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Comparative study of Power Quality Enhancement Using SRF Theory, SMC & TSMC Controlled Dynamic Voltage Restorer

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***Abstract*— In the present year we face the power system issues, one of the major power system problem is associated to power quality. Power quality issue is an occurred due to a current, variable voltage or variable frequency so the failure occurred in at load side voltage. One of the sever issue related to power quality is power sag. To resolve this problem, the Dynamic Voltage Restorer (DVR) is used, which is one of the most methodical and potent modern custom power device exploit in power distribution networks to solve power quality issue.**

The advantages of DVR is its smaller in size, lower in cost, and its fast-in dynamic response to the external disturbance. In this research paper modeling, analysis, simulation and comparative study between 3 different control methods which are -1) SRF theory – it contain Park's transformation controlled Dynamic Voltage Restorer (DVR), 2) sliding mode control (SMC) - it is the combination of SRF theory & SMC, & 3) Terminal sliding mode control – it is the combination of robust and SMC, finite time convergence for fast response, high accuracy and strong robustness by using a MATLAB (2018) Simulink model.

Keywords: ***Power Sag,* DVR (*Dynamic voltage restorer), SRFT (synchronous reference frame theory), SMC (Sliding mode control) TSMC (Terminal Sliding mode controller), voltage sag, MATLAB simulation.***

I. INTRODUCTION

In the power system, the power quality issues analogous to voltage sag, voltage swell, harmonics. voltage sag is the most extreme severe disturbance in the distribution network. To reduce voltage sag custom power devices are used. [1]. DVR is one of the modern custom devices, which is the most proficient and compelling.

DVR is solid-state device which is associated in series, the device inject voltage into the distribution network system to control the load-side voltage. DVR is usually introduced in a distribution network system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and voltage swells compensation, DVR also has different attribute like line voltage harmonic settlement, a decrease of transients in voltage and fault current limitations.

The Dynamic Voltage Regulator (SAPF/ DVR) contain of a Voltage-Source Inverter (VSI) with a depot element on the DC side. The capacity of the DVR to eliminate low-frequency events is exclusively a result of the control algorithms used to get components of a reference voltage.

A DVR is a conventional power device which acts as a harmonic isolator to obstruct the harmonics in the source voltage transpire at the load as well as balancing the voltages and furnish voltage regulation.

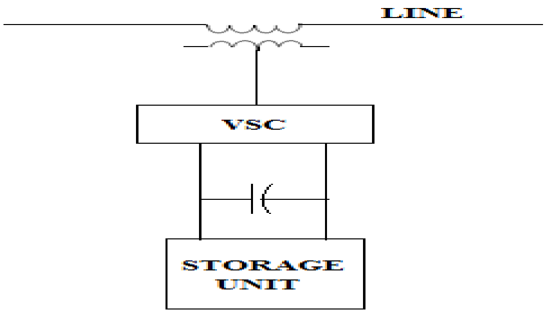

Fig: 1: DVR-Series connected system

II. DYNAMIC VOLTAGE REGULATOR (DVR)

The Dynamic Voltage Regulator (SAPF/ DVR) contain Voltage-Source Inverter (VSI) with DC side depot element. The VSI is associate in a series with the network through an isolation transformer. Shown in fig.2, the regulator behaves as a controllable source of reactive power to accomplish desired voltage regulation. [5] The capacity of SAPF/DVR to diminish low frequency components because of the control technique exploits to pull out components of reference voltage.

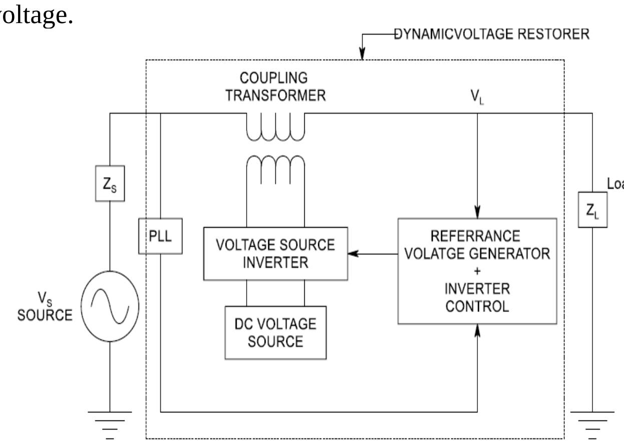

Fig. 2 Dynamic Voltage Restorer

There are main two theories initiate for appliance these control methodology.

1) Instantaneous Reactive Power Theory (IRPT) 2) Synchronous Reference Frame Theory (SRFT).

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In this paper SRFT for control of DVR with an additional attribute of the Selective Harmonic Compensation to enable DVR as power conditioning device.

The main components of DVR:

First components is-An Injection transformer, second is- DC charging element, third is- depot Devices, fourth is- A Voltage Source Converter (VSC) , fifth is- Harmonic filter and sixth is- A Control and Protection system

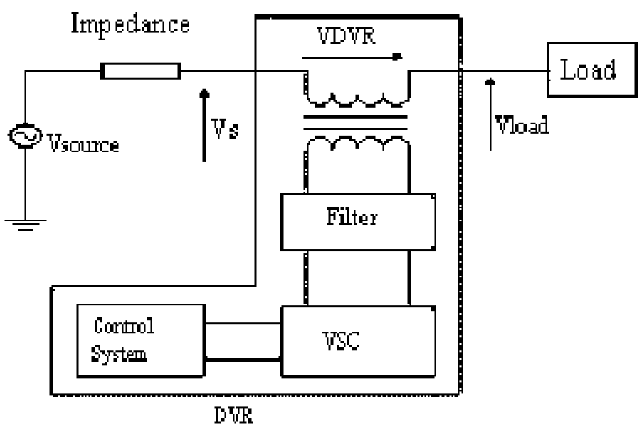

Fig.3. Diagram of Dynamic Voltage Restorer

III. METHOD OF CONTROLLING

i) Sliding-mode Controller Design of DVR

The averaged model of DVR based Sliding Mode Controller.

To facilitate the controller, the HSAPF system model can be defined as

$$\dot{x} = f(x) + g(x) * u$$
$$y=h(x) \qquad (1)$$

Where,

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

It is seen from the differential equations that first-time derivatives of output($dVcd/dt$) and($dVcq/dt$) does not explicitly contain control variables(μd) and (μq). Thus we differentiate the compensating voltages concerning the time until the control variables appear explicitly which leads us to follow equations such as,

$$\frac{d^2V_{cd}}{dt} = -\omega^2 v_{cd} - \omega\frac{i_{cq}}{cf} + \omega\frac{i_{sq}}{cf} - \frac{V_{cd}}{Lfcf} - \omega\frac{i_{cq}}{cf} - \frac{\mu dV_{dc}}{Lfcf} + \frac{di_{sd}}{dt} * \frac{1}{cf} \quad \ldots.(2)$$

$$\frac{d^2V_{cq}}{dt} = -\omega^2 v_{cq} - \omega\frac{i_{cd}}{cf} + \omega\frac{i_{sd}}{cf} - \frac{V_{cq}}{Lfcf} - \omega\frac{i_{cd}}{cf} - \frac{\mu qV_{dc}}{Lfcf} + \frac{di_{sq}}{dt} * \frac{1}{cf} \quad \ldots\ldots\ldots.(3)$$

The equation (2-3), shows that 2nd derivative term of the output depends on control inputs (μd) and (μq). No further time derivative is required. Using equation (1) sliding mode controller is designed. To force the compensating voltages Vcd, Vcq is nothing but the control purpose of the DVR system. [7] Sliding surface mathematical expressions is as follows:

$$\bar{S} = \begin{bmatrix}\bar{S}_d \\ \bar{S}_q\end{bmatrix} \quad \ldots\ldots.(4)$$
$$\bar{S} = S + \gamma\dot{S} \quad \ldots\ldots(5)$$
$$\overline{S_d} = \dot{S}_d + S_d \quad \ldots\ldots\ldots..(6)$$
$$\overline{S_q} = \dot{S}_q + S_q \quad \ldots\ldots.(7)$$

Substituting values of $Vcompd$ and Vcq in equations (6) and (7) and using the design process of sliding mode controller which is represented as,

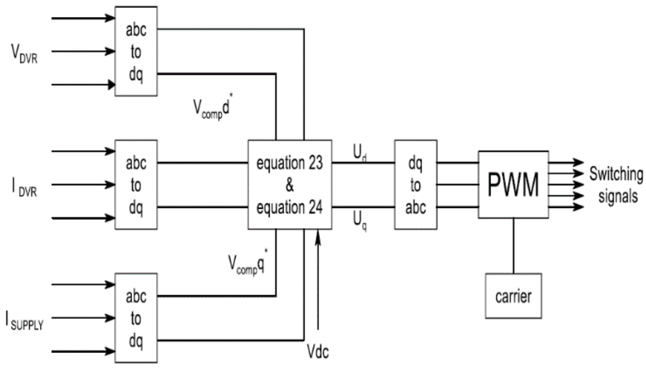

Fig: 4: Sliding-mode Control Strategy of DVR

$$\dot{\bar{S}} = 0 \quad \ldots\ldots\ldots (8)$$
$$\dot{\overline{S_d}} = 0 \quad \ldots\ldots\ldots\ldots. (9)$$
$$\dot{\overline{S_q}} = 0 \quad \ldots\ldots (10)$$

Using the equations (9) and (10) and substituting appropriate values from output equations the equivalent control law in d and q domain is obtained as

$$\mu_{eq} = -\left(\dot{V}_{cd^*} + \ddot{V}_{cd^*}\right) + \frac{Lf}{V_{dc}}(cf\omega V_{cd} - i_{cd} + i_{sd}) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{cd} - \omega i_{cq} + \omega i_{sq} - \frac{V_{cd}}{Lf} - \omega i_{cq} + i_{sq}\right) \quad \ldots..(11)$$

$$\mu_{eq} = -\left(\dot{V_{cq^*}} + \ddot{V_{cq^*}}\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{cq} - i_{cq} + i_{sq}\right) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{cq} - \omega i_{cd} + \omega i_{sd} - \frac{V_{cq}}{Lf} - \omega i_{cd} + i_{sq}\right) \quad \ldots (12)$$

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

$$U = \mu_{eq} + \mu_{sw} \quad \ldots\ldots\ldots (13)$$

Putting the values of μdeq and μqeq the nonlinear control law in d-q domain is as follows

$$\mu_d = -\left(\dot{V_{cd^*}} + \ddot{V_{cd^*}}\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{cd} - i_{cd} + i_{sd}\right) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{cd} - \omega i_{cq} + \omega i_{sq} - \frac{V_{cd}}{Lf} - \omega i_{cq} + i_{sq}\right) - \varepsilon_{11} signal(S_d) - \varepsilon_{11} signal(\dot{S_d}) \quad ..(14)$$

$$\mu_q = -\left(\dot{V_{cq^*}} + \ddot{V_{cq^*}}\right) + \frac{Lf}{V_{dc}}\left(cf\omega V_{cq} - i_{cq} + i_{sq}\right) + \frac{\gamma Lf}{V_{dc}}\left(-cf\omega^2 V_{cq} - \omega i_{cd} + \omega i_{sd} - \frac{V_{cq}}{Lf} - \omega i_{cd} + i_{sq}\right) - \varepsilon_{11} signal\left(S_q\right) - \varepsilon_{11} signal\left(\dot{S_q}\right) \quad \ldots. (15)$$

Switching law for the controller can be shown as

$$\mu_{eq} = \mu_{sw}$$

$$\mu_{eq} = \begin{cases} +1, when\ S > 0 \\ -1, when\ S < 0 \end{cases} \quad \ldots (16)$$

ii) Terminal Sliding Mode Control-

TSM is non-linear robust control system approach. In Conventional sliding mode controller convergence time is infinite. In the TSM controller, a nonlinear term of system is introduced in the sliding surface design therefore multiple is formulated as an attractor.

TSMC (Terminal Sliding Mode Control) advanced structure of the CSMC (Conventional SMC) to gain finite time convergence to the steady state condition. TSMC give rise to a robust control with tuneable finite time convergence for strong robustness, fast response and high accuracy. Robust control has high gain feedback so effect of any disturbance parameter on a system is negligible. In the robust control the system is stable after the disturbance occurred. [9]

The difference resides in the many where the system trajectories slide, by changing the linear hyper planes of the CSMC (Conventional Sliding Mode Control) to nonlinear switching surfaces in TSMC (Terminal Sliding Mode Control). With these new changes, TSMC maintain all the benefits of the CSMC (Conventional Sliding Mode Control) but achieves finite time convergence to the origin.

Consider a canonical form of continuous nonlinear system

$$\dot{x_1}(t) = x_2(t) \quad \ldots\ldots\ldots. (17)$$

$$\dot{x_{n-1}}(t) = x_n(t) \quad \ldots\ldots\ldots. (18)$$

$$\dot{x_n}(t) = \alpha(x) + b(x) * u(t) \quad \ldots\ldots..(19).$$

Where x (t) ∈ R^n is the state vector, u ∈ $R$is the control input, $\alpha(x)$ and $b(x)$ are nonlinear functions in x(t). Then a sequence of TSMS can be designed as follows:

$$s_1(t) = \dot{s_0}(t) + \alpha_1(t) * s_0^{\gamma 1}(t)$$

$$s_2(t) = \dot{s_1}(t) + \alpha_2(t) * s_1^{\gamma 2}(t) \ldots$$

$$s_{n-1}(t) = \dot{s_{n-2}}(t) + \alpha_{n-1}(t) * s_{n-2}^{\gamma n-1}(t) \quad (20)$$

Where $s_0(t) = x_1(t)$and $\gamma_i = \frac{p_i}{q_i}$..

i = 1, 2, …… (n-1) and$p_i . q_i$ Are positive odd numbers and$p_i \leq q_i$...

IV. SIMULATION & RESULTS

The simulation study gives the comparative study of the system without sliding mode DVR, system with sliding mode-controlled DVR and terminal sliding mode-controlled DVR. The comparative analysis is done by observing a reduction of supply voltage harmonics and voltage sag restoration ability.

1) Simulink model for system with DVR without sliding mode control

The Simulink model for system with DVR is shown in the following figure 8. DVR part in the Simulink model consist of control technique block- for controlling inverter operation i.e. to control voltage, IGBT based Inverter- for injecting voltage in the system , LC filter- for removing harmonics generated in the system and 1:1 isolation transformer- for providing isolation. The control technique is based on the SRF theory i.e. Synchronous Reference Theory... The control technique is based on Park's transformationi.ie. Covert abc parameter to dq parameter for easier control and inverse Park's transformation to convert dq to abc parameter. We can independently control active (d) and reactive (q) components of current and voltage. Is shown in the figure 5

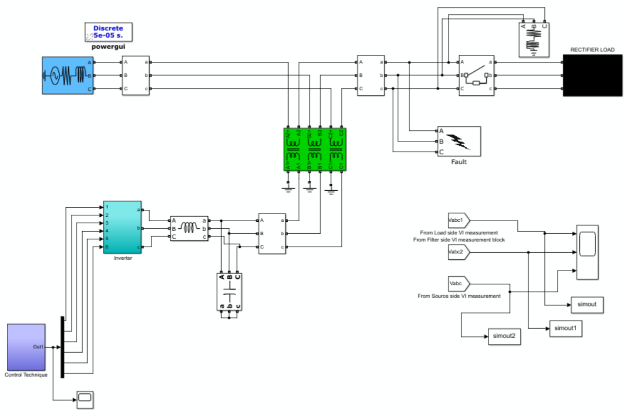

Fig: 5: Simulation diagram of System with DVR

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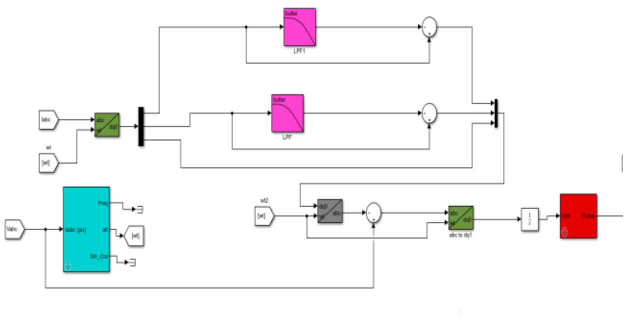

Fig: 6: Control Algorithm for System with DVR

In this model also a three phase fault is created from (0.4 sec) to (0.5 sec) .and analysis the results i.e. The load voltage, DVR's injected voltage and restored supply voltage are shown in below figure, the figure numbers are fig.- 6 (a) fig.- 6 (b) and fig.- 6 (c) respectively.

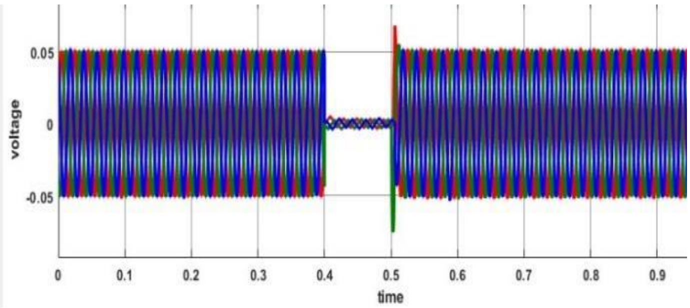

Fig: 6 (a): Load Voltage due to Fault on Load side

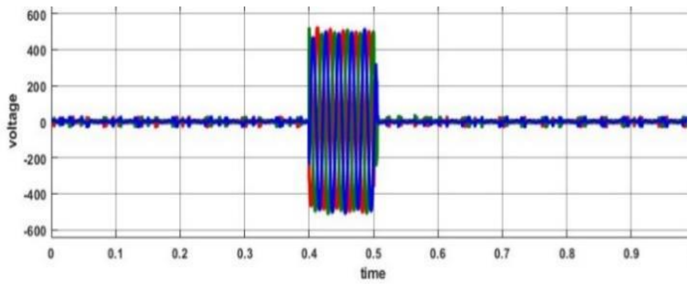

Fig: 6 (b): Injected Voltage by DVR

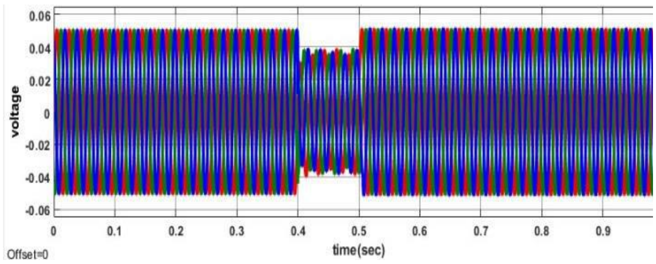

Fig: 6 (c): Restored supply voltage

Figure 6(a) to figure 6(c) shows that during fault condition the voltage will restore by injecting opposite phase voltage in the system. The supply voltage is restored to some extent than that of the uncompensated system but the sag isn't restored totally likewise the voltage harmonics are presents along with transients present in supply voltage which shows that functioning of DVR is not satisfactory or the results of SRF theory is not good.

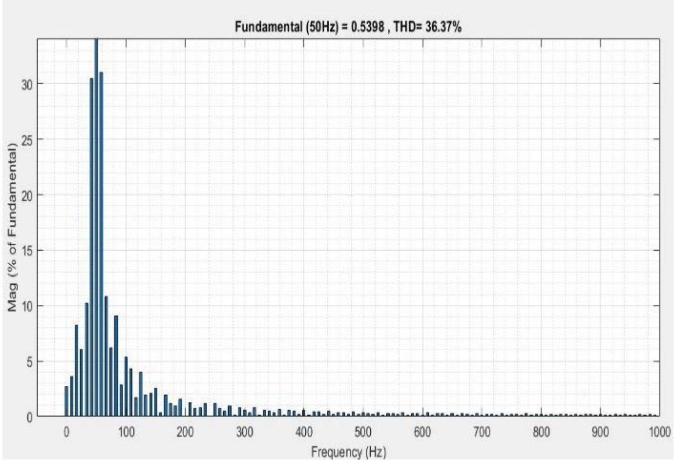

Fig: 7: Load Voltage THD during Sag

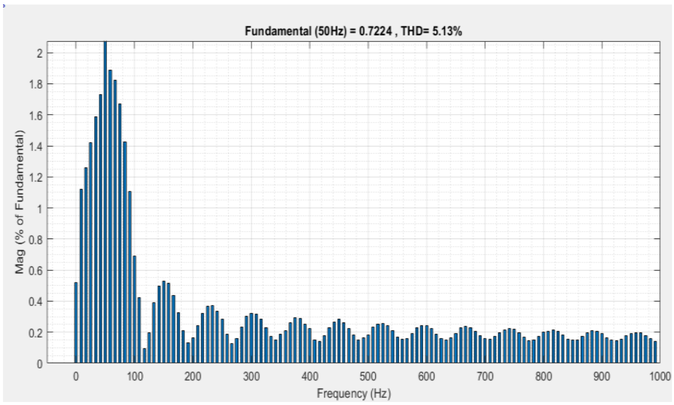

Fig: 8: THD of Restored Supply Voltage

From figure (7) it shows the load voltage THD is 36.37% during sag period and from figure (8) shows the THD of restored supply voltage without SMC DVR it is reduced to 5.13%

2) Simulink model for system with Sliding mode-controlled DVR

To reduce the voltage THD the system is simulated utilizing a SMC algorithm. The supply voltage is restored with SMC DVR. Proposed control Strategy is explained earlier and the same is applied in the Simulink model. The proposed control technique is- first convert Supply current, injected current and injected voltage are first converted abc to dq domain using Park's Transformation second step all converted parameter given to sliding mode equations and then the output from sliding mode equation which is in dq domain so again it converted into abc domain using inverse Park's transformation. By Using PWM technique the switching signals are provided to the Inverter.

Simulation parameters:

Source Voltage (Vims) = 400V, Fundamental frequency = 50 Hz, Three phase Fault Resistance = 1Ω, source impedance (X/R) ratio = 7, Passive filter inductance = 1.35mH, Passive filter capacitance= 60μF, Series filter inductance= 1.35mH, Series filter capacitance = 60μF, Carrier switching frequency = 2 kHz.

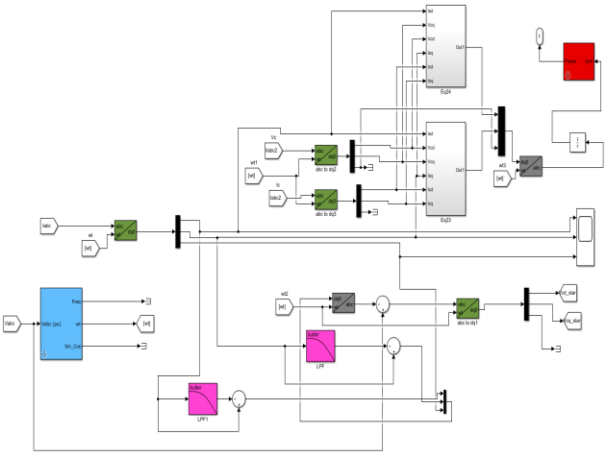

Fig: 9. Simulation diagram for Sliding-mode Controlled DVR

Fault created from 0.4 sec to 0.5 sec for same system to check control operation. The load voltage reduced due to fault on the load side, load side voltage will improve by injected voltage by DVR and restored supply voltage due to sliding-mode controlled DVR is shown in following figure from fig.10 (a), to fig.10 (c) respectively.

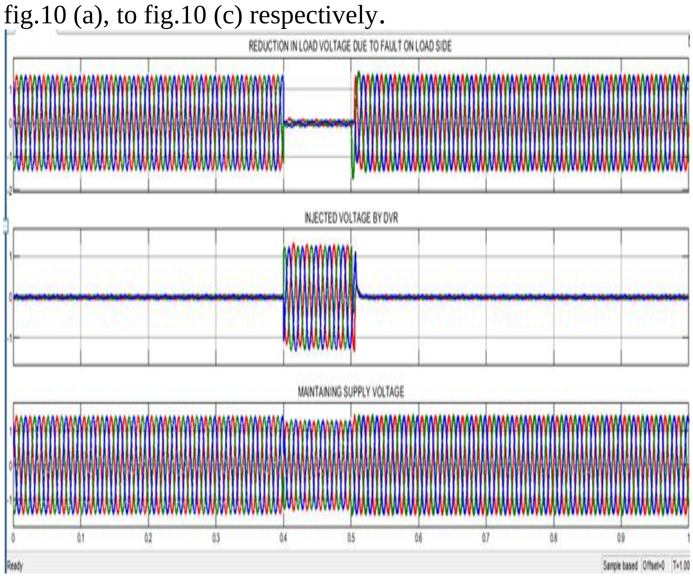

Fig: 10. (A): Load Voltage due to Fault on Load side
(b): Injected Voltage by DVR, (c): Restored supply voltage using Sliding-mode Controlled DVR

It is concluding from the above results that the supply voltage is an improved and the transients of the voltage are reduced as compared to DVR system without SMC. The following figure 11 shows THD of supply voltage with sliding-mode controlled DVR. From the figure that the supply voltage THD is 4.32 % for SMC DVR system.

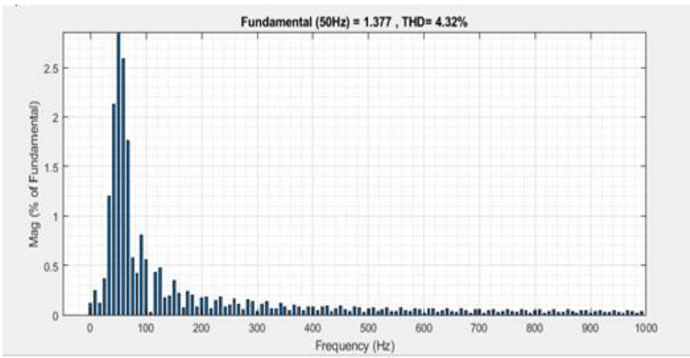

Fig: 11: THD of Restored Supply Voltage with Sliding-mode Controlled DVR

3) Simulink model for system with DVR Terminal Sliding Mode Control

Terminal Sliding Mode Control-(TSMC) is advanced structure of the CSMC i.e. Conventional Sliding Mode Control to achieve finite time convergence to the steady state condition. Terminal sliding model control is combination of two controller, i.e. robust control and conventional sliding mode control. Robust control system is used to remove uncertainty in the system or remove disturbances present in system. System will be stable after clearing fault by controller due to its robust nature. So we get better results by using TSMC as compare to SMC and SRFT.

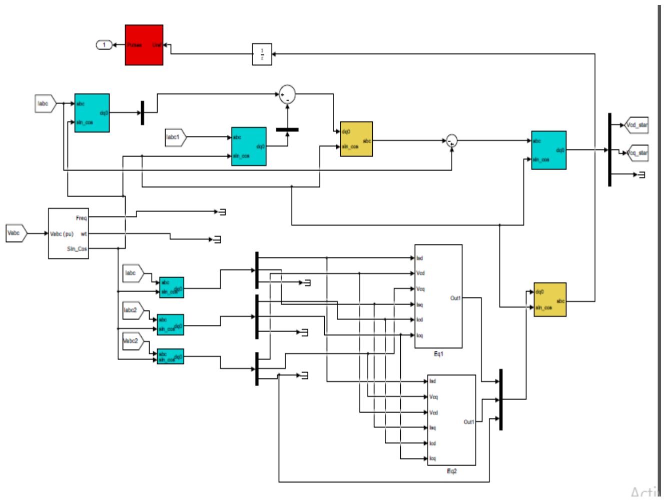

Fig: 12: Control method for System with TSMC DVR

A figure 12 shows the control method of TSMC-DVR Proposed control Strategy is explained earlier and the same is applied in the Simulink model. The proposed control technique is- first convert Supply current, injected current and injected voltage are first converted abc to dq domain using Park's Transformation second step all converted parameter given to terminal sliding mode equations and then the output from sliding mode equation which is in dq domain so again it converted into abc domain using inverse Park's transformation. By Using PWM technique the switching signals are provided to the Inverter.

Fault created from 0.4 sec to 0.5 sec for same system to check control operation. The load voltage reduced due to

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fault on the load side, load side voltage will improve by injected voltage by DVR and restored supply voltage due to sliding-mode controlled DVR is shown in following figure from fig.13 (a), to fig. 13 (c) respectively.

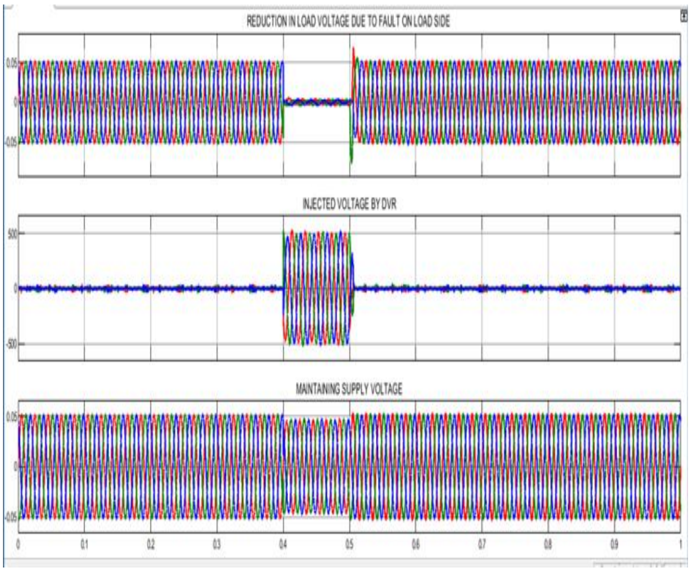

Fig: 13. (a): Load Voltage due to Fault on Load side(b): Injected Voltage by DVR ,(c): Restored supply voltage using Terminal Sliding-mode Controlled DVR

The following figure 7 shows THD of supply voltage with terminal sliding-mode controlled DVR. From the figure 14. that the supply voltage THD is 3.88 % for TSMC DVR system.

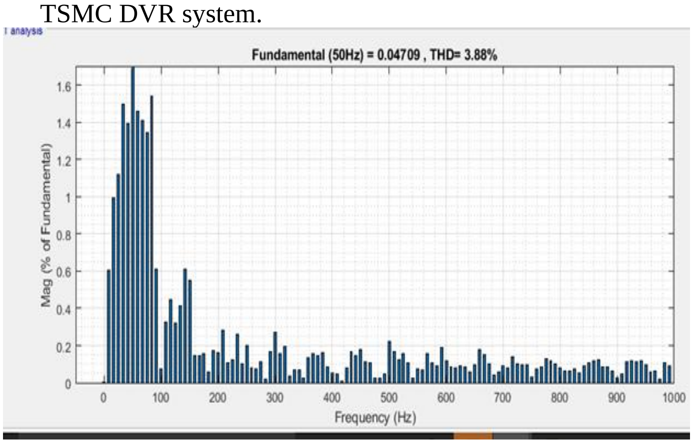

Fig: 14: THD of Restored Supply Voltage with terminal Sliding-mode Controlled DVR

V. CONCLUSION:

The DVR is cost- effective solution to mitigate voltage disturbances. A sliding mode-controlled DVR is used for to remove power quality problems. The TSMC control technique is used to remove power quality problem with robust nature because TSMC is combination of two controller, i.e. robust control (RC) and sliding mode control (SMC).

The proposed technique of control is based on SRF theory with the control law of the SMC and TSMC (robust + SMC) generate control signals of DVR. The all three control method explain in this paper will enhances the power quality by compensating a different kinds of power quality problems such as voltage swell, voltage sag, harmonics and transients.

The simulation results for different methods-

1) Without SMC DVR (**SRF theory**) - System THD is reduced up to **5.13%**
2) With **SMC DVR**- System THD is reduced up to **4.32%**
3) **TSMC DVR**- System THD is reduced up **to 3.88%**

From simulation results the efficient method is **TSMC DVR** as compare to SMC DVR and SRFT DVR.

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