Power Quality Improvement using Dynamic Voltage Restorer with Real Twisting Sliding Mode Control

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Abstract- Higher Power Quality (PQ) is a common demand of sensitive industrial customers. PQ issues are gaining attention from both end-users and electrical utility companies since they are generating significant economic losses to sensitive industrial loads. Voltage sags/swells are the most significant and usually occurring PQ issues in a secondary distribution system. Dynamic Voltage Restorer (DVR), is a fast, flexible, effective, and dynamic Custom Power Device (CPD), that can be used to eliminate voltage sags and swells. Its performance is mostly determined by the control strategy established for switching Voltage Source Converters (VSCs). This research work develops a fused control method for VSC of DVR based on the Real-Twisting Algorithm (RTA) and Sliding Mode Control (SMC) that successfully eliminates the impacts of voltage sags/swells. RTA along with the conventional SMC reduce the effect of chattering, which is a disadvantage of SMC while retaining its additional qualities like robustness, quicker response time, and insensitivity to load variations. To evaluate the performance of the proposed control approach, the MATLAB/Simulink SimPower System toolbox was employed. According to the simulation findings, the Real Twisting Sliding Mode Controller (RTSMC) for DVR can detect and mitigate voltage sags/swells within 2.5ms which is much lower than the allowable limit of 20ms as per semiconductor industrial equipment voltage sag immunity standard (SEMI F-47 standard) for sensitive loads. Total Harmonics Distortion (THD) is determined to be less than 5% in all simulated instances. A comparative study is also performed between the conventional SMC and the suggested RTSMC, revealing that the proposed method outperforms the classical SMC.

Keywords-dynamic voltage restorer; power quality issues; sliding mode control; real-twisting algorithm; voltage sag/swell

I. INTRODUCTION

Power Quality (PQ) is a key problem of today's power systems, since it may have an impact on sensitive loads and utilities [1-2]. Most of the industrial devices are typically based on electronic devices like the programmable logic controller, microprocessors, computers, and adjustable speed drives that are very sensitive to variations such as voltage sags/swells and harmonics [3]. As the Distribution System (DS) is the weakest link in a power system, these PQ problems have a higher impact on it [4-5]. To mitigate these issues, Custom Power Devices (CPDs) like the Dynamic Voltage Restorer (DVR), the Active Filter (AF), the Unified Power Quality Conditioner (UPQC), and the Distribution Static Synchronous Compensator (DSTATCOM) are some of the most often utilized power devices [6]. DVR, due to its superior performance, is regarded as the best solution for minimizing the PQ issues. It is a fast, dynamic, and efficient technology that is employed to effectively mitigate voltage magnitudes [7]. Several control schemes, e.g. state feedback, self-tuning, Instantaneous Reactive Power (IRP) theory, direct quadrature (dq), reference adaptive model, phase shift control, vector template method, PCC regulated voltage, instantaneous symmetrical components, DC-link with Proportional-Integral (PI) controller, Synchronous Reference Frame (SRF) theory, feedback, feedforward, phase shift control, PI resonant, P + resonant,

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Artificial Neural Network (ANNs), Fuzzy Controller (FC) are used as VSCs of the DVR [8-11]. All these control schemes have advantages and disadvantages, when it comes to generating a clean sinusoidal AC waveform at the DVR's VSC output. They're constructed for creating a highly precise linearized mathematical model of the system that performs well under certain operating circumstances. On the other hand, these control techniques are unable to provide optimal performance when system parameters change. As a result, an efficient and robust control system is required, capable of performing functions with high precision and stability in dynamic conditions. The SMC for DVR overcomes these problems because it is not sensitive to changes in system parameters and does not require an exact mathematical model of the system, but it has an important disadvantage, named the chattering effect [12]. In order to avoid the chattering effect, some algorithms such as real-twisting, super-twisting, optimal, sub-optimal, global, integral, and state-observer algorithm have been used [4, 13-15]. Among these algorithms, the real-twisting algorithm has the upper hand due to its stability, robustness, and high tracking accuracy with less chattering effect.

In this research, an SMC control strategy based on the second order RTA for VSC of DVR is presented, which can successfully prevent the impacts of voltage sags/swells in distribution systems and decrease chattering, which is a drawback of the traditional SMC. RTSMC and DVRs can successfully minimize the percentage of THD and voltage disturbances according to [16], using the MATLAB/ SIMULINK software platform.

II. MATHEMATICAL MODELING OF DVR IN A DISTRIBUTION SYSTEM

A DVR is a power electronics switching device, connected in series with the distribution line in order to inject the desirable controlled voltage. Figure 1 depicts the generalized DVR model as well as the way it is linked to the grid. DVR essentially consists of an energy storage unit and a control system, with a VSC linked in series with grid through a boosting injection transformer.

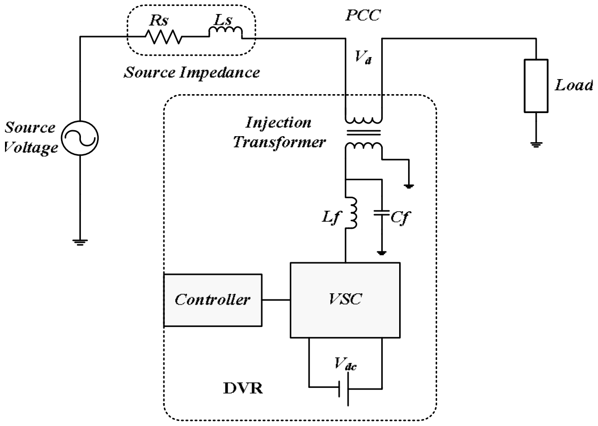

Fig. 1. Generalized single line model of DVR in the distribution network.

The equivalent circuit diagram of DVR is shown in Figure 2, where load voltage is represented by V_L and source voltage is represented by V_{source}, so the voltage inserted by DVR V_{dvr} can be written as:

$$V_L = V_{source} + V_{dvr} \quad (1)$$

C_{fc} and L_{fc} are the filter parameter as shown in Figure 2. The filter capacitor current i_{fc} can be defined as:

$$i_{fc} = C_{fc}\frac{dV_{dvr}}{dt} \quad (2)$$

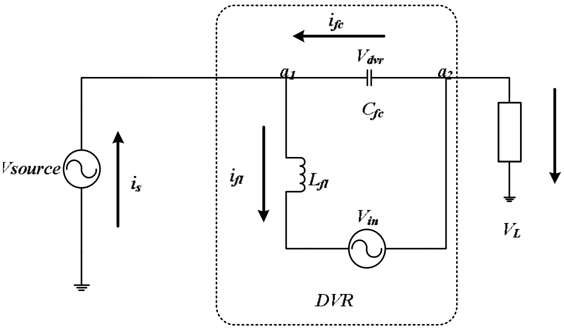

Fig. 2. Equivalent circuit diagram of DVR.

Now, KCL is applied at node (a_1) in the given Figure 2, the result is:

$$i_s - i_{fl} + i_{fc} = 0 \quad (3)$$

In (3), i_s represents the source current, while i_{fl} and i_{fc} are representing the filter inductor and capacitor current respectively. Now, putting the value of i_{fc} in (3), gives (4) and after simplification, we get (5):

$$i_s - i_{fl} + C_{fc}\frac{dV_{dvr}}{dt} = 0 \quad (4)$$

$$\frac{dV_{dvr}}{dt} = \frac{\left(i_{fl} - i_s\right)}{C_{fc}} \quad (5)$$

The DVR first state equation is produced in (5). To generate the second state equation, KVL is applied in Figure 2 at closed loop. So:

$$V_{dvr} + V_{fl} - V_{in} = 0 \quad (6)$$

where V_{in} is the output AC voltage of VSC, V_{dvr} is the voltage injected by the DVR, and V_{fl} is the voltage across the inductor, given in (7). By putting (7) in (6), we get (8), and, after simplification, we get (9):

$$V_{fl} = L_{fl}\frac{di_{fl}}{dt} \quad (7)$$

$$V_{dvr} + L_{fl}\frac{di_{fl}}{dt} - V_{in} = 0 \quad (8)$$

$$\frac{di_{fl}}{dt} = \frac{(V_{in} - V_{dvr})}{L_f} \quad (9)$$

Therefore, the state space model of the series connected DVR is shown in (10):

$$\frac{d}{dt}\begin{bmatrix} i_{fl} \\ V_{dvr} \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{-1}{L_{fl}} \\ \dfrac{1}{C_{fc}} & 0 \end{bmatrix}\begin{bmatrix} i_{lf} \\ V_{dvr} \end{bmatrix} + \begin{bmatrix} 0 & \dfrac{1}{L_{fl}} \\ \dfrac{-1}{C_{fc}} & 0 \end{bmatrix}\begin{bmatrix} i_s \\ V_{in} \end{bmatrix} \quad (10)$$

where i_{fl} and V_{dvr} are the state variables while i_s and V_{in}.are the the input variables.

III. DESIGNING THE SECOND ORDER RTSMC

Two steps are necessary for the implementation of SMC. The first is selecting the sliding surface. The DVR displays the desired performance when the state trajectory is pushed on the specified sliding line. The second stage is to drive the system's state to reach and remain on the chosen sliding surface in a finite period. Hence, the difference between the reference voltage and the voltage inserted by the DVR is the standard for the suggested procedure for the sliding surface as given in (11). After this, a comparator is applied on the sliding surface (S) with ±c reference quantity. After the comparator, the produced value is passed through the multiplexer. The aim of passing a signal via a multiplexer is to apply the law of switching to a single signal, and then to apply the control law to the surface.

$$S = V_{err} + k\frac{d}{dt}V_{err} \quad (11)$$

To bring the state variable on the sliding surface and to ensure the existence of operation, the given conditions must be satisfied:

$$S = 0 \quad (12)$$

$$\dot{S} = 0 \quad (13)$$

The switching law can be written as:

$$x(t) = \begin{cases} +1 if\ S > +c \\ -1 if\ S < -c \end{cases} \quad (14)$$

In (14,) $x(t)$ is the switching control, and c is a constant. If we get $x(t)$ =+1 then two switches sw_1 and sw_2 are on. If we get $x(t)$ =-1 then the other two switches, sw_3 and sw_4, are on. On the bases of this control law, a gating signal is produced for the VSC. The VSC produced the required magnitude of voltage and inserted it with the help of the injection transformer. Thus the control strategy used in this paper senses and corrects faults like sags and swells in a short time, i.e. 2.5ms. The state trajectory in an ideal SMC is aimed at the sliding manifold with an infinite switching frequency. On the other hand, real power converters cannot work at an infinite switching frequency. As a result, the state trajectory does not go to the origin S=0 and instead follows a discontinuous surface with undesirable oscillations, also known as chattering. The system's un-modeled dynamics can be stimulated by such oscillations. Therefore RTA is utilized in SMC to remove the chattering effect. The block diagram of SMC along RTA is shown in Figure 3.

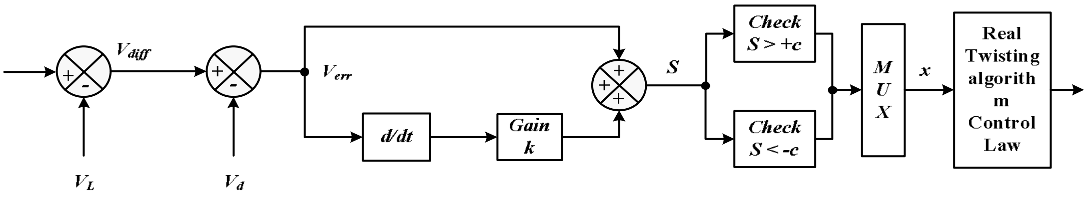

Fig. 3. Sliding mode block diagram.

By applying the RTA on the sliding surface, the switching law gives the modified input of control Z as given in (15):

$$Z = -n_1 sign(s) - n_2 sign(\dot{S}) \quad (15)$$

To remove the undesirable switching components, two tuning constants, n_1 and n_2, are used in the control law of RTA. The sliding manifold term $sign(s)$, removes the switching frequency of the components to increase the life of switches. When the designed sliding surface s is greater or less than zero, the sign function $sign(s)$ of the sliding manifold gives the +1 and -1 output respectively. The total effect of RTA on SMC results in less chattering effect, faster response, and robustness against external parameter variations.

IV. SIMULATION RESULTS AND DISCUSSION

To test the efficiency of the RTSMC for DVR in Matlab/Simulink, a test system was developed. The parameter details are given in Table I. Figure 4 depicts the suggested distribution system that was used to model and simulate the DVR using the RTSMC. Three-phase programming source produces voltage sags/swells in the distribution test system which are then corrected by the DVR. The following analysis is carried out to evaluate the effectiveness of the suggested control approach.

- Voltage sag/swell mitigation.
- Total harmonic distortion.

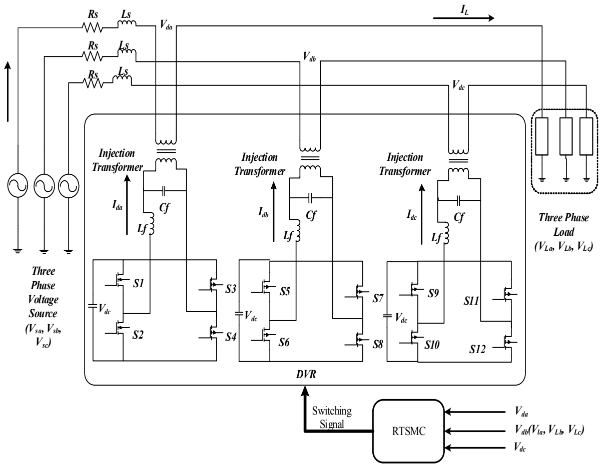

Fig. 4. A three phase system with connected DVR.

TABLE I. PARAMETERS OF THE DISTRIBUTION TEST SYSTEM

Parameter description	Values
Grid voltage(phase-phase)	400 V
Frequency of the system (*fo*)	50 Hz
Impedance of line (*Rs*, *Ls*)	0.8929 Ω, 16.58 mH
Loads Rating (3Ø)	Linear Load: P = 10 kW, Q = 1 kvar
Switching constant ±c	0.1
Energy storage(DC)	40v
LC-Filter: L_f, C_f	1.8 mH, 5.5 μF
Power rating for coupling transformer	100 kVA
Control action	RTSMC
SMC gain γ	0.142 μ
Switching frequency (F_s)	10 kHz
Solver for simulation	Ode23tb (stiff/TR-BDF2)
Time of sampling	5 μsec
Filter cutoff frequency	405 Hz
RTSMC tuning gains, n_1 and n_2	0.5 and 0.5

The RTSMC does not provide any switching signal to run the DVR when the system voltage does not change (normal state). When the voltage of the system deviates from its tolerated range, the controller begins to operate. RTSMC operates in the following manner:

- Detect voltage sags/swells.
- Compute the voltage sags/swells (percentage).
- Determine the signal of the switching control.
- Generate the switching signal (PWM) for VSC to activate source and load voltage.
- Generate the necessary switching signal uninterruptedly to ensure that voltage sags/swells are compensated.
- Terminate the switching PWM signal, when the voltage sag/swell is resolved.

A. *Voltage Sag Mitigation*

Due to the sudden switching ON of the sensitive load at the supply-side, a three-phase balanced voltage sag of 30% occurs. This sag starts at 0.1s and ends at 0.2s, as displayed in Figure 5(a). The controller is used to correct the disturbance. During normal operation, if there is no sag then no voltage is inserted. Once a fault occurs (voltage sag), the controller will detect it and evaluate its magnitude.

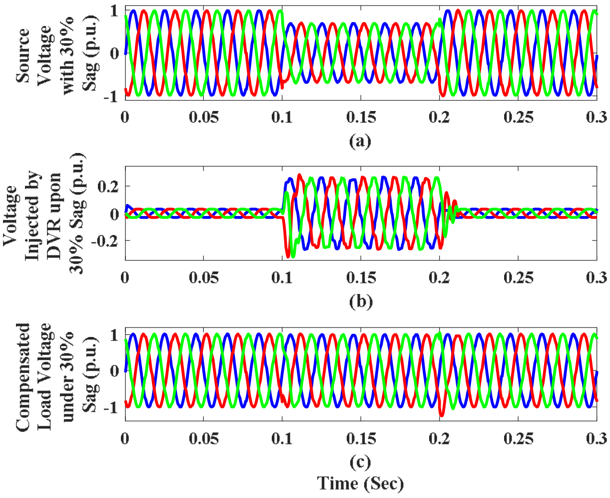

Fig. 5. Voltage sag waveform before and after mitigation: (a) Source voltage with 30% sag, (b) voltage injected by the DVR to mitigate the sag, (c) the compensated load voltage.

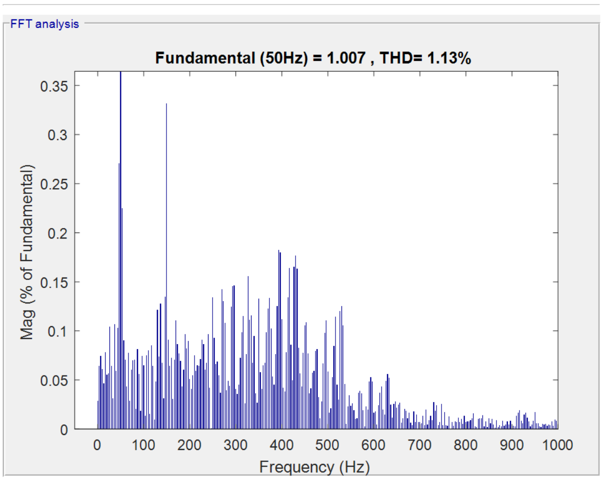

Fig. 6. THD value of the compensated load voltage under voltage sag for phase A.

The fault (voltage sag) is corrected in a very small duration of time (2.5ms) as compared to the allowable limit of IEEE standard that is 20ms. Figure 5(b) shows that DVR injects only the missing value to eliminate the unnecessary high frequency element by utilizing a low pass filter. The pure and sag free compensated system voltage is shown in Figure 5(c). The compensated voltage THD value is given in Table II and Figure 6. The harmonic content which is present in load voltage is lower than 5% which is proposed by the IEEE standard 1159-1995.

B. *Voltage Swell Compensation*

Due to the switching OFF of sensitive load, a 30% swell is produced in the three-phase source voltage, which starts at 0.1s and ends at 0.2s as shown in Figure 7(a). The simulation result shows that the good and quick feedback of sliding mode retains the load voltage of the sensitive load according to the ITIC standard. Due to the voltage swell, the distortion in the supply-side voltage is corrected in 2.5ms which is very small time duration, as shown in Figure 7(b). After the compensation, the system voltage is shown in Figure 7(c) with a magnitude of 1pu. The compensated voltage THD value is given in Table II and Figure 8. This value is less than the IEEE standard value.

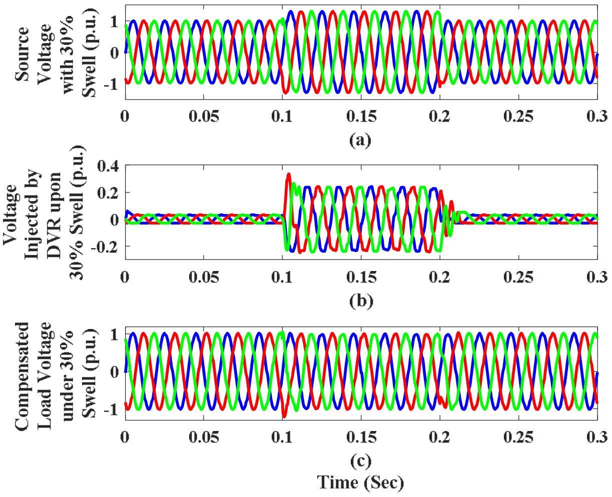

Fig. 7. Voltage swell waveform before and after mitigation: (a) Source voltage with 30% swell, (b) voltage injected by DVR to mitigate swell, (c) compensated load voltage.

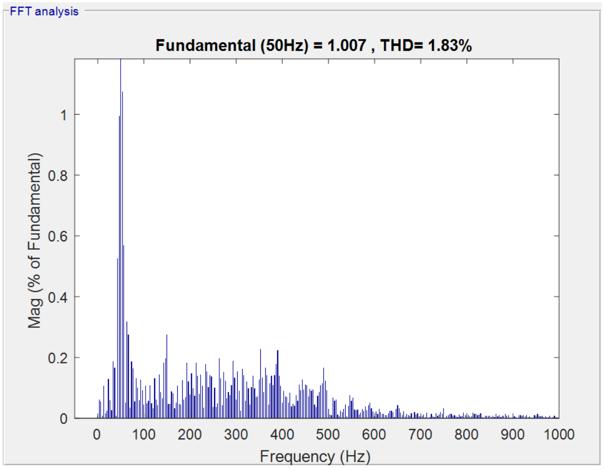

Fig. 8. THD value of compensated load voltage under voltage swell for phase A.

TABLE II. THD VALUES BEFORE AND AFTER COMPENSATION

Disturbances	**Phase A**	**Phase B**	**Phase C**
THD when voltage sag occurs	10.59%	11.83%	11.82%
THD when voltage sag is resolved	1.13%	4.62%	4.05%
THD when voltage swell occurs	8.70%	9.71%	9.69%
THD when voltage swell is resolved	1.83%	4.91%	4.51%

In this research, an SMC control scheme based on a second order RTA for VSC of DVR is proposed and implemented, which can successfully prevent the impacts of voltage sags/swells in distribution systems and decrease chattering, which is a major drawback of the traditional SMC. RTSMC with DVRs successfully minimizes the percentage of THD and voltage disturbances as per IEEE standards.

In Table III, the proposed RTSMC is compared with the classical SMC, revealing that the proposed method with SMC outperforms the classical SMC in terms of voltage sag/swell recovery, THD, transients, and multimode oscillations.

TABLE III. PROPOSED RTSMC-SMC COMPARISON

Parameter	**RTSMC**	**SMC**
Voltage sag/swell recovery (p.u.)	Excellent	Good
Voltage sag/swell recovery (s)	2.5 ms	4 ms
THD	Between 1% to 4%	Between 2% to 8%
Transients	Fewer	More
Robustness	Excellent	Excellent
Multi-mode oscillations	Fewer	Observed

V. CONCLUSION

In this paper, an SMC technique based on RTA for three-phase DVR is presented. The suggested control mechanism eliminates chattering, while attains constant switching frequency. As a result of using RTA in DVR control, a continuous control input is generated, which can be contrasted to the triangular carrier signal to generate pulse width modulation signals. To evaluate the performance of the suggested control approach, the MATLAB/Simulink SimPower System toolbox is employed. According to the simulation outcome, the designed RTSMC for DVR effectively corrects voltage sags/swells and provides the required power within 2.5ms with THD less than 5% for sensitive loads using the ITIC curve and the SEMI-F-47 standard. The suggested control approach provides faster response, less disturbances, and better of sag/swell voltage adjustment. A comparative study was performed between the conventional SMC and the suggested RTSMC, revealing that the proposed method outperforms the classical SMC.

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