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Power quality improvement using ultra capacitor based dynamic voltage restorer with real twisting sliding mode control

*Introduction. Power quality is a major problem in today's power system, since it may have an impact on customers and utilities. **Problem.** Power quality is important issue of financial consequences for utilities, their consumers and load apparatus vendors. Voltage sag/swell are the most significant and usually occurring power quality issues in a secondary distribution system for sensitive loads. **Goal.** Dynamic voltage restorer is a fast, flexible, effective and dynamic custom power device can be used to compensate voltage sag/swell with integration of energy storage. Ultra capacitors have ideal properties of great power density and low energy density for elimination of voltage sag/swell. Their performance is mostly determined by the control strategy established for switching of voltage source converters. **Originality.** In this research, a strategy for the voltage source converter of dynamic voltage restorer based on the real twisting sliding mode control and ultra capacitor is developed to correct the fault that successfully eliminates the impacts of voltage sag/swell. **Methodology.** Ultra capacitor along with real twisting sliding mode control gives the more robustness and faster response, with also increasing the compensation time of the dynamic voltage restorer. **Testing environment.** To evaluate the performance of the proposed control approach, the MATLAB / Simulink SimPower System tool box is employed. **Practical values.** According to Simulation results clearly shows that the ultra capacitor along with real twisting sliding mode control effectively eliminate the voltage sag/swell in a very short time of 2 ms as compared to IEEE standards that is 20 ms, with less than 5 % total harmonic distortion for sensitive loads as per Information Technology Industry Council Curve and SEMI-F-47 Standards. References 18, tables 1, figures 8.*
Key words: **dynamic voltage restorer, power quality issues, sliding mode control, real twisting algorithm, voltage sag/swell.**

*Вступ. Якість електроенергії являє собою серйозну проблему в сучасній енергосистемі, оскільки вона може впливати на споживачів та комунальні служби. **Проблема.** Якість електроенергії є важливим питанням з точки хору фінансових наслідків для комунальних підприємств, їх споживачів та постачальників апаратури-навантажень. Провали/стрибки напруги є найбільш серйозними проблемами з огляду на якість електроенергії, які зазвичай виникають у вторинній системі розподілу для чутливих навантажень. **Мета.** Динамічний відновник напруги — це швидкий, гнучкий, ефективний і динамічний пристрій живлення, який можна використовувати для компенсації провалів/стрибків напруги за допомогою інтеграції накопичувача енергії. Суперконденсатори мають ідеальні властивості високої щільності потужності та низької щільності енергії для усунення провалів/стрибків напруги. Їх ефективність переважно визначається стратегією управління, встановленої для комутації перетворювачів джерел напруги. **Оригінальність.** У цьому дослідженні розроблено стратегію для перетворювача джерела напруги динамічного відновника напруги на основі керування реальним ковзним режимом скручування та суперконденсатора для виправлення несправності, яка успішно усуває наслідки провалу/стрибка напруги. **Методологія.** Суперконденсатор разом із керуванням реальним ковзним режимом скручування забезпечує більшу надійність та швидшу реакцію, а також збільшує час компенсації динамічного відновника напруги. **Середовище для тестування.** Для оцінки ефективності запропонованого підходу до управління використовується комплекс програмного забезпечення MATLAB/Simulink SimPower System. **Практична цінність.** Згідно з результатами моделювання ясно видно, що суперконденсатор разом з керуванням реальним ковзним режимом скручування ефективно усувають провали/стрибки напруги за дуже короткий час 2 мс у порівнянні зі стандартами IEEE, у відповідності до яких він становить 20 мс, із загальним спотворенням гармонік менше 5 % для чутливого навантаження відповідно зі стандартами Information Technology Industry Council Curve та SEMI-F-47. Бібл. 18, табл. 1, рис. 8.*
Ключові слова: **динамічний відновник напруги, проблеми з якістю електроенергії, керування ковзним режимом, реальний алгоритм скручування, провали/скачки напруги.**

1. Introduction. Power quality is a key problem in today's power system, since it may have an impact on customers and utilities [1, 2]. The development in the new technology lead to improve the sensitive load that presents in the distribution system, these sensitive loads have badly effected on the quality of power supply. Power quality frequently occurred due to the problems like voltage sag/swell and harmonic distortion [3]. According to IEEE standards, voltage sag is defined by IEEE 1152-1995 as a sudden reduction in RMS value of the AC voltage from the 0.1 to 0.9 p.u. during a half-cycle to 1 min. While the voltage swell is defined as an increase in rated voltage caused by an abrupt disengagement of the load or by a highly capacitive load from 1.1 p.u. to 1.8 p.u. for duration of 0.5 cycles to 1 min [4]. These issues voltage sag/swell are small period voltage change that do not present for more than 1 min as available in Fig. 1 [5].

To eliminate these power quality problems, Dynamic Voltage Restorer (DVR) is the most efficient and best solution over other custom power devices like unified power quality conditioner (UPQC), distribution static synchronous compensator (DSTATCOM), static var compensator (SVCs) and uninterrupted power supply (UPS), due to its smaller size, fast response, effective and dynamically behavior [6-8].
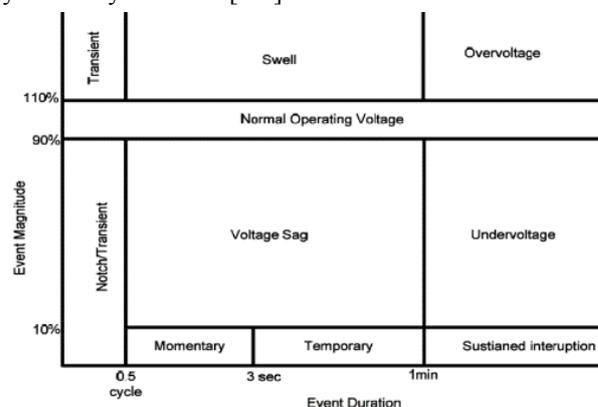

Fig. 1. IEEE Standard 1159-1995 for voltage decrease

The DVR contains Voltage Source Converter (VSC) with ultra capacitor (UC) as battery storage, LC filter, injection transformer and control circuit, which are

connected with source voltage and load voltage at point of common coupling (PCC) as shown in Fig. 2 [9], where R_s, L_s are the source resistance and inductance, respectively; V_d is DVR injected voltage; V_L is load voltage; L_f, C_f are the filter inductance and capacitance, respectively.
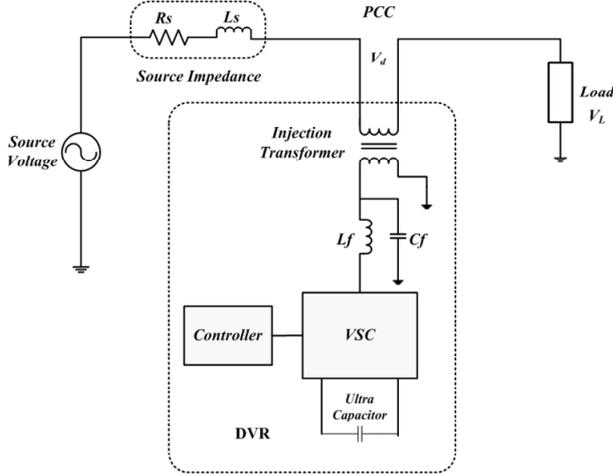

Fig. 2. DVR component

Various forms of rechargeable energy storage technologies are contrasted, including flywheels, ultra capacitors, superconducting magnets energy storage, and batteries in [10]. The method of ultra capacitors rises the DVR compensation time as compared to the previous techniques because of its properties of great power density and low energy density [11]. It connects to the system to improve the sag/swell compensation. In [12-14] many control schemes are discussed for the VSC of DVR to remove voltage sag/swell, but this has some disadvantage of depending on mathematical modeling of system and some stability problem. Therefore, a non-linear sliding mode controller is introduced as it has advantage of independent on mathematical modelling of the system, but it has important disadvantage named chattering effect [15]. To avoid this chattering effect, some algorithms such as real twisting, super-twisting, optimal, sub-optimal, global, integral and state-observer algorithms are used in literature [16-18]. Among these algorithms, real twisting algorithm has upper hand due to its stability, robustness and more tracking accuracy with less chattering effect.

The goal of the article. In this research, a control scheme of real twisting sliding mode controller (RTSMC) with integration of ultra capacitor is presented for the voltage source converter of dynamic voltage restorer using MATLAB/Simulink software package which can successfully mitigate voltage sag/swell and total harmonic distortion according to IEEE Standard [5].

2. Mathematical modeling of DVR in distribution system. Figure 3 depicts the equivalent circuit diagram of a DVR. In the figure, the distribution system is linked in series with a DVR, as well as source and load. The voltage injected by DVR stated as

$$V_L + = V_{source} + V_{dvr}, \tag{1}$$

where V_L, V_{source}, V_{dvr} are the load, source and DVR voltages, respectively.

Filter parameters L_f and C_f are depicted in Fig. 3. These filter settings are used to remove the high-frequency component present in the VSC's AC output. The filter capacitor is defined as follows:
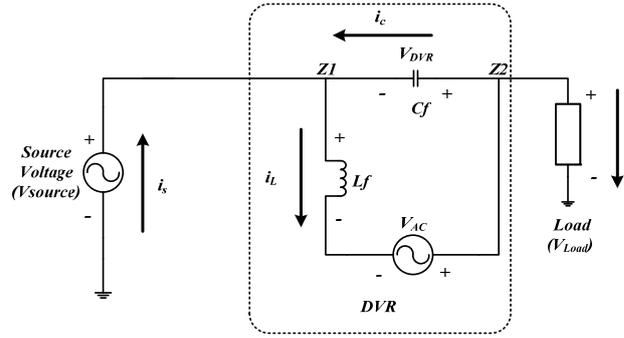
$$i_c = C_f \cdot \frac{dV_{dvr}}{dt}. \tag{2}$$

Fig. 3. DVR equivalent circuit

By applying Kirchhoff's circuit law at node Z_1 in Fig. 3 we have

$$i_s - i_L + i_C = 0. \tag{3}$$

where i_s is the source current; i_L is the inductor current of filter.

By putting i_c from (2) in (3), we have

$$i_s - i_L + C_f \cdot \frac{dV_{dvr}}{dt} = 0. \tag{4}$$

Equation (4) after the simplification gets the form

$$\frac{dV_{dvr}}{dt} = \frac{(i_L - i_s)}{C_f}. \tag{5}$$

The above equation (5) is the 1st DVR state equation. For the second DVR state equation, apply Kirchhoff's voltage law at closed loop (Fig. 3)

$$V_{dvr} + V_L - V_{in} = 0, \tag{6}$$

where V_{in} is the VSC AC voltage; V_l is the load voltage

$$V_L = L_f \cdot \frac{di_L}{dt}. \tag{7}$$

So, substituting (7) in (6) we have

$$V_{dvr} + L_f \cdot \frac{di_L}{dt} - V_{in} = 0. \tag{8}$$

After the simplification, we get

$$\frac{di_L}{dt} = \frac{(V_{in} - V_{dvr})}{L_f}. \tag{9}$$

Finally, the state space model DVR is

$$\frac{d}{dt}\begin{bmatrix} i_L \\ V_{dvr} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & 0 \end{bmatrix} \cdot \begin{bmatrix} i_L \\ V_{dvr} \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{L_f} \\ -\frac{1}{C_f} & 0 \end{bmatrix} \cdot \begin{bmatrix} i_s \\ V_{in} \end{bmatrix}, \tag{10}$$

where i_L and V_{dvr} are the state variables, while the i_s and V_{in} are the input variables.

3. Mathematical modelling of ultra capacitor (UC). The ultra capacitor model consists of equivalent series resistance (ESR), capacitance and equivalent parallel resistance (EPR) as shown in Fig. 4. The charging and discharging resistances of system are represented by the ESR, while EPR represents the self-discharging losses of the system.

The UC voltage with the capacitance and resistance can be described as follows

$$V(t) = V_i \cdot \exp(-t/\tau), \tag{11}$$

where $\tau = R \cdot C$ is the time constant to determine the charging and discharging process for some capacitor initial voltages.
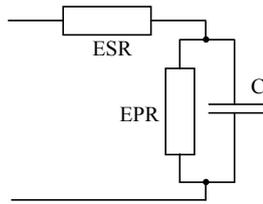
Fig. 4. UC equivalent model

The change in voltage terminal and the capacitance are directly proportional to the energy drawn from the UC expressed as

$$E = \frac{1}{2} \cdot C \cdot \left(V_i^2 - V_f^2 \right),\qquad (12)$$

where V_i is the initial voltage before discharging start; V_f is the final voltage after discharging start.

The total UC system resistance (R_{total}) and capacitance (C_{total}) of the UC bank are calculated as

$$R_{total} = n_s \cdot \frac{ESR}{n_p};\qquad (13)$$

$$C_{total} = n_p \cdot \frac{C}{n_s},\qquad (14)$$

where n_s is the number of capacitor cells in series; n_p is the number of capacitor cells in parallel.

4. Designing of second order real twisting sliding mode control. There are two steps, which are necessary for the implementation of sliding mode control. The first stage is to select 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 finite period.

4.1: Sliding surface selection. Create a control strategy for DVR that is free of system parameters and load. This approach will be used to eliminate voltage sag/swell, hence the state vector will be defined as

$$V = \begin{bmatrix} v \\ \dot{v} \end{bmatrix},\qquad (15)$$

where V is the state vector; v is the state variable and $\dot{v}$ is the first derivative state variable V.

Select which sliding surface that is utilized to adjust the DVR's VSC AC output voltage for these state variables. For the chosen method, the change between reference and load voltage is a sliding surface (S). The sliding surface is indicated by signal (S) in Fig. 5. As indicated in Eq. (16), this signal (S) is based on the computed error voltage (V_{error})

$$V_{error} = V_{reference} - V_{load}.\qquad (16)$$

In (16) the sliding surface which comprises the difference of $V_{reference}$ and V_{Load} and after this takes derivative of this error voltage and finally add it

$$S = V_{error} + k \cdot \frac{dV_{error}}{dt},\qquad (17)$$

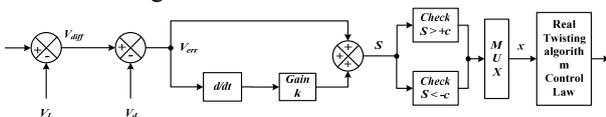where k is the gain of feedback.

Fig. 5. RTSMC block diagram

When detect the error in actual voltage compare the sliding surface (S) with $\pm c$ constant quantity. When comparison is done, then outcomes go through the

multiplexer. Multiplexer is used for applying the switching law on the desired signal.

4.2 Reachability condition. The following condition must be satisfied in order to obtain the state trajectory onto the sliding surface and confirm the operation's existence

$$S = 0;\qquad (18)$$

$$\dot{S} = 0.\qquad (19)$$

In a short period of time, the control approach used here will turn all of the state vectors into a sliding surface. The switching law that we employ will reveal the system's stability status while it is in the sliding mode. The following is the criterion for the presence of sliding mode

$$S \cdot \dot{S} = 0.\qquad (20)$$

The above equation is basically the Lyapunov function, used to check the stability condition for the system stability. Some key points are listed below.

• if $S > 0$ and $\dot{S} < 0$, then S will be reduce to 0;

• if $S < 0$ and $\dot{S} > 0$, then S will be increase to 0.

4.3 Determination of control law. The switching law may be expressed as follows

$$x(t) = \begin{cases} +1, \text{if } S > +c; \\ -1, \text{if } S < -c, \end{cases}\qquad (21)$$

where $x(t)$ is represented as the variable for switching control; c is the constant for the comparison with faulty signal.

If we receive $x(t) = +1$, inverter switch S1 and switch S4 are turned on as shown in Fig. 6. If we receive $x(t) = -1$, inverter S2 and S3 will be turned on as shown in Fig. 6.
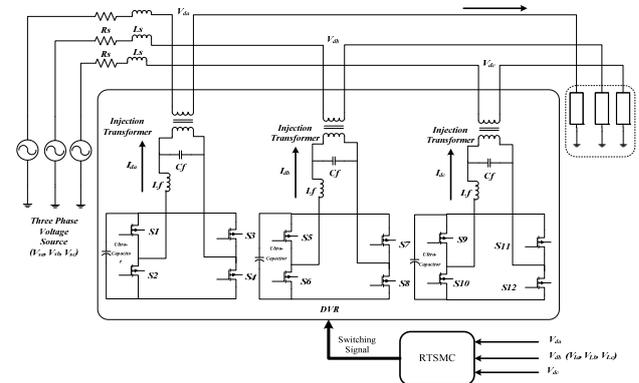

Fig. 6. Three phase system with connected DVR

Basically an ideal SMC is working on the infinite frequency, when the state vector is aimed directly towards the sliding surface. However, power converters do not have an infinite switching frequency, that is why the converter does not operate properly and state vector will not move towards origin, but keep travelling with the some discontinuous surface with unwanted oscillation, which is known as chattering. Therefore real twisting algorithm (RTA) is utilized in SMC to remove the chattering effect.

The block diagram of SMC along RTA is show in Fig. 5. When the RTA is apply on sliding surface, switching law gives the modified input of control Z as given below

$$Z = -n_1 \cdot sign(S) - n_2 \cdot sign(\dot{S}),\qquad (22)$$

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 components to increase the life of switches. When the designed sliding surface s is greater or less than zero, the signum 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 to variation in external parameter.

5. Simulation result and discussion. To test the efficiency of a real twisting sliding mode control (RTSMC) for DVR in MATLAB/Simulink, a test system is develop (Fig. 6). All the parameter detail is given in Table 1.

Figure 6 depicts the suggested distribution system that used to model and simulate the UC based DVR using the RTSMC. Three-phase programming source produces voltage sag/swell in distribution test system, which is then corrected by DVR. The following analysis is carried out to evaluate the effectiveness of the suggested control approach.

- voltage sag/swell mitigation;
- Total harmonic distortion.

Table 1

Parameter of distribution test system

No.	Description of parameters	Values
1	Grid voltage(phase-phase)	400 V
2	Frequency of system(f)	50 Hz
3	Impedance of line (R_s, L_s)	0.8929 Ω, 16.58 mH
4	Loads rating	Linear load: $P = 10$ kW, $Q = 1$ kVar
5	Switching constant ±c	0.1
6	Ultra capacitor	40 V
7	LC filter (L_f, C_f)	1.8 mH, 5.5 μF
8	Power rating for coupling transformer	100 kVA
9	Control action	RTSMC
10	SMC gain γ	$0.142 \cdot 10^{-6}$
11	Switching frequency (f_s)	10 kHz
12	Solver for simulation	Ode23tb (stiff/TR-BDF2)
13	Time of sampling	5 μs
14	Filter cutoff frequency	405 Hz
15	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 (voltage sag/swell) of the system deviates from its tolerated range, the controller begins to operate. RTSMC operates in the following manner:

- detect voltage sag/swell;
- compute the voltage sag/swell (in percentage);
- determine the signal of switching control;
- generate switching signal of pulse width modulation (PWM) for VSC to activate source and load voltage;
- generations of necessary switching signal uninterruptedly to ensure that voltage sag and swell is compensated;
- Terminate the switching PWM signal, when voltage sag/swell is resolved.

5.1. Voltage sag mitigation. A three-phase balanced voltage sag of 30 % arises as a result of the rapid switching ON of sensitive load on the supply side. As shown in Fig 7,*a*, the occurrence time of this sag begins at 0.1 s and ends at 0.2 s. To correct the disturbance, the controller is utilized. If there is no sag during normal operation, no voltage is introduced. When a fault occurs, the controller detects the sag and evaluate the sag magnitude.

The problem (voltage sag) is resolved in a relatively short period (2 ms) compared to the IEEE Standard acceptable limit of 20 ms. Figure 7,*b* illustrates that DVR just injects the missing value. To reduce unwanted high frequency elements, a low pass filter is used. Figure 7,*c* shows the pure and sag-free corrected system voltage. The voltage corrected Total Harmonic Distortion (THD) value for phase A, B and C is 1.13 %, 4.62 % and 4.05 % respectively, indicating that the harmonic content in the load voltage is less than the 5 % suggested by IEEE Standard 1159-1995.
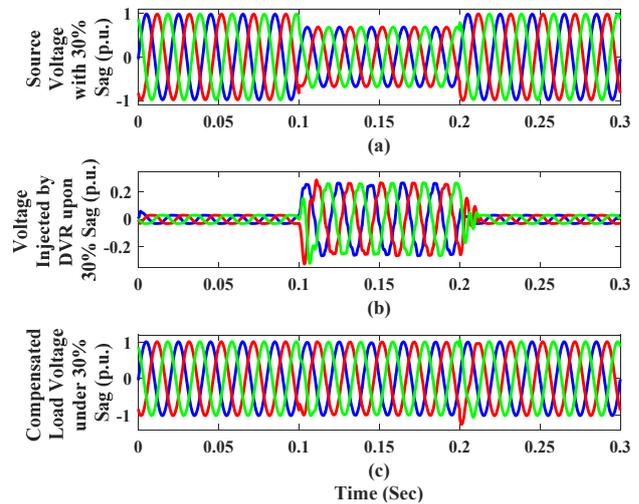

Fig. 7. Voltage sag waveform before and after mitigation:
(*a*) source voltage with 30 % sag;
(*b*) voltage injected by DVR to mitigate sag;
(*c*) compensated load voltage

5.2. Voltage swell compensation. A three-phase balanced voltage swell of 30 % arises as a result of the rapid switching ON of sensitive load on the supply side. As shown in Fig 8,*a*, the occurrence time of this swell begins at 0.1 s and ends at 0.2 s.
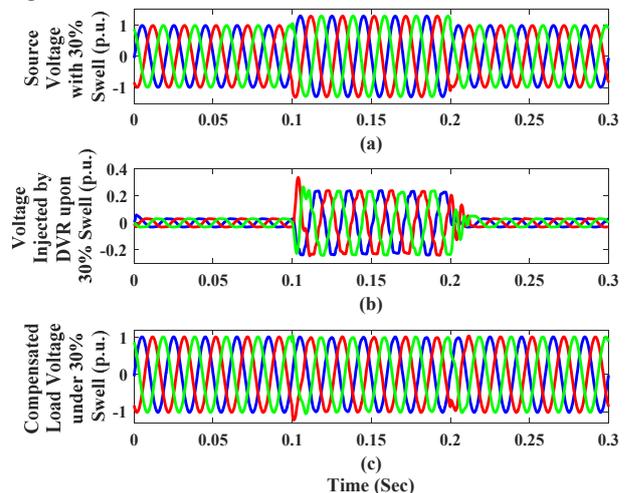

Fig. 8. Voltage swell waveform before and after mitigation:
(*a*) source voltage with 30 % swell;
(*b*) voltage injected by DVR to mitigate swell;
(*c*) compensated load voltage

The problem (voltage swell) is resolved in a relatively short period (2 ms) compared to the IEEE Standard acceptable limit of 20 ms. Figure 8,*b* illustrates that DVR just injects the missing value. To reduce unwanted high frequency elements, a low pass filter is used. Figure 8,*c* shows the pure and swell-free corrected system voltage.

The corrected voltage THD value is for phase A, B, and C is 1.83 %, 4.91 % and 4.51 % respectively, indicating that the harmonic content in the load voltage is less than the 5 % suggested by IEEE Standard 1159-1995.

Conclusion. A control scheme of real twisting sliding mode control with integration of ultra capacitor is presented for the voltage source converter of dynamic voltage restorer using MATLAB/Simulink software package which can successfully mitigate voltage sag/swell and total harmonic distortion according to IEEE Standard. The ultra capacitors rise the dynamic voltage restorer compensation time due to its ideal properties of great power density and low energy density for elimination of voltage sag/swell and control mechanism eliminates chattering, while attains a constant switching frequency. As a result of using real twisting algorithm in dynamic voltage restorer 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 approach, the MATLAB/Simulink SimPower System tool box is employed. According to simulation results this clearly shows that the ultra capacitor along with real twisting sliding mode control effectively eliminates the voltage sag/swell in a very short time of 2 ms as compared to IEEE Standards that is 20 ms, with less than 5 % total harmonic distortion for sensitive loads as per Information Technology Industry Council Curve and SEMI-F-47 standards.

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

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