by DVR

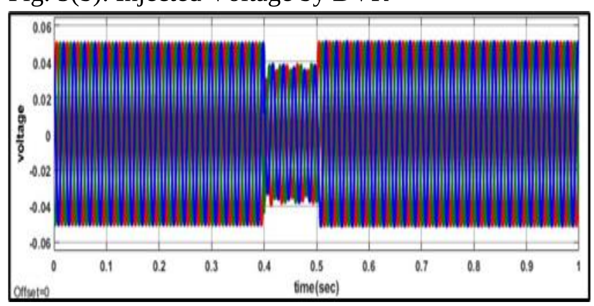

Fig. 5(c): Restored Supply Voltage

Figure 5(a) to figure 5(c) shows that though there is the injection of antiphase voltage to load voltage to restore it during fault condition the sag is not restored completely also the voltage harmonics along with transients are also present in supply voltage which shows that operation of DVR is not satisfactory.

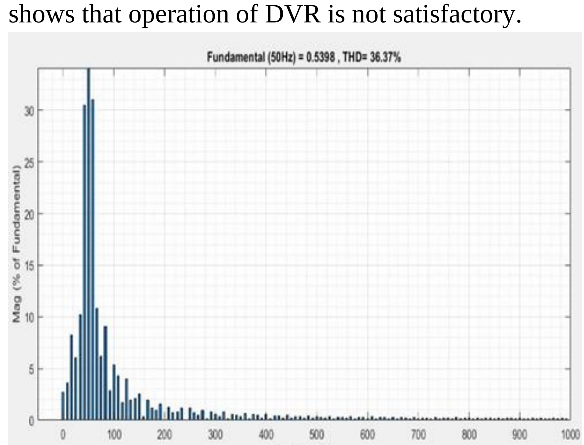

Fig. 6: THD of Load Voltage During Sag

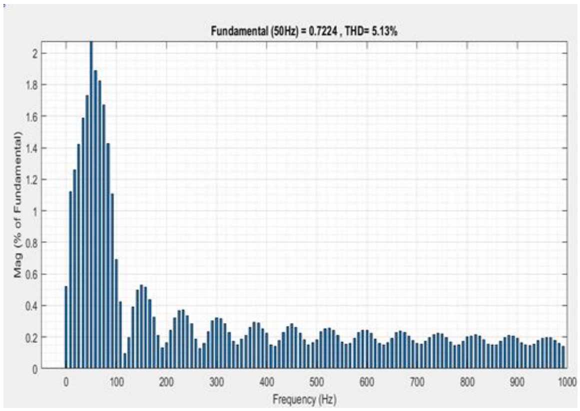

Fig. 7: THD of Supply Voltage with DVR

The figure (6) shows the total harmonic distortion of the load voltage is 36.37 % during sag period and figure (7) shows the THD of restored supply voltage without sliding mode .it is observed that the THD is reduced to 5.13%.

To reduce the voltage THD further the system is simulated using a sliding mode-controlled algorithm. The supply voltage is restored with sliding mode-controlled DVR. the maintained supply voltage and THD of the plot of supply voltage with the help of sliding mode controller approach is shown in figure 8 and figure 9 respectively.

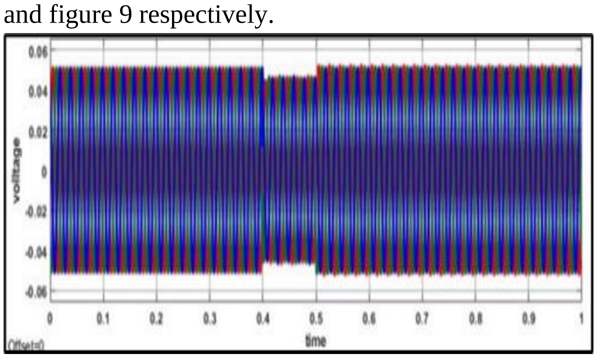

Fig 8: Restored Supply Voltage with Sliding Mode-Controlled DVR

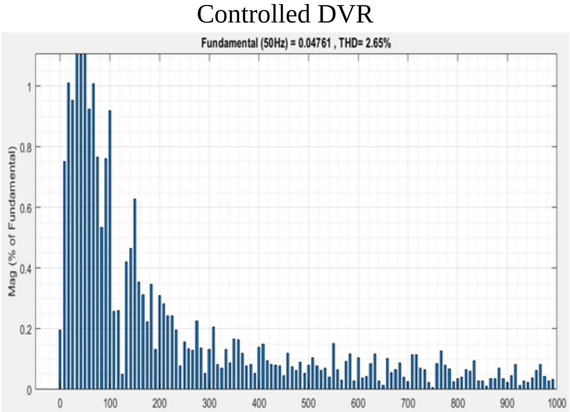

Fig. 9: THD of Supply Voltage with Sliding Mode-Controlled DVR

Figure 8 confirms that voltage sag is restored with improved magnitude and distortion is also minimised. also, the THD is reduced to 2.65% which is well within the IEEE limits.

V.CONCLUSION

In this paper, a sliding mode-controlled DVR is presented for mitigation of power quality issues. The proposed method has a control algorithm based on Park's transformation with the control law of the sliding mode controller to generate control signals of DVR. The proposed control strategy improves the power quality by compensating a variety of power quality issues like voltage sag, transients and harmonics effectively as compared to a traditional approach. Even the need for an accurate mathematical model is reduced by using a sliding mode controller. Simulation analysis confirms the usefulness of the proposed control strategy and comparative study has been carried out. THD of the system without sliding mode DVR and with sliding mode-controlled DVR depicts the robustness of sliding mode control approach. The same control can be used to compensate for any variation in load voltage.

REFERENCE

[1] Rammohan rao Erabelli, Y.Y. kolhatkar, "Experimental investigation of DVR with Sliding Mode Control," 2006 IEEE Power India Conference, New Delhi ,2006, pp.5

[2] Soumya Ranjan Das, Prakash K.Ray, Asit Mohanty," Enhancement of Power Quality Disturbances Using Hybrid Power Filters," 2017 International Conference On circuit, Power and Computing Technologies [ICCPCT] kollam, 2017, pp. 1-6.

[3] G.V.Nagesh Kumar and D.Deepak Chowdary, "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, Kharagpur, India December 8-10,2008, pp. 1-4.

[4] P.K. Nandan and P.C.sen," Comparative study of proportional integral proportional controllers for DC motor drives, "International Journal on control, vol 44, no 1, pp 283-297,1986

[5] P.C.Sen, "Electric motor drives and control-past, present and future" IEEE Trans. ind. electron. Vol 37, pp 562-575, DEC 1990.

[6] J.Fernando Silva, "control Methods for power converters," Hand Book of power electronics, M.H. Rashid (Editor),2002,pp 431-486

[7] G. Spiazzi," Application of sliding mode control to switch mode power supplies ", website of dept of electrical engineering University of Padova (www.unipd.it)

[8] Sushree Diptimayee Swain, Pravat kumar Ray, member IEEE and Kanungo Barada Mohanty, senior member, IEEE," Improvement of power quality using a robust hybrid series active power filter," IEEE trans. on power electronics, Vol 32 no. 5 pp. 3490-3498, May 2017.