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Power Quality Improvement with Reduced Switching Frequency in Grid Connected Wind Energy System

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***Abstract*—The rapid developments in the technology, industrial revolution and growing population stimulated the demand for energy. Fossil fuels have dominated energy sector for many years. But the situation is rapidly changing due to climate changes trigged by greenhouse gas emissions of fossil fuels and fast depletions in the reserves of fossil fuels. This has forced the policy makers to encourage use of renewable energy instead of fossil fuels. The use of grid integrated wind turbines has been increasing at a greater pace, leading to power quality problems in the grid. In this a paper, a STATCOM control scheme is proposed to mitigate the power quality problems posed due to grid integration of wind turbines. Power Balance Theory (PBT) is employed to generate reference currents for grid synchronization. Another advantage of the proposed scheme is to obtain the desired Unity Power Factor (UPF) and Total Harmonic Distortion (THD) in the system at the desired levels with a reduced switching frequency of the IGBT switches of the STATCOM. The proposed system along with control scheme is simulated in MATLAB/SIMULINK. To highlight the reduced switching frequency capability of proposed Space Vector Current Controller (SVCC), a comparative analysis is also performed with simple two step On-Off Current Controller (OOCC) and the results have been presented for both the controllers for the purpose of comparison.**

***Index Terms*— Wind Energy System (WES), Total Harmonic Distortion (THD), Static Synchronous Compensator (STATCOM), Power Balance Theory (PBT), On-Off Current Controller (OOCC), Space Vector Current Controller (SVCC).**

I. INTRODUCTION

Modern human being needs energy for almost all activities. Nowadays a country's economic development and quality of life of people can be directly measured by the amount of energy consumption of a country. The global energy consumption is increasing day-by-day due to rapid technological advances, growing population and industrial revolution [1].Fossil fuels contributed to 70 % of global energy requirements in the year 2017. The dominance of fossil fuels in energy sector is due the mature technology and infrastructure of fossil fuels [2]. But the situation is fast changing for fossil fuels due to emission of Green House Gases (GHG) and the associated climate changes. The fossil fuels for generating electricity alone contribute to one-third of GHG in the world. The change in climate also trigged the global ecological balance change [3]. Understanding the need for protection of environment, world political leaders signed the Paris agreement to limit the global temperature rise to a level below 2 ^{o}C [4]. The Earth has only limited sources of fossil fuels and it is not sure how much reserves

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are present in the layers of Earth's crust. The estimates for the number of years the fossil fuels will serve with the current rates of consumption and production is 50 years for crude oil and 300 years
for coal. The estimate in years for other fossil fuels is anywhere between 50 years and 300 years [5]. This has forced policy makers to design policies to encourage renewable energy instead of fossils fuels. The world's energy demand will be at its peak in 2030 as per the report of World Energy Council (WEC)[6]. To meet the future increased energy demand with uncertain fossil fuel reserves is not possible. Due to these factors, there has been tremendous growth in renewable energy sector particularly in wind energy sector. As per the latest data of International Renewable Energy Agency (IRENA), the wind power has been increased 75 times in the last two decades,that is from the years 1997 to 2018 from values of 7.5 GW to 564 GW. From the years of 2013 to 2016, the electricity generation from wind turbines has been doubled and in the year 2016, the wind alone contributed 16 % of total energy of all the renewables [7].

In the early years of development of electricity generation from wind turbines and its grid integration, the rules were not stringent as the power due to wind turbines is nominal and also to encourage wind energy [8]. Normally the electrical energy is generated from the alternators and these alternators are connected to a grid in a power system grid. But in the wind turbines, electrical power is normally generated using Induction Generators (IG) and the features of IG are different from the conventional alternators. Due to the mismatch of the characteristics of the generators and with the bulk wind power integrated in to the grid, Power Quality (PQ) and grid stability have become major issues [9, 10]. Electrical utilities are now considering grid integration of wind power is risky and a major concern for PQ and grid stability. In order to facilitate effective grid integration of wind turbines, International Electrotechnical Commission (IEC) has developed draft IEC-61400-21 standard in 1995 and published first edition of IEC-61400-21 in the year 2001 [11, 12]. Induction generator is rugged and cheap in cost but it requires reactive power support to operate, unlike traditional alternators. This has caused additional burden on grid to supply reactive power to load as well as Induction Generator. The proposed control scheme of the STATCOM shall supply required reactive power to load as well as IG and thus helps to maintain Unity Power Factor (UPF) at the source. It also injects currents in to system to nullify the harmonics injected in to the grid by nonlinear loads and thus helps to maintain the Total Harmonic Distortion (THD) in the system at the prescribed levels.

II. Grid Integrated Wind Energy System

The proposed grid integrated Wind Energy System (WES) to study the PQ issues and the effectiveness of the proposed STATCOM controller is shown in Fig. 1. The system shown in Fig. 1 has a source of supply, STATCOM, WES coupled with IG and a nonlinear load with reactive power requirement i.e., R-L load, all connected to Point of Common Coupling (PCC). The system shown in Fig. 1 is again shown in Fig. 2 with the details of control structure to highlight the control mechanism of the proposed system.

A. Wind Energy System

A generator is connected to a Wind Turbine (WT) for the transformation of the kinetic energy of wind to electrical energy. Generally, a gear mechanism is employed in WES so as match the low-speed WT and high-speed electrical energy generator. The electrical generators that are normally connected to WT are three phase synchronous generators, IG and Permanent magnet synchronous generators. But IG and Permanent Magnet Synchronous Generators (PMSG) are more generally preferred generators due to cheaper in cost and reliable. In the proposed system in this paper, an Induction Generator is employed due to its advantages like: no need of any

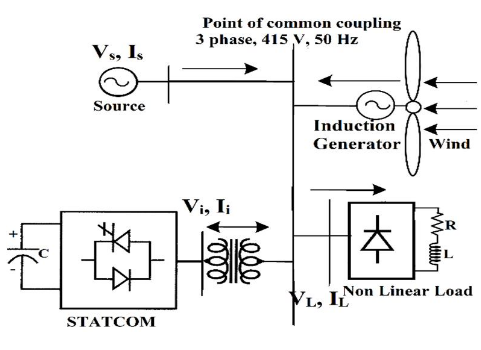

Figure 1. Grid integrated WES

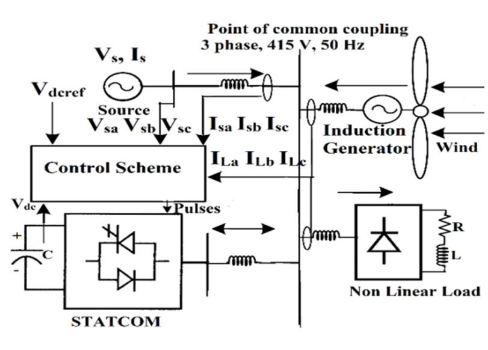

Figure 2. Control scheme

extra DC power for magnetic circuit, rugged, economical and simple [13].

B. Generation of reference currents

To achieve the desired PQ norms in the proposed system, the control scheme must derive desired reference currents. The block diagram of Fig. 3 shows the extraction of reference currents. Once the reference currents are generated, the actual currents and reference currents are compared to obtain signals for current controller. In this paper, a Space Vector Current Controller (SVCC) is employed to generate the switching signals for IGBTs of STATCOM. In order to highlight the reduced switching frequency capability of SVCC, a comparative analysis has been done using a simple two step On-Off Current Controller (OOCC).

Power Balance Theory (PBT) based control strategy has been employed, as shown in Fig. 3, to generate the reference currents for grid synchronisation.The voltages v_{sa}, v_{sb}, and v_{sc} at PCC are sensed to calculate voltage amplitude, V_t [14].

$$V_t = \left\{ \left(2/3 \right) \left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2 \right) \right\}^{1/2} \tag{1}$$

The unit templates u_a, u_b, and u_c, which are in phase, are calculated as

$$u_a = \frac{v_{sa}}{V_t}, \quad u_b = \frac{v_{sb}}{V_t}, \quad u_c = \frac{v_{sc}}{V_t} \tag{2}$$

The load active and reactive powers (instantaneous) are obtained as,

$$p_L = v_{sa} i_{La} + v_{sb} i_{Lb} + v_{sc} i_{Lc} \quad \text{and} \quad q_L = 1/\sqrt{3} \{ (v_{sa} - v_{sb}) i_{Lc} + (v_{sb} - v_{sc}) i_{La} + (v_{sc} - v_{sa}) i_{Lb} \} \tag{3}$$

Using a low pass filter, P_{LD} and Q_{LD}, active power and reactive powers of fundamental DC component are obtained. The fundamental active, I_{LpD}, and reactive, I_{LqD}, load currents are calculated as,

$$I_{LpD} = 2/3 \left(\frac{P_{LD}}{V_t} \right) \quad \text{and} \quad I_{LqD} = 2/3 \left(\frac{Q_{LD}}{V_t} \right) \tag{4}$$

The in-phase value of grid current reference is $I_{sp}^{ref} = I_{loss} + I_{LpD}$ (5)

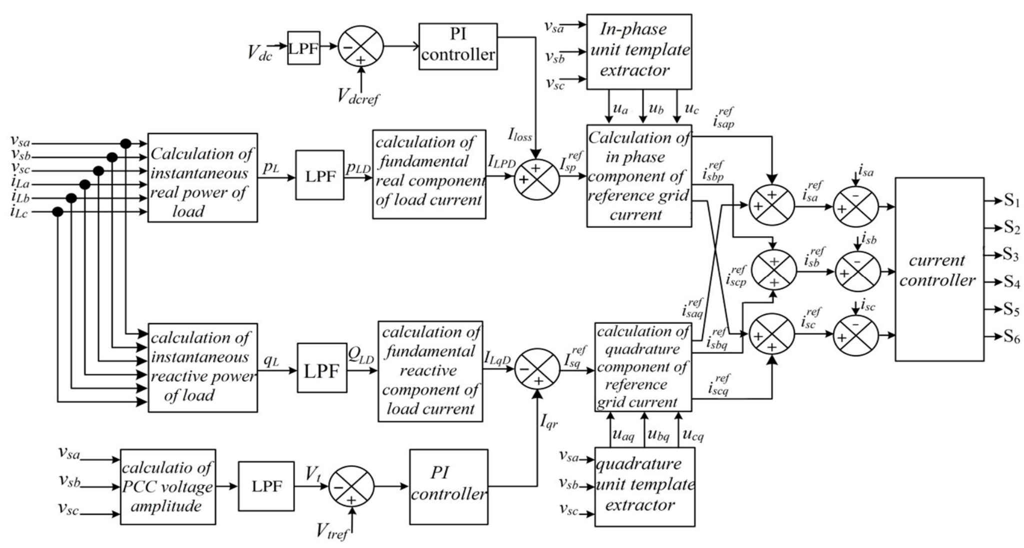

Figure 3. Extraction of reference currents using Power Balance Theory

The reference grid currents can be computed as follows,

$$i_{sap}^{ref} = u_a I_{sp}^{ref}, \; i_{sbp}^{ref} = u_b I_{sp}^{ref}, \; i_{scp}^{ref} = u_c I_{sp}^{ref} \tag{6}$$

The amplitude of quadrature component of reference grid current is computed by subtracting I_{LqD} from the output of AC voltage PI controller (I_{qr}). $I_{sq}^{ref} = I_{qr} - I_{LqD}$ (7)

The value of reference grid currents (quadrature component) are calculated as,

$$i_{saq}^{ref} = u_{aq} I_{sq}^{ref},\ i_{sbq}^{ref} = u_{bq} I_{sq}^{ref},\ i_{scq}^{ref} = u_{cq} I_{sq}^{ref} \tag{8}$$

The unit templates (quadrature), u_{aq} , u_{bq} , and u_{cq} are evaluated as,

$$u_{aq} = \frac{(-u_b + u_c)}{\sqrt{3}},\ u_{bq} = \frac{(3u_a + u_b - u_c)}{2\sqrt{3}},\ \text{and}\ u_{cq} = \frac{(-3u_a + u_b - u_c)}{2\sqrt{3}} \tag{9}$$

The reference currents needed for grid synchronization are computed as,

$$i_{sa}^{ref} = i_{sap}^{ref} + i_{saq}^{ref},\ i_{sb}^{ref} = i_{sbp}^{ref} + i_{sbq}^{ref},\ \text{and}\ i_{sc}^{ref} = i_{scp}^{ref} + i_{scq}^{ref} \tag{10}$$

C. On-Off Current Controller (OOCC)

This is a simple current controller to implement and it is shown in Fig. 4. The actual currents are sensed through sensors and these currents are compared with reference currents as calculated in (12). The error is fed to the OOCC to obtain switching pulses ofSTATCOM so as to force the actual currents to follow reference currents in order to achieve the desired PQ norms [15].

D. Space Vector Current Controller (SVCC)

Though OOCC is simple to implement, it has some drawbacks. There are three independent controllers for three phases and each leg of the STATCOM is controlled by each independent controllers. This causes lack of coordination among three independent controllers, leading to higher switching frequency and more current error [16, 17]. To overcome these drawbacks, a SVCC is proposed for current control in this paper. The three phase voltages are converted in to stationary coordinate system using the relation

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \tag{11}$$

The STATCOM shall have eight conducting states. All the conducting states and its corresponding output voltages of STATCOM are shown in Fig. 5. With a width of δ, three hysteresis bands are defined for three phase reference currents, as shown in Fig. 6. This hysteresis band is now transformed in to stationary system leading to a hexagon region, as shown in Fig. 7.The three phase reference currents when transformed in to a stationary system, gives a current vector with its tip forming a circle, as shown in Fig. 7 [18]. The control system shall take care to keep the current, i, with in the hexagon region so as to obtain desired PQ norms. The difference between the reference current, i_{ref}, and actual current, i, is the current error, i_e. The switching logic

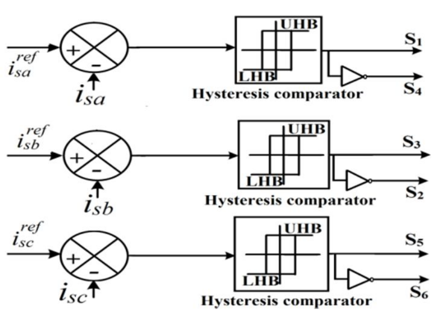

Figure 4. On-Off current controller

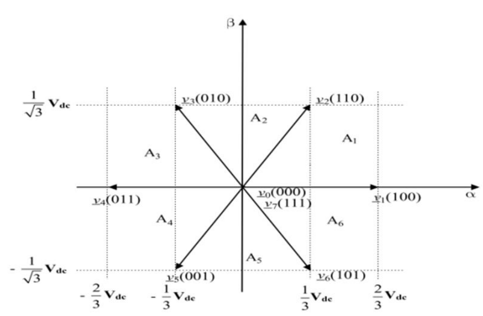

Figure 5. Switching states and corresponding output voltages

should see that current error should stay within the hexagon region so as to achieve the desired PQ norms. The switching logic should select the best possible voltage vector among eight to bring back the current error in to the hexagon region as quickly as possible in order to have good dynamic response. For example, if the error is

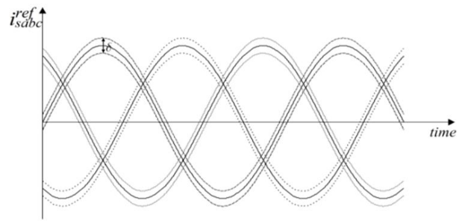

Figure 6.Hysteresis bands

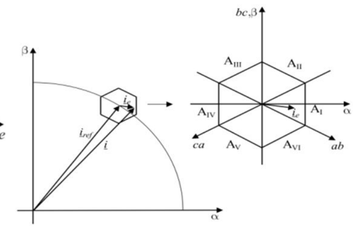

Figure 7.Reference and error currents variation in stationary system

touching the boundary of hexagon in A_{IV} region then the voltage vector exactly opposite to the A_{IV} region i.e, $\underline{v}_1$ is applied. The control system is shown in Fig. 8 and the switching logic is shown in table I.

III. RESULTS AND DISCUSSION

A. Without STATCOM

The system shown in Fig. 1 is simulated in MATLAB/SIMULINK without STATCOM and the results are obtained. The load is a nonlinear RL load and so the load current and source currents are distorted. Due to nonlinear load, the THD of source current is 26.12 % and the power factor at the source is lagging. The waveforms for this case are shown in from Fig. 9 to Fig. 12.

B. With STATCOM and OOCC

With presence of STATCOM and its controller, the source current waveform is improved even with the presence of nonlinear RL load and this is clear from source current THD value of 4.34 %. The source power factor is also improved to unity. The waveforms for this case are shown in from Fig. 13 to Fig. 16.

C. With STATCOM and SVCC

With presence of STATCOM and its SVCC controller, the source current waveform is improved even with the presence of nonlinear RL load and this is clear from source current THD value of 3.36 %. The source power factor is also improved to unity. The waveforms for this case are shown in from Fig. 17 to Fig. 18.

D. Switching Frequency

For the comparative analysis of switching frequency, plots of switching frequency of IGBT at top most position in phase A are plotted for OOCC and SVCC controllers, as shown in Fig. 19 and Fig. 20. From the plots it is clear that SVCC is operating at 50 KHz and where as OOCC is operating at 100 KHz.

IV. CONCLUSIONS

The PQ improvement of grid integrated WES with PBT based STATCOM controller with SVCC is presented in this paper. The proposed system has effectively improved THD of source current from 26.12 % to 3.36 %, which is an acceptable value as per standards. The source power factor is also maintained at UPF with proposed controller as the controller is effectively supplying reactive power to load and IG. The advantage of the proposed SVCC is its ability to mitigate PQ problems of grid integrated WES at reduced switching frequency. This fact is clear from the comparative analysis of switching frequency of OOCC and SVCC, as SVCC has shown to operate at 50 % lower frequency when compared to OOCC.

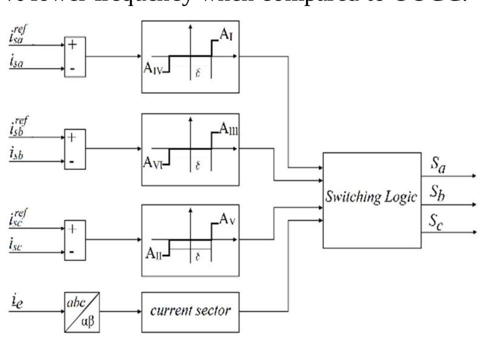

Figure 8. Control system

TABLE I. SWITCHING LOGIC

Area of current error vector, $\underline{i}_e$	A_I	A_{II}	A_{III}	A_{IV}	A_V	A_{VI}
Applied Voltage vector	$\underline{v}_4$	$\underline{v}_5$	$\underline{v}_6$	$\underline{v}_1$	$\underline{v}_2$	$\underline{v}_3$

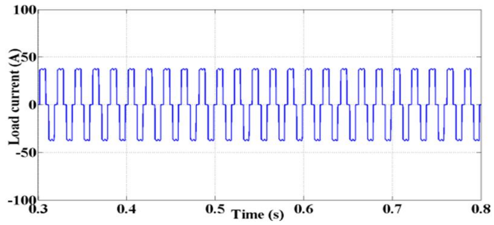

Figure 9. .Load current

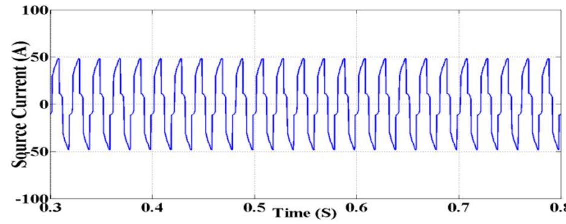

Figure 10.Source current

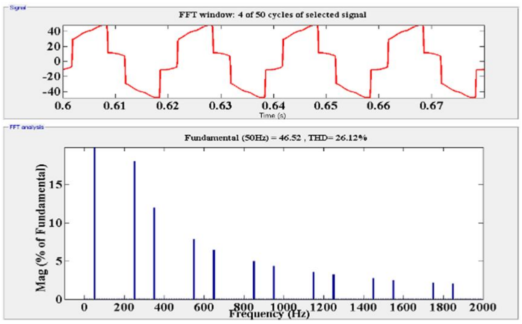

Figure 11. FFT analysis of source current

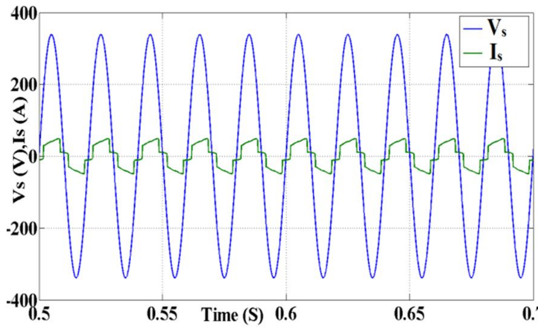

Figure 12.Source voltage and source current

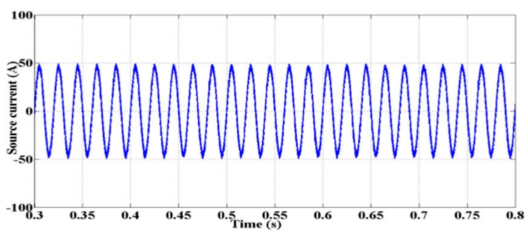

Figure 13.Source current

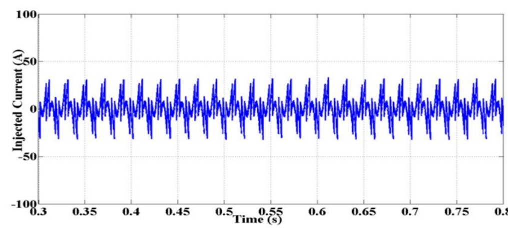

Figure 14. STATCOM injected current

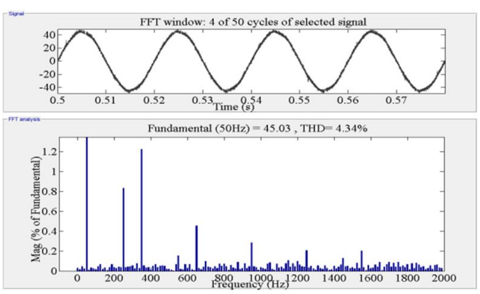

Figure 15. FFT analysis of source current

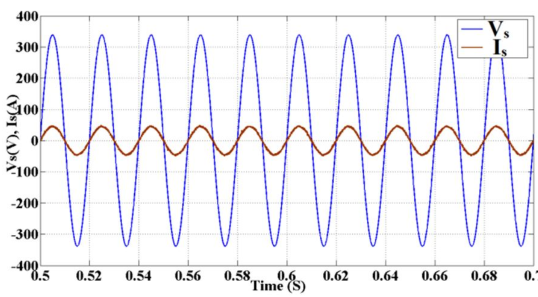

Figure 16.Source voltage and source current

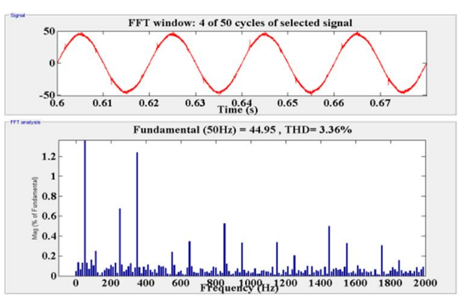

Figure 17. FFT analysis of source current

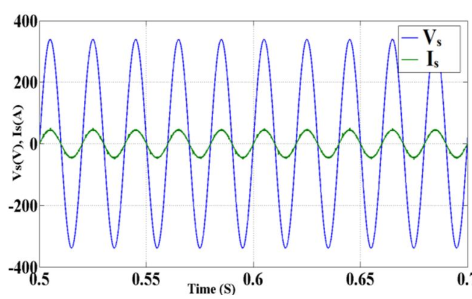

Figure 18.Source voltage and source current

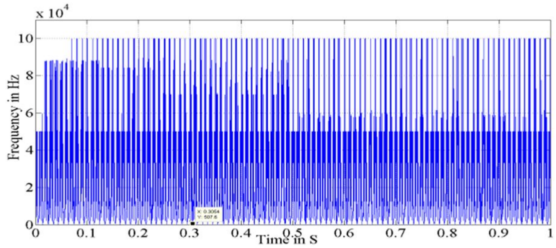

Figure 19. Switching frequency with OOCC

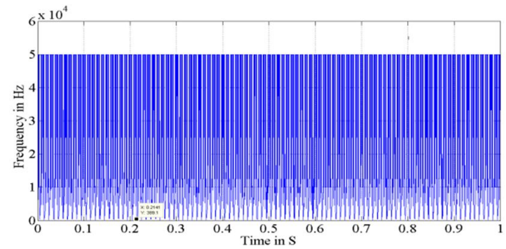

Figure 20. Switching frequency with SVCC

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