Voltage Fluctuation and their Mitigations

Taha M.E.M., Kozhevnikov A.V.
Cherepovets State University, Cherepovets, Russia

Abstract. *Voltage fluctuation is one of a major power quality concern for both power companies and customers. This article discusses the performance of a Distribution Static Synchronous Compensator (D-STATCOM) for mitigation of voltage fluctuation. The D-STATCOM is designed to replace the widely used static var compensator (SVC). A D-STATCOM is used to regulate voltage on a 25-KV distribution network. The D-STATCOM protects the utility transmission or distribution system from voltage sag and /or fluctuation caused by rapidly varying reactive current demand. The D-STATCOM organizes bus voltage by absorbing and generating reactive power. This voltage is supplied by a voltage-sourced PWM inverter. The simulation is executed by using MATLAB/SIMULINK and the simulation results show the performance of D-STATCOM in mitigation of voltage fluctuation.*

Keywords: *D-STATCOM, Power Quality, Voltage Flicker, Voltage Fluctuation.*

I. Introduction

Voltage flicker is considered as one of the most severe power quality problems (especially in loads like electrical arc furnaces) and much attention has been paid to it lately [1].

The term flicker is used to refer to the subjective impression that is experienced by human beings when subjected to changes occurring in the illumination intensity of light sources [1], [2], [4], [6], [7], [9], [16], [17]. One of the reasons for the complexity in the evaluation of this phenomenon is the human factor involved in its definition, since it forces one to take into account the characteristics of the physiological process of perception [3].

In addition to the perceptible and sometimes irritating lighting flicker to humans, voltage flicker can also cause electrical equipment efficiency drop, torque and power oscillations, and interference in protection systems [12].

From an electrical point of view, flicker is caused by voltage fluctuations with amplitude which is generally much lower than the threshold of immunity for electrical equipment. So, it can be said that the major effect of rapid voltage fluctuations is flicker. Voltage variations on the order of only a few tenths of a percent can produce a very significant malaise, especially if the frequency of repetitive deviations is between 8 and 10 Hz [3].

Voltage flicker occurs when large industrial loads, such as electric arc furnaces [5], [8], [9], [17], Welders [3], [4], [7], [9], rolling mills [9], [17], and pumps [3] operate periodically in a weak power distribution system. It causes voltage fluctuation at the Point of Common Coupling (PCC) [1], [8], [9] with other loads.

ANSI C84.1-1992 recommends that the system voltages should lie in the range 0.9–1.1 pu [2], [6].

Very small variations are enough to induce lightning disturbance for human eye for a standard 230V, 60W coiled-coil filament lamp [1], [5].

IEEE519-1992 indicates that only 0.5% changes in the voltage amplitude leads to light intensity change which harms the human eyes. So voltage flicker mitigation is essential for the power systems [8].

In this paper, the configuration and construction of the D-STATCOM will be explained in brief. And discusses the performance of a (D STATCOM) for mitigation of voltage fluctuation on a distribution network.

II. Basic Configuration and Operation of D-STATCOM:

The D-STATCOM is a three-phase and shunt connected power electronics based device. It is connected near the load at the distribution systems.[11] The major components of a D-STATCOM are shown in Fig. 1. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control strategy. The basic electronic block of the D-STATCOM is the voltage-sourced inverter that converts an input dc voltage into a three-phase output voltage at fundamental frequency. [10], [12-14]

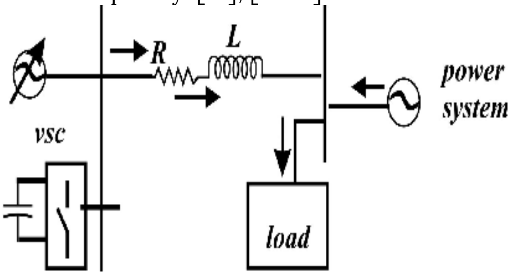

Figure 1: Basic Building Blocks of the D-STATCOM

The D-STATCOM employs an inverter to convert the DC link voltage Vdc on the capacitor to a voltage source of adjustable magnitude and phase. Therefore the D-STATCOM can be treated as a voltage-controlled source. The D-STATCOM can also be seen as a current-controlled source [12-14].

Fig. 1 shows the inductance L and the resistance R which represent the equivalent circuit elements of the step down transformer and the inverter will be the main component of the D-STATCOM. The voltage Vi is the effective output voltage of the D-STATCOM and δ is the power angle [14].

The reactive power output of the D-STATCOM inductive or capacitive depending can be either on the operation mode of the D-STATCOM. The construction controller of the D-STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the D-STATCOM generates or absorbs the desired VAR at the point of connection. The phase of the output voltage of the thyristor-based inverter, Vi, is controlled in the same way as the distribution system voltage, Vs. [12], [14]

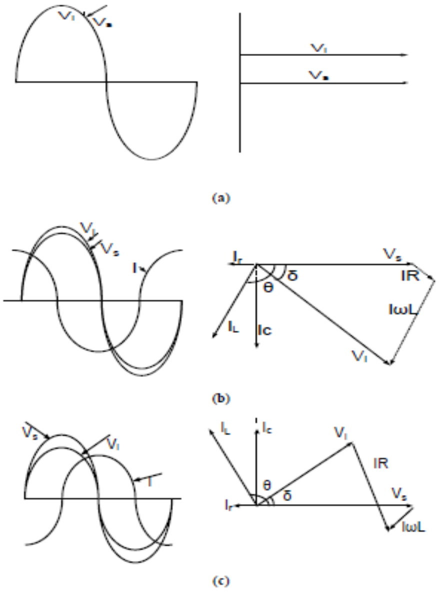

Fig. 2 Operation of D-STATCOM (a) No load mode (Vs=VI), (b) Capacitive mode, (c) Inductive mode

Fig. 2 shows the three basic operation modes of the D-STATCOM output current, I, which varies depending upon Vi. If Vi is equal to Vs, the reactive power is zero and the D-STATCOM does not generate or absorb reactive power. When Vi is greater than Vs, the D-STATCOM shows an inductive reactance connected at its terminal [10], [14].

The current I, flows through the transformer reactance from the D-STATCOM to the ac system, and the device generates capacitive reactive power. If Vs is greater than Vi, the D-STATCOM shows the system as a capacitive reactance. Then the current flows from the ac system to the D-STATCOM, resulting in the device absorbing inductive reactive power [14].

III. VOLTAGE SOURCE CONVERTERS (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics [14].

Synchronous Reference Frame Theory (d-q theory) For Flicker Mitigation:

The synchronous reference theory is based on the transformation of the stationary reference frame three phase variables (a,b,c) to synchronous reference frame variables (d,q,0) whose direct (d) and quadrature (q) axes rotate in space at the synchronous speed ωe. ωe is the angular electrical speed of the rotating magnetic field of the three phase supply, given by ωe=2πfs, where fs is the frequency of the supply. If θ is the transformation angle, then the current transformation from abc to d-q-0 frame is defined as [15]

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

The block diagram of the D-STATCOM controller for flicker mitigation based on d-q theory is shown in **Fig**. 3. The three- phase source voltages (Vsa, Vsb and Vsc) are applied to three-Phase Locked Loop (PLL) to synchronize the three-phase voltages at the converter output with the zero crossings of the fundamental component of the supply phase voltages. The PLL provides the synchronous reference angle θ required by the abc-dq0 (and dq0-abc) transformation.

The three phase source currents (isa, isb, isc) and bridge inverter currents (iia, iib, iic)are converted into equivalent direct axis and quadrature axis component currents (id, iq) by using (1). [15]

In order to maintain the reactive power drawn from the source as zero, the output currents of the three phase bridge inverter are controlled in such a way that the inverter supplies the required reactive power. Thus for flicker mitigation, the source reactive power has to be zero. Therefore iq reference (iqref) is set at zero for inverter control. The reactive current supplied by the source (iq) is subtracted from the reference value (iqref=0) to obtain the error in reactive current for full compensation. This error signal is processed through a PI controller block to obtain the reference voltage signal (Vqref), which is fed to the dq0- abc transformation block. The reference for id (idref) comes from the DC link voltage PI controller, which maintains the DC link voltage (Vdc) at reference value. [15]

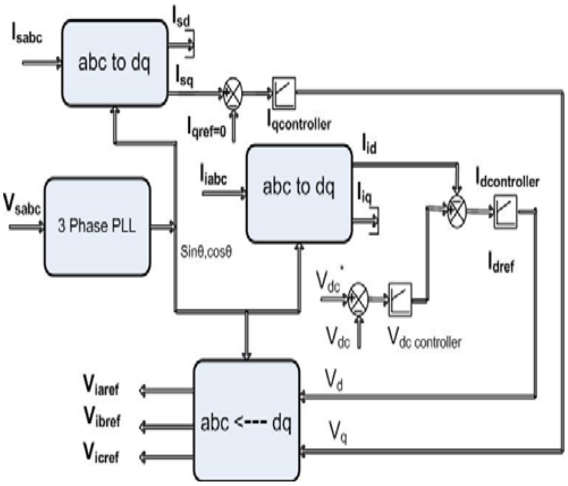

Fig. 3: D-STATCOM controller with d-q theory.

IV. Model Description:

A D-STATCOM is used to regulate voltage on a 25-KV distribution network simulated in Matlab as shwon in **Fig**. 4 . Two feeders (21 km and 2 km) convey power to loads connected at buses B2 and B3. A shunt capacitor is used for power factor improvement at bus B2. The 600-V load jointed to bus B3 through a 25KV/600V transformer acts as a plant absorbing continuously changing currents, alike to an arc furnace, thus generating voltage fluctuation. The variable load current magnitude is modulated at a frequency of 5 Hz so that its manifest power varies approximately between 1 MVA and 5.2 MVA, while keeping a 0.9 lagging power factor. This load variation will allow us to observe the ability of the D-STATCOM to mitigate voltage fluctuation.

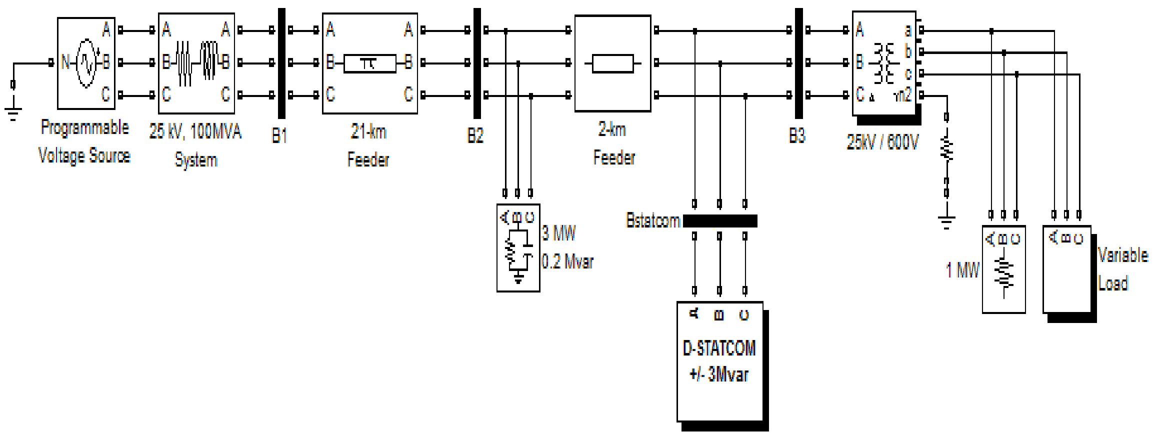

Fig. 4 Simulation of D-STATCOM connected to the power system:

The D-STATCOM organizes bus B3 voltage by absorbing or producing reactive power. This reactive power convey is done by the leakage reactance of the coupling transformer through producing a secondary voltage in phase with the primary voltage (network side). This voltage is given by a voltage-sourced PWM inverter. When the secondary voltage is lower than the bus voltage, the D-STATCOM working as an inductance absorbing reactive power. When the secondary voltage is higher than the bus voltage, the D-STATCOM working a a capacitor producing reactive power.

The D-STATCOM consists of the following components:

- A 25KV/1.25KV coupling transformer which guarantee coupling between the PWM inverter and the network.
- A voltage-sourced PWM inverter is composed of two IGBT bridges. This twin inverter's construction produces fewer harmonic than a single bridge, resulting in smaller filters and enhanced dynamic response. In this situation, the inverter modification frequency is 28*60=1.68 kHz so that the first harmonics will be approximately 3.36 kHz.
- LC damped filters jointed at the inverter output. Resistances jointed in series with capacitors provide a quality factor of 40 at 60 Hz.
- A 10000-microfarad capacitor working as a DC voltage source for the inverter
- A voltage organizer that controls voltage at bus B3
- A PWM pulse generator using a modification frequency of 1.68 kHz
- Anti-aliasing filters used for voltage and current gaining.

The D-STATCOM controller consists of several functional blocks:

- A Phase Locked Loop (PLL). The PLL is is coincided with the fundamental of the transformer primary voltages.
- Two measurement systems. Vmeas and Imeas blocks count the d-axis and q-axis components of the voltages and currents by implementing an abc-dq transformation in the synchronous reference specified by sin (wt) and cos(wt) took from by the PLL.
- An inner current regulation loop. This loop consists of two proportional-integral (PI) organizer that organize the d-axis and q-axis currents. The organizer's outputs are the Vd and Vq voltages that the PWM inverter has to produce. The Vd and Vq voltages are converted into phase voltages Va, Vb, Vc which are used to gather the PWM voltages. The Iq reference comes from the outer voltage organization loop (in automatic position) or from a reference imposed by Qref (in manual position). The Id reference comes from the DC-link voltage organizer.
- An outer voltage regulation loop. In automatic position (regulated voltage), a PI controller maintains the primary voltage equal to the reference value defined in the control system dialog box.
- a DC voltage controller which maintains the DC link voltage constant to its nominal value (Vdc=2.4KV)

V. Simulation Results:

1) D-STATCOM Dynamic Response:

During this test, the variable load will be maintained constant and you will note the dynamic response of a D-STATCOM to step changes in source voltage. Make sure that the modulation of the Variable Load is not in service (modification Timing [Ton Toff]=[0.15 1]*100 > Simulation Stop time). The Programmable Voltage Source block is used to adjust the internal voltage of the 25-KV equivalent. The voltage is first programmed at 1.077 pu in order to maintain the D-STATCOM in the beginning floating (B3 voltage=1 pu and reference voltage Vref=1 pu). Three steps Have been set at 0.2 s, 0.3 s, and 0.4 s , one after another increase the supply voltage by 6%, reduce it by 6% and bring it back to its first value.

Start the simulation. Observe on **Fig**. 5 the phase voltage waveform of the D-STATCOM as well as Output voltage of voltage source inverter on **Fig**. 6. After a transient lasting about 0.15 sec., the steady state is reached. In the beginning, the source voltage is such that the D-STATCOM is inactive. It does not absorb or provide reactive power to the system. At t = 0.2 s, the source voltage is increased about 6%. The D-STATCOM compensates for this voltage increase by absorbing reactive power from the system (Q = +2.7 Mvar on **Fig**. 7). When t = 0.3 s, the supply voltage is reduced about 6% from the value corresponding to Q = 0. The D-STATCOM should produce reactive power to maintain a 1 pu voltage (Q changes from +2.7 MVAR to -2.8 MVAR). Observe that when the D-STATCOM changes from inductive to capacitive case, the modulation index of the PWM inverter is raised from 0.56 to 0.9 which corresponds to a proportional increase in inverter voltage. Reversing of reactive power is very fast, about one cycle, as observed on D-STATCOM current (**Fig**. 8).

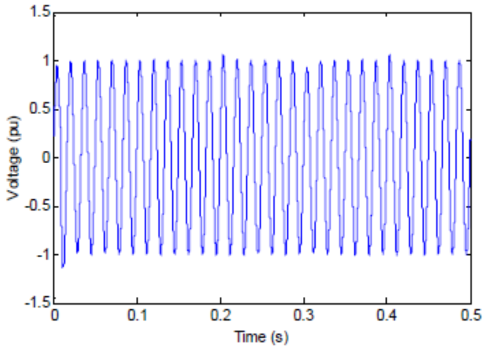

Fig. 5: Output voltage of D-STATCOM.

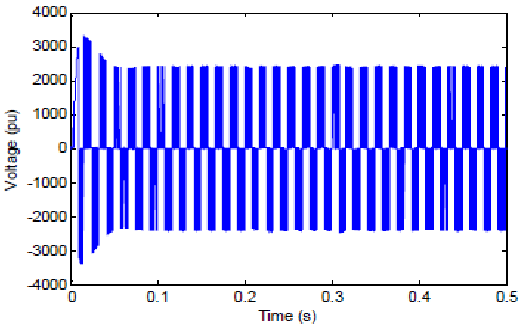

Fig. 6: Output voltage of voltage source inverter.

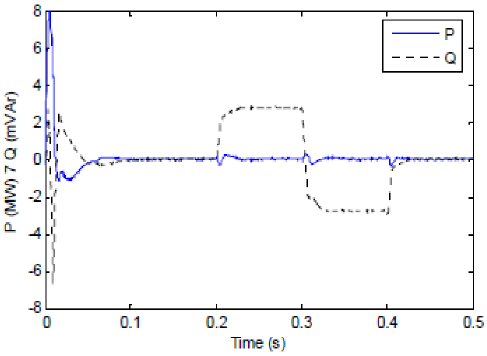

Fig. 7: Output P & Q of D-STATCOM.

2) Mitigation of Voltage Flicker:

During this test, voltage of the Programmable Voltage Source will stay constant and you can adjust the Variable Load so that you can observe how the D-STATCOM can mitigate voltage fluctuation. In the Programmable Voltage Source block menu, change the "Time Variation of" limit to "None". In the Variable Load block menu, adjust the modification Timing limit to [Ton Toff] = [0.15 1] (remove the 100 multiplication factor). Finally, in the D-STATCOM Controller, change the "Mode of operation" parameter to "Q regulation" and ensure that the reactive power reference value Qref (2nd line of parameters) is set to zero. In this mode, the D-STATCOM is floating and implements no voltage correction.

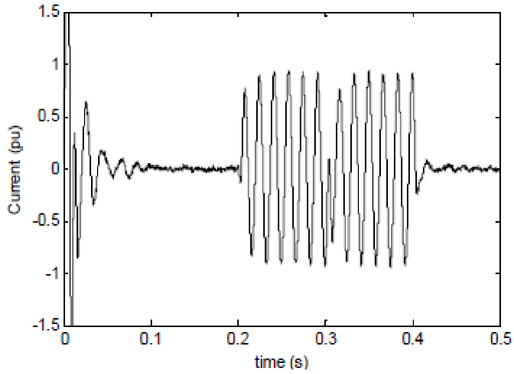

Fig. 8: Output current of D-STATCOM

Run the simulation and observe on Fig. 9 variations of P and Q at line B3 as well as voltages at lines B1 and B3 Fig 10. Without D-STATCOM, B3 voltage varies between 0.96 pu and 1.04 pu (+/- 4% variation). Now, in the D-STATCOM Controller, change the "position of operation" limit back to "Voltage regulation" and restart simulation. Notice on Fig. 9 that voltage fluctuation at bus B3 is now reduced to +/- 0.7 %. The D-STATCOM compensates voltage by generating a reactive current modified at 5 Hz and varying between 0.6 pu capacitive when voltage is low and 0.6 pu inductive when voltage is high.

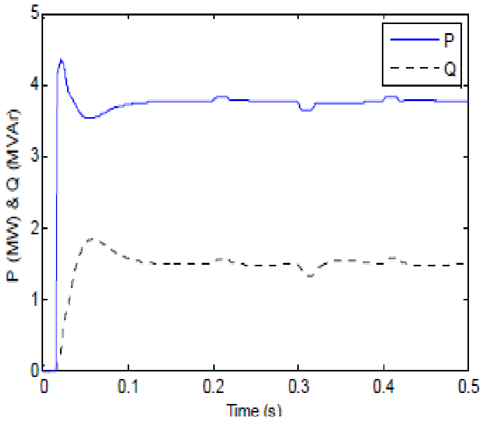

Fig. 9: P and Q of terminal B3.

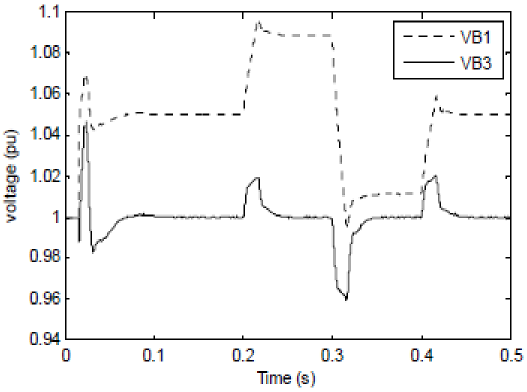

Fig. 10: Terminal voltages B1 and B3.

Conclusion

In this article, D-STATCOM controller is derived by using synchronous reference theory. The model is simulated in MATLAB/SIMULINK and D-STATCOM for voltage fluctuation mitigation. The D-STATCOM is confirmed to be effective for fluctuation mitigation with improved dynamic response of the system and compensating reactive currents will help the mitigation of voltage fluctuation.

References:

1. Joorabian, Mahmood, Davar Mirabbasi, and Alireza Sina. "Voltage flicker compensation using STATCOM." 2009 4th IEEE Conference on Industrial Electronics and Applications. IEEE, 2009.
2. Padiyar, K. R. FACTS controllers in power transmission and distribution. New Age International, 2007.
3. Baggini, Angelo. Handbook of power quality. John Wiley & Sons, 2008.
4. Kennedy, Barry W. Power quality primer. McGraw Hill Professional, 2000.
5. Schlabbach, J., D. Blume, and T. Stephanblome. Voltage quality in electrical power systems. Vol. 241. London, 2001.
6. Vedam, R. Sastry, and Mulukutla S. Sarma. Power quality: Var compensation in power systems. CRC press, 2017.
7. Virulkar, Vasudeo B., and Mohan V. Aware. "Modeling and Control of DSTATCOM with BESS for mitigation of Flicker." International Conference on Energy System & Power Electronics in Emerging Economics (ICEESPEEE-2009), SRM University. 2009.
8. Za'fari, Ali. "Mitigation of flicker using STATCOM with three-level 12-pulse voltage source inverter." International Journal of Engineering and Technology 5.1 (2011): 263-268.
9. Virulkar, Vasudeo B., and Mohan V. Aware. "Voltage flicker mitigation using statcom and ess." 2008 Joint International Conference on Power System Technology and IEEE Power India Conference. IEEE, 2008.
10. Mahyavanshi, Alpesh, M. A. Mulla, and R. Chudamani. "Reactive power compensation by controlling the DSTATCOM." International Journal of Emerging Technology and Advanced Engineering 2.11 (2012): 212-218.
11. Tejwani, Vinod S., et al. "Power quality improvement in power distribution system using D-STATCOM." 2013 Nirma University International Conference on Engineering (NUiCONE). IEEE, 2013.
12. Rao, Kolli Nageswar, C. Hari Krishna, and Kiran Kumar Kuthadi. "Implementation of D-STACTOM for Improvement of Power Quality in Radial Distribution System." International Journal of Modern Engineering Research (IJMER) www. ijmer. com 2.5 (2012).
13. Reddy, D. Mohan, and T. Gowrimanohar. "Cascaded multilevel inverter based DSTATCOM for restructured power systems to compensate the reactive power and harmonics using shift carrier techniques." IOSR Journal of Electrical and Electronics Engineering 4.3 (2013): 39-48.
14. Sundar, G., and S. RamaReddy. "Digital Simulation of D-Statcom for voltage fluctuations." International Journal of Engineering Science and Technology 2.5 (2010): 1131-1135.
15. Anuradha, K., B. P. Muni, and AD Raj Kumar. "Modeling of Electric Arc Furnace & Control Algorithms for voltage flicker mitigation using DSTATCOM." 2009 IEEE 6th International Power Electronics and Motion Control Conference. IEEE, 2009.
16. Kuwalek, P. "The application of kernel density estimation for aided the process of locating sources of voltage fluctuations." Przeglad Elektrotechniczny 95.8 (2019): 70-74.
17. Choudhury, Subhashree. "Voltage Flicker Compensation of STATCOM Through Novel Bee Colony Optimization." 2020 International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2020.