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Simulation-based analysis of dynamic voltage restorer with sliding mode controller at optimal voltage for power quality enhancement in distribution system

Introduction. *Nowadays, power quality issues are of considerable interest to both utilities and end users as they cause significant financial losses to the industrial customers. Due to this, power quality assurance in power distribution systems is very important, when considering commercial and industrial applications.* ***Problem Statement.*** *Unfortunately, sudden faults such as sag, transients, harmonics distortion and notching in the power system create disturbances and affect the load voltages. Out of these, voltage sag and harmonics seriously affect sensitive devices. Harmonics in the power system cause increased heating of equipment and conductors, misfires in variable speed drives, and torque pulsations in motors. Harmonics reduction is considered desirable.* ***Methodology.*** *This paper presents an efficient and robust solution to this problem by using dynamic voltage restorer in series with distribution system. Dynamic voltage restorer is economical and effective solution for protecting sensitive loads from harmonics and sag. Control strategy is adopted with dynamic voltage restorer topology and the performance with the proposed controller is analyzed.* ***Novelty.*** *In this research work modelling, analysis and simulation of dynamic voltage restorer with proportional integral controller and dynamic voltage restorer with sliding-mode controller at optimal voltage is used to improve the dynamic voltage restorer performance by reducing total harmonic distortion.* ***Results.*** *The simulation is performed in MATLAB / Simulink software package and comparative analysis of dynamic voltage restorer with different controllers for distribution system is presented. The proposed scheme successfully reduced percentage total harmonics distortion and voltage sag using dynamic voltage restorer with sliding mode controller at optimal voltage which is found to be 0.38 %.* References 22, tables 1, figures 19.
Key words: **dynamic voltage restorer, sliding-mode controller, total harmonics distortion, voltage sag, power quality improvement**.

Вступ. *Сьогодні питання якості електроенергії викликають значний інтерес як для комунальних підприємств, так і для кінцевих споживачів, оскільки вони завдають значних фінансових втрат промисловим споживачам. У зв'язку з цим забезпечення якості електроенергії в розподільних системах є дуже важливим при розгляді комерційних та промислових застосувань.* ***Постановка задачі***. *На жаль, раптові несправності, такі як прогини, перехідні процеси, спотворення гармонік і виїмки в енергосистемі створюють збурення та впливають на напругу навантаження. З них провали напруги та гармоніки серйозно впливають на чутливі пристрої. Гармоніки в енергосистемі викликають посилений нагрів обладнання та провідників, пропуски запалювання в приводах із змінною частотою обертання, пульсації крутного моменту в двигунах. Зниження гармонік вважається бажаним.* ***Методологія***. *У цій статті представлено ефективне та надійне рішення цієї проблеми за допомогою динамічного відновника напруги послідовно з розподільною системою. Динамічний відновник напруги – це економне та ефективне рішення для захисту чутливих навантажень від гармоній та провисань. Прийнято стратегію керування з топологією динамічного відновника напруги та проаналізовано ефективність при використанні запропонованого контролера.* ***Новизна***. *У цій дослідницькій роботі використовується моделювання, аналіз та чисельне дослідження динамічного відновника напруги з пропорційним інтегральним контролером та динамічного відновника напруги з регулятором ковзного режиму при оптимальній напрузі для підвищення ефективності динамічного відновника напруги за рахунок зменшення сумарних гармонійних спотворень.* ***Результати***. *Моделювання виконано в програмному комплексі MATLAB / Simulink та представлено порівняльний аналіз динамічного відновника напруги з різними контролерами для розподільчої системи. Запропонована схема успішно зменшила відсоток спотворення сумарних гармонік і провалів напруги за допомогою динамічного відновника напруги з регулятором ковзного режиму при оптимальній напрузі, який становить 0,38 %.* Бібл. 22, табл. 1, рис. 19.
Ключові слова: **динамічний відновник напруги, регулятор ковзного режиму, загальні гармонічні спотворення, провал напруги, покращення якості електроенергії**.

1. Introduction. Nowadays, power quality issues are of considerable interest to both utilities and end users as they cause significant financial losses to the industrial customers. Due to this, power quality assurance in power distribution systems is very important when considering commercial and industrial applications. Unfortunately, sudden faults such as sag, transients, harmonics distortion and notching in the power system create disturbances and affect the load voltages. Out of these, voltage sag and harmonics seriously affect sensitive devices. Harmonics in the power system cause increased heating of equipment and conductors, misfires in variable speed drives, and torque pulsations in motors. Harmonics reduction is considered desirable. Voltage total harmonics distortion (THD) also plays very important role in a power system and power quality. According to standard of IEEE 519-1992, the value of THD should be equal or less than 5 % of the fundamental frequency. Standard of IEEE 1152-1995 define the voltage sags root mean square i.e. RMS voltage variation having a magnitude in between (0.1-0.9) p.u. of value of nominal voltage and its duration typically varies from 0.5 cycle to 60 s. Installation of custom power device, voltage mitigation or compensation can be achieved to remove/cancel out the disturbances at the load side [1, 2]. Number of customized power devices are obtainable each having its own Pros and Cons for voltage reduction compensation such as DSTATCOM, Superconducting Magnetic Energy Storage (SMES), Dynamic Voltage Restorer (DVR) and Static VAR Compensation (SVC).

DVR refers a controllable voltage source usually inserted between the sensitive load voltage and network, which accurately generates a disturbance that perturbs the sensitive load voltage by inserting the voltage into the distribution line through a transformer. Lead-acid battery-powered DVRs are the best and most attractive technology, providing superior dynamic voltage restoration compared to shunt-connected devices. The main function of a voltage source inverter power system equipped with a DVR is to inject the desired three-phase voltage into the load [3, 4]. In this paper modelling, analysis and simulation of DVR with PI controller and DVR with Sliding-Mode Controller (SMC) at optimal voltage is used to reduce THD to improve DVR performance. DVR with SMC at optimal V_{dc} has successfully reduced THD and voltage sag to 0.38 %.

2. Dynamic Voltage Restorer. DVR is a series connected power electronics switching device and is connected in series with the distribution line to inject the desirable controlled voltage. The DVR includes injection transformer, harmonic filter, voltage source inverter, control unit and DC storage unit [3-7].

The heart of DVR is the control unit, which is mainly used to monitor the presence of drop in voltage in the network and if necessary to compensate/insert the missing voltage after determining its phase and magnitude. Control unit has a reference voltage (V_{ref}) structure for the purpose of comparison. A three-phase reference voltage scheme is used as a reference in a dynamic voltage restorer. However, the V_{ref} three-phase voltage must be needs to synchronize with the load voltage (V_L) to correctly inject the missing voltage based on magnitude and phase. Simulink diagram for obtaining the reference waveform of voltage is shown in Fig. 1.

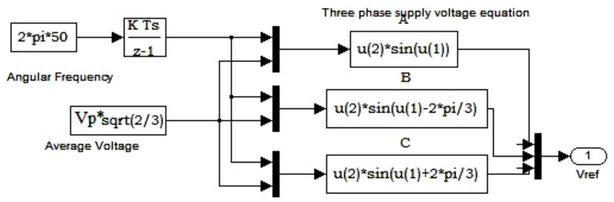

Fig. 1. Simulink reference voltage diagram

In the control unit, a Park transformation also known as direct-quadrature-zero ($dq0$) transformation has been used to control the DVR. The 3-phase system is more of a simplified system, and it can easily be controlled after transformation from 3-phase abc voltage to two voltage components i.e. V_d and V_q. The V_0 which is zero sequence components are ignored for simplicity

$$\begin{vmatrix} V_d \\ V_q \\ V_0 \end{vmatrix} = \frac{1}{3} \cdot |M| \cdot \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix}, \qquad (1)$$

where M is as follow

$$\begin{vmatrix} V_d \\ V_q \\ V_0 \end{vmatrix} = \frac{1}{3} \cdot \begin{vmatrix} 2\sin\omega t & 2\sin\left(\omega t - \frac{2\pi}{3}\right) & 2\sin\left(\omega t + \frac{2\pi}{3}\right) \\ 2\cos\omega t & 2\cos\left(\omega t - \frac{2\pi}{3}\right) & 2\cos\left(\omega t + \frac{2\pi}{3}\right) \\ 1 & 1 & 1 \end{vmatrix} \cdot \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix}, \qquad (2)$$

where ω is the angular frequency.

There are two modes of DVR which are given below.

In first injection mode, voltage inject operation has been done using DVR to correct the sag. While in the second mode, monitoring operation is usually done in standby mode [8-10]. So, there is no type of other voltage is being injected. Injected transformer low voltage side is shorted using the voltage source inverter. The sag voltage, DVR voltages and load current are written as

$$I_L = (P_L + jQ_L)/V_L; \qquad (3)$$

$$V_{DVR} = V_L + (Z_S \times I_S) - V_S; \qquad (4)$$

$$V_{SAG} = V_S - (I_L \times Z_S), \qquad (5)$$

where I_L is the load current; P_L, Q_L are load active and reactive powers respectively; V_L, V_S are the load and supply voltages respectively; Z_S, I_S are source impedance and current respectively; V_{DVR} is the injection voltage by DVR and V_{SAG} is sag voltage.

The equivalent circuit of the power system under study is shown in Fig. 2 and phasor diagram of distribution system with DVR is shown in Fig. 3 [11, 12].

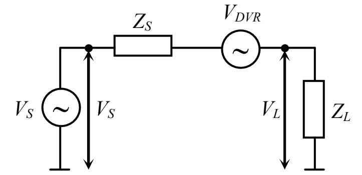

Fig. 2. Equivalent circuit of the power system under study

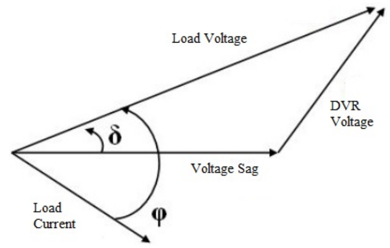

Fig. 3. Phasor diagram of distribution network using DVR

3. DVR with PI controller. The DVR plays a key role in detecting voltage sag events, correcting voltage sag problems, and generating Pulse Width Modulation (PWM) trigger pulses. The control unit generates a three-phase V_{ref} and compares the V_L to the V_{ref} value [13]. An error signal is generated when voltage is missing from the power system due to voltage sag. If the difference between V_{ref} missing V_L is equal to the error signal, the DVR starts to work and injects the missing voltage into the power distribution network. That is, an error signal is transmitted to the PI controller and then PI controller output is converted back to a Park transformation. The signal is transmitted in a discrete pulse width modulation block. Discrete PWM compares the input three-phase converted signal to a saw tooth wave and the PWM generates a pulse to trigger the PWM V_S (voltage source) inverter with the desired firing arrangement. The DVR collects the required direct current voltage from the storage device (e.g. 500 V). A voltage source inverter is used to invert the DC storage unit voltage to an AC voltage, and eventually the missing voltage is injected through a three-phase injection transformer, which is then connected in series with the distribution line. The phase-locked loop for a DVR with PI controller is shown in Fig. 4 and the Simulink model is shown in Fig. 5.

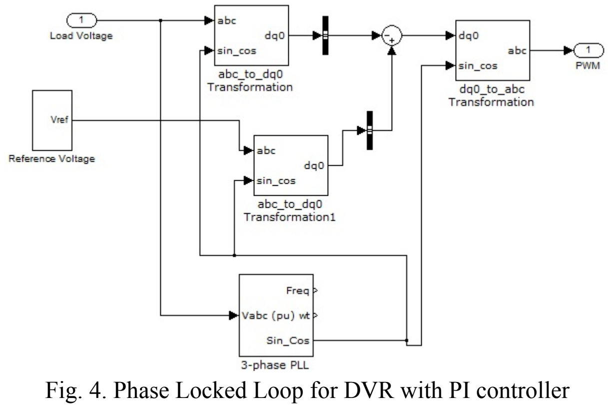

Fig. 4. Phase Locked Loop for DVR with PI controller

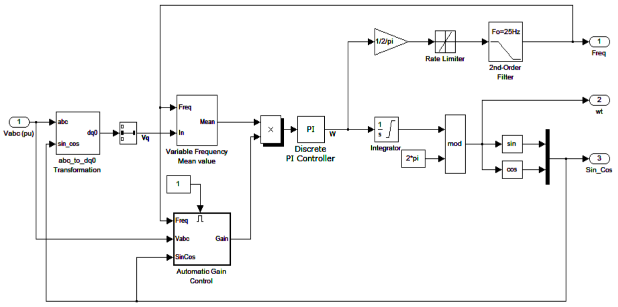

Fig. 5. Simulink Model of DVR with PI controller

4. Control circuit for DVR with SMC. SMC is a robust and nonlinear control scheme at which the arrangement of the controller is being modified in reaction to the varying state of the system to obtain a desire result. The control procedure for fast switching is used and the trajectory of the system is forced to move along the selected switching area in the state space [14].

There are three major advantages of SMC i.e. model reduction, performance design and robustness parameters. The *sliding phase* (S.P.) at which a system slides and properly to approach to zero to make the system stable i.e. $S = 0$ (S is the sliding surface variable). While a system approaches to sliding phase is known as *reaching phase* (R.P.) i.e. $S \neq 0$. Equation (6) gives the main equation of SMC

$$u = -sign(S); \tag{6}$$

$$S = \dot{x} + a \cdot x, \tag{7}$$

where $S = 0$ and a is the variable

$$\dot{x} = -a \cdot x, \tag{8}$$

Reachability phase is very simple and it says that any controller which obeys $S\dot{S} < 0$ will reach to sliding surface/phase. The system has an inertia due to which the reaching phase will little bit move forward as shown in Fig. 6.

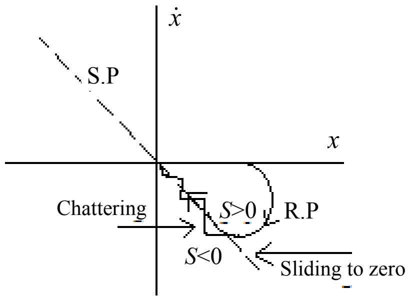

Fig. 6. Phase plot for actual SMC control

The control law determination of reaching phase is given below in (9) to maintain the system in the sliding surface and due to system inertia, the sliding mode trajectories often chatter back and forth motion along the sliding surface to reach the system at origin which is a chattering also known as oscillation [14]. The S and $\dot{S}$ signs are always opposite to each other and $\delta|t|$ is the switching function of the voltage source inverter i.e. 1 or –1

$$\delta|t| = \begin{cases} 1\,(\text{on time})\text{ for } S < 0; \\ -1\,(\text{off time})\text{ for } \dot{S} < 0. \end{cases}, \tag{9}$$

The equivalent circuit of the DVR has been checked and it is investigated that the DVR can work on the sliding surface and is following the rule of reaching phase $S{\cdot}\dot{S} < 0$ to reach at the sliding surface. The tracking error of injection voltage dynamics, when the system is on sliding mode, is stable and is given in (10) [4-6]

$$u_f = -V_d \cdot sign(S), \tag{10}$$

where u_f is control input to voltage source inverter; V_d is DVR voltage.

So, the voltage source inverter switches DC storage unit voltage according to sliding function. SMC was traditionally defined using the state space formulation and this practice continuous in sliding mode studies but in recent studies, sliding mode can also be attained by relay control system because this approach is very simple [15, 16]. The relay sliding mode controller does not compulsory any knowledge of system states and a complete system model is not required in relay sliding mode controller [17, 18]. SMC has been added at the end of Park transformation or dq0 to abc transformation. The error signal coming from dq0_to_abc transformation will become input of SMC which is being used to switch the inverter. We have tuned the SMC to reduce the THD to make our DVR valuable and effective [19-22]. Phase locked loop for DVR with SMC is shown in Fig. 7 and its Simulink model is shown in Fig. 8.

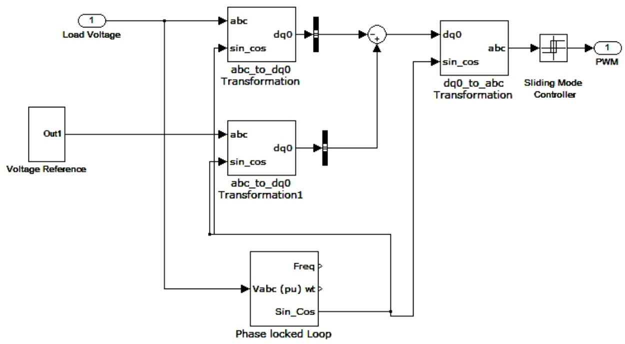

Fig. 7. Phase locked loop for DVR with SMC

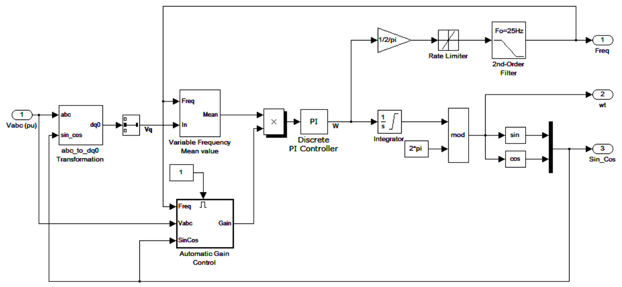

Fig. 8. Simulink model of DVR with SMC

5. Simulation and results. The power system parameters selected for the simulation are given in the Table 1.

Table 1. Power system and DVR parameters

Parameter	Value
Line resistance, Ω	1
Line inductance, mH	5
Line frequency, Hz	50
Filter series capacitance, F	100
Filer series resistance, Ω	1
Load phase voltage, V	220
Load power per phase, W	100
Load inductive reactive power per phase, kVar	0.2
DC supply voltage, V	500
Injection transformer turns ratio	1:1
Load capacitive reactive power per phase, kVar	0.5
Saw-tooth carrier wave frequency, Hz	5500

5.1. Test system with DVR for distribution system. Three phase power test system with DVR coupled with injection transformer is shown in Fig. 9.

The DVR coupling boost transformer is connected in delta in a voltage source inverter side. The 13 kV, 50 Hz three phase supply is step up using three phase transformer star/delta/delta, 13/66/66 kV feeding two transmission lines. Both transmission lines are step down to 380 V to drive the sensitive load and non-sensitive load. The performance of the system with DVR has been simulated and investigated under three phase short circuit fault.

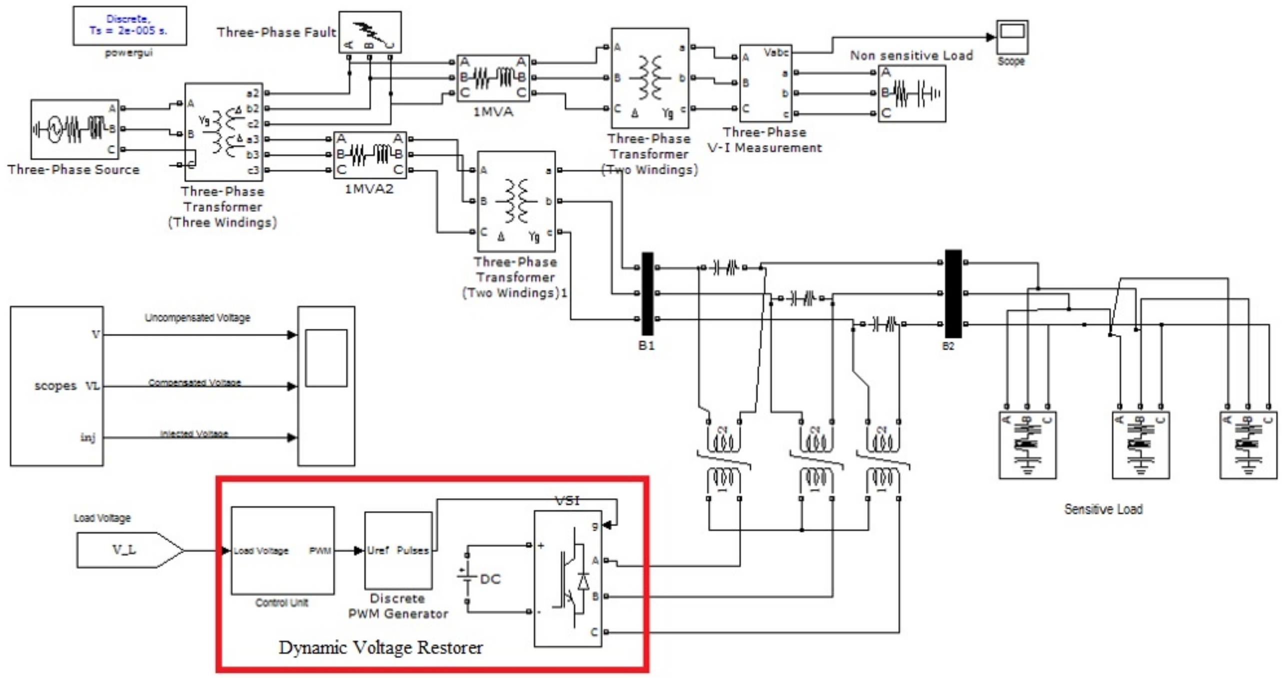

Fig. 9. Test System with DVR

5.2. Distribution system without DVR. The first simulation did not include a DVR and a three-phase fault was applied to one of the transmission lines, creating a voltage sag before the injection transformer through a fault resistor of 2 kΩ. A voltage drop event occurred on the transmission line for 0.05 to 0.185 s and the fault reduced the three-phase load voltage, which could disturb sensitive loads and cause system failure. Also, without a DVR, the voltage drop increased THD to 5.16 %. The load voltage obtained in this case is shown in Fig. 10 and the THD without DVR is shown in Fig. 11.

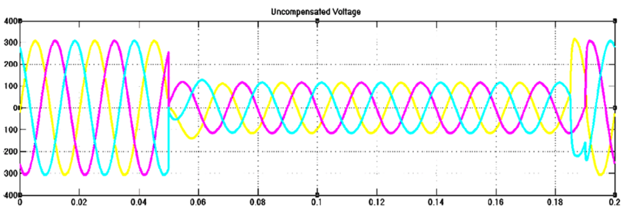

Fig. 10. Load voltage during fault without DVR

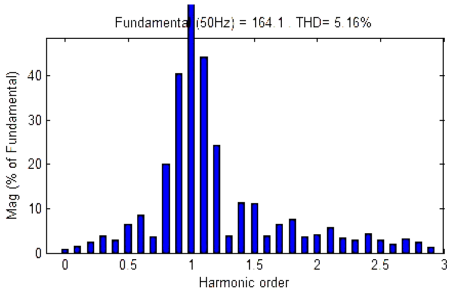

Fig. 11. THD during fault without DVR

5.3. Distribution system using DVR with PI controller. The second simulation is carried out using DVR based on PI controller which is connected to distribution system through an injection transformer. We have investigated that the missing voltage in the distribution line has been mitigated completely. Furthermore, THD has also been reduced as per power quality standard to 1.03 % with DVR with PI controller is shown in Fig. 12. Load voltage obtained in this case is shown in Fig. 13.

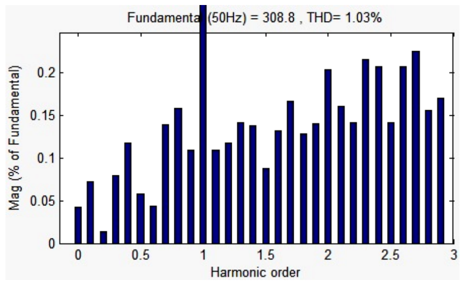

Fig. 12. THD during fault using DVR with PI controller

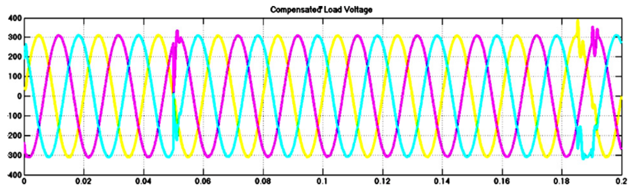

Fig. 13. Load voltage during fault with DVR using PI controller

5.4. Distribution system using DVR with SMC. The third simulation is being carried out using DVR with SMC which is connected to mitigate more voltage sag margin with reduction in THD. The load voltage obtained using DVR with SMC is shown in Fig. 14 and THD obtained in this case is shown in Fig. 15.

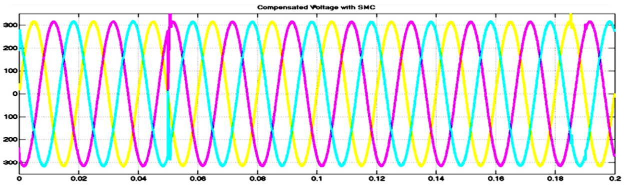

Fig. 14. Load voltage during fault using DVR with SMC

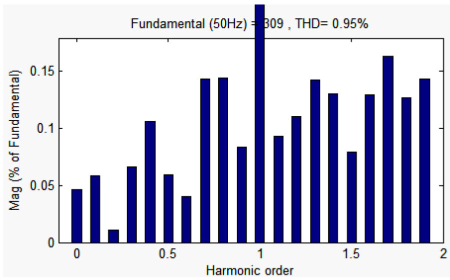

Fig. 15. THD during fault with DVR with SMC

5.5. Selection of optimal V_{dc} for THD reduction. The fourth simulation of DVR with SMC is based on the different values of V_{dc} to get optimal V_{dc} for THD reduction. The DC storage unit has a main impact on THD, we have simulated the DVR on different V_{dc} values and analyzed that at 1500 V storage unit, THD has been reduced to 0.44 %. Furthermore, we have changed the reference voltage i.e. 385 V and tuned on/off time of SMC i.e. 0.00001 s and –0.070 s then THD has been reduced from 0.44 % to 0.38 % as shown in Fig. 16. Load voltage obtained in this case is shown in Fig. 17 and THD is shown in Fig. 18.

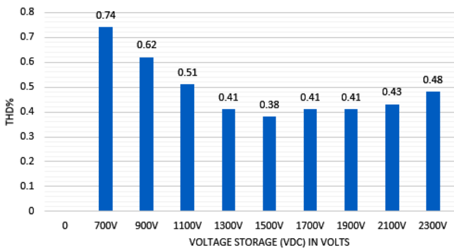

Fig. 16. Selection of optimal V_{dc} for THD reduction

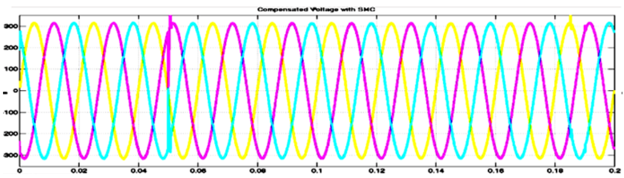

Fig. 17. Load voltage using DVR with SMC at optimal V_{dc}

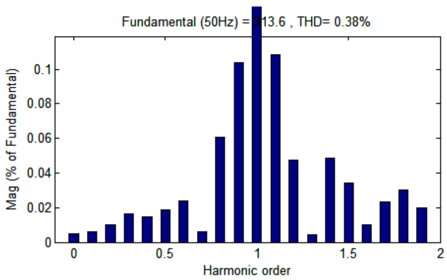

Fig. 18. THD for selected signal during fault using DVR with SMC at optimal V_{dc}

6. Comparative analysis of DVR with different controllers for distribution system. MATLAB / Simulink software package is employed to get a comparison of all the results offered by DVR with different controllers for distribution system. Initially, three phase fault has been applied in transmission line to create voltage sag. This fault has reduced the three-phase load voltage with increase of THD up to 5.16 %. The second simulation is carried out using DVR with PI controller which is connected to distribution system through an injection transformer. We have investigated that the missing voltage in the distribution line has been mitigated completely and THD has also been reduced to 1.03 % using DVR with PI controller. The third simulation is being carried out using DVR with SMC which is connected to mitigate more voltage sag margin with reduction in THD up to 0.95 %. Finally, DVR with SMC at optimal V_{dc} gives reduction of THD up to 0.38 %. The performance comparison of DVR with different controllers is shown in Fig. 19.

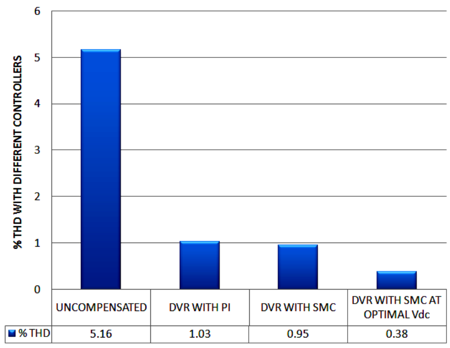

Fig. 19. Comparative analysis of DVR with different controllers for distribution system

Conclusions.

In this research paper, dynamic voltage restorer with PI controller and dynamic voltage restorer with sliding mode controller at optimal voltage V_{dc} is used to enhance the performance of dynamic voltage restorer by reducing THD. The effectiveness and performance of the proposed control scheme under voltage sag condition are examined. Simulation results shows that percentage total harmonic distortion and voltage sag are successfully reduced by using dynamic voltage restorer with sliding mode controller in distribution system under random fault condition. Percentage total harmonic distortion during fault using dynamic voltage restorer with PI controller, dynamic voltage restorer with sliding mode controller and dynamic voltage restorer with sliding mode controller at optimal voltage is 1.03 %, 0.95 % and 0.38 % respectively. It is obvious that dynamic voltage restorer with sliding mode controller at optimal value of voltage V_{dc} can mitigate the voltage sag very quickly with minimum percentage total harmonic distortion as compared to dynamic voltage restorer with PI controller to keep the voltage balance under fault events circumstances.

Conflict of interest. The authors declare that they have no conflicts of interest.

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