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Comparative study of SPWM and SVPWM techniques for the control of three-phase grid connected inverter

Abstract: *The importance of three-phase grid connected inverters has increased due to the increasing use of renewable energy such as photovoltaic energy, wind energy, and others. This study presents a comparison between two methods of controlling the work of the inverter. The first method is SPWM technique, and the second method is SVPWM. The comparison is in terms of THD level in the output voltage and current, as well as comparing the controlling steps for both methods under the same working conditions. The value of the coils and capacitors required in the filter circuit connecting the inverter and the grid are calculated for a power of 200KVA. An active power is injected from the inverter to the network, and it was found that the angle between the grid voltage and the inverter current is zero degrees, as well as reactive power is injected, and it is found that the angle became 90 degrees as expected. The MATLAB program is used to build both techniques. The study provides an analysis of voltages and currents at different locations between the inverter and the grid, in addition to the frequency analysis of these variables.*

Streszczenie. *Znaczenie inwerterów podłączonych do sieci trójfazowej wzrosło ze względu na rosnące wykorzystanie energii odnawialnej, takiej jak energia fotowoltaiczna, energia wiatrowa i inne. W pracy przedstawiono porównanie dwóch metod sterowania pracą falownika. Pierwsza metoda to technika SPWM, a druga metoda to SVPWM. Porównanie dotyczy poziomu THD w napięciu wyjściowym i prądzie, a także porównanie kroków kontrolnych dla obu metod w tych samych warunkach pracy. Wartość cewek i kondensatorów wymaganych w obwodzie filtra łączącego falownik z siecią obliczono dla mocy 200KVA. Moc czynna jest wprowadzana z falownika do sieci i stwierdzono, że kąt między napięciem sieci a prądem falownika wynosi zero stopni, podobnie jak moc bierna jest wtryskiwana i stwierdzono, że kąt wynosi 90 stopni, ponieważ oczekiwany. Program MATLAB jest używany do budowy obu technik. Opracowanie zawiera analizę napięć i prądów w różnych miejscach między falownikiem a siecią, oprócz analizy częstotliwościowej tych zmiennych.* (***Badanie porównawcze technik SPWM i SVPWM do sterowania falownikiem trójfazowym podłączonym do sieci***)

Keywords: Inverters, grid connected, PWM, SVPWM
Słowa kluczowe: przekształtnik, PWN, SWPW

1. Introduction

With the increase in the need for electrical energy and the increase in people's knowledge of its impact on the environment, it has become important to develop renewable energy. The power electronics architecture has been expanded to accommodate this rapid development. Single or three-phase inverters are the focus of power electronics devices, and researchers' interest in turn has increased steadily [1]. Three-phase inverters are connected to the grid to support it by injecting electric current from the inverter to the grid [2]. The study and development of methods of controlling the work of inverters have grown widely [3]. The way of controlling the active and reactive power injected into the grid and controlling DC link voltage ensure high efficiency of the injected power which help to reduce the THD of the system and reduces the value of the DC component injected into the grid. The traditional technique of sinusoidal pulse width modulation (SPWM) technique is highly used for controlling the voltage source inverters [4-5]. In three-phase inverters, the transformer secondary is normally connected in delta to eliminate triplen harmonics (n = 3, 6, 9….) appearing on the output voltages. The employment of SPWM technique to control the output voltage of the inverter help to reduce the distortion factor (DF) and the low order harmonics (LOH) significantly [6-8]. The other important technique is the development in space vector pulse width modulation SVPWM technology made it preferred in applications because of its clear effect in reducing the amount of THD in the system compared to other technologies [9-11]. In multi-level inverters the eliminations of desired harmonics are based on optimized switching techniques [12]. The conventional proportional-integral PI and the phase locked loop PLL-based control scheme that needs both a grid voltage and a current sensor is extremely used in the grid -connected inverters. Three-phase inverters for grid-connected applications require a method for grid voltage phase detection to synchronize the grid and control real and reactive power. This phase detection is usually based upon some type of grid voltage and current sensing [13-16]. The other important parameter in grid connected inverter is the LCL filter. This filter is required as an interface between the inverter and the electric grid. The most effective filter for suppressing of the current harmonics occurring from the switching frequency injected into the grid [17-20]. Both the voltage and current control concept in the three-phase grid connected inverter is based on transformation of the three-phase voltages and currents into two frame axes using the concept of Clark transformation and then back to the three-phase control reference voltage and currents by the inverse Clark transformation [21-22].

2. Working principals of the three-phase grid connected inverter

The control algorithm is based on synchronous rotating reference theory. To implement the controller the voltages and currents are sensed as shown in figure (1). The three – phase line voltages from the grid side are transformed to the corresponding alpha beta voltages using the Clark transformation method. Then the phase locked loop is then implemented to get the synchronous timing signal (wt). The inverter side currents are used in the same manner to get the corresponding alpha beta references. The alpha beta from both the voltage and current sides are then transformed to the DC domain using the inverse Clark transformation. Now, the values of the direct(d-axis) and the quadrature(q-axis) are ready to feed into the PI controller circuit. The output of the controller comparator are the reference signals of the SPWM or the SVPWM techniques. These three-phase 50Hz reference signals are compared to the high frequncy carrier signals to get the six pulses to drive the six transistors in the inverter circuit.

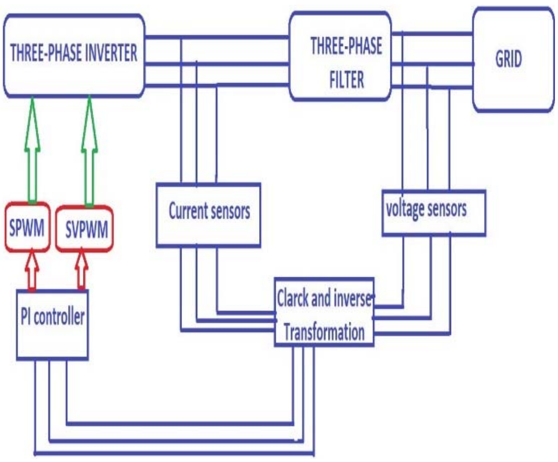

Fig. 1. Schematic diagram of three-phase grid connected inverter

3. Filter design

The inverter is connected to the grid via a filter to smooth the current injected into the grid by the inverter. The filter is composed of LCL connection either of T section or π section. The filter plays a significant role by eliminating a sweep of unwanted high frequency components in the injected current. To illustrate how to determine the value of the filter capacitance and inductance, a single and three phase filters is shown in figure (2) and figure (3) respectively.

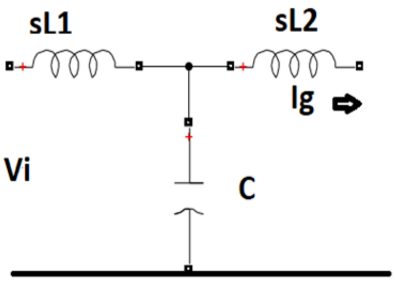

Fig. 2 Single Phase filter

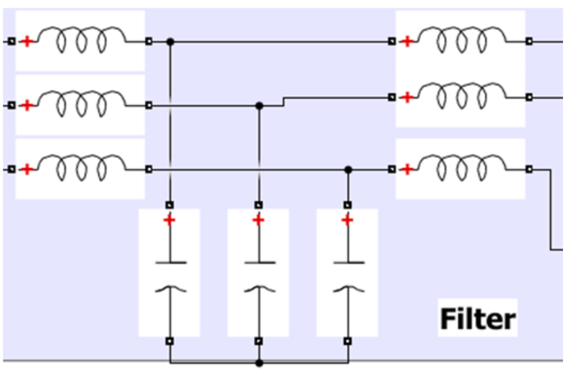

Fig. 3 Three-phase filter

The specifications of the system are chosen as 200kKVA, 230V, 50Hz. The standard permissible reactive power is 5% of the rated power (S). For three phase system, the reactive power Q is given by:

(1) $$\boldsymbol{Q} = \frac{V^2/3}{1/(w*C)} = 5\%\ of\ S\ .....,$$

where: S is the apparent power, w=redian frequency and C is the capacitance.

$$C = \frac{0.05 * S/3}{V^2 * 2 * pi * 50} = 200\mu F.$$

Let $L1 = L2 = L$ and the parallel connection $L_p = \frac{L_1 L_2}{L_1 + L_2}$ and the radian resonance frequency $\boldsymbol{w}_{res} = \frac{1}{\sqrt{CL_p}}$. The transfer function of figure (2) is found to be:

(2) $$\frac{I_g}{v_i} = \frac{1}{sL(1+s^2 CL_p)}$$
$$\frac{\boldsymbol{I_g}}{\boldsymbol{v_i}} = \frac{\boldsymbol{1}}{\boldsymbol{sL}\left(\boldsymbol{1}+\frac{s^2}{w_{res}^2}\right)}\ ....$$

The switching frequency is defined as the frequency of the carrier signal in SPWM and SVPWM techniques and is chosen to be f_{sw} = 10kHz. The resonance frequency is $\boldsymbol{f}_{res} = \frac{f_{sw}}{10}$ = 1kHz.
Letting $s = jw_{sw}$ in equation (2)

(3) $$L = \frac{1}{w_{sw}\frac{I_{g_{sw}}}{v_{i_{sw}}}(1-\frac{w_{sw}^2}{w_{res}^2})}\ ....$$

The grid current $I_g = \frac{S}{V} = \frac{200*10^3}{230} = 290$A.

The value of the grid current at switching frequency $i_g = 0.3\%\ of\ I_g$ i_g=0.87A. the terminal input voltage of the filter $v_{i_{sw}} = 0.9 * V_g$= 0.9*230 = 207V. From equation (3) the value of the filter inductance is:

$$L = \frac{\boldsymbol{1}}{(\boldsymbol{2*pi*10000})(\frac{0.87}{207})(1-\frac{(2*pi*10000)^2}{(2*pi*1000)^2})} = 38\mu\text{H}$$

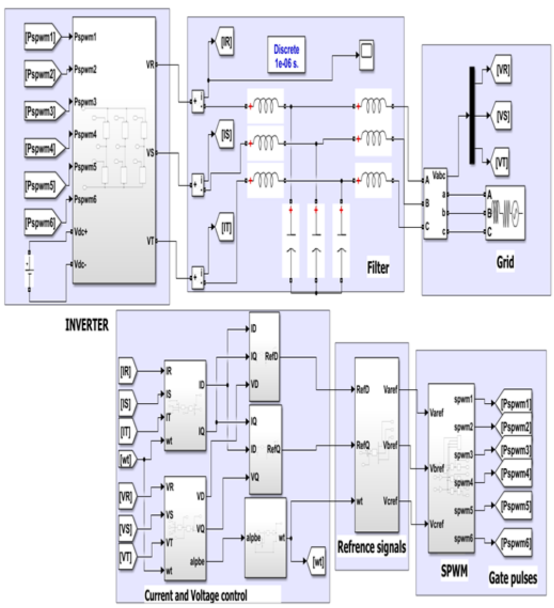

Fig. 4. Simulink model for the three-phase grid connected inverter

4. Simulink model of three phase grid connected inverter

Figure (4) shows the Simulink MATLAB of three-phase connected inverter. The diagram consists of five parts. The first is three phase- inverter which consists of six IGBT or MOSFET transistors. The second is the three-phase filter section which is formed by connecting three-single phase filters. The third part is the grid section where it is connected to the inverter via the filter. The fourth part is the voltage and the current controllers aiming to output the required reference voltages. In the fifth part, these voltages are employed as references in SPWM and SVPWM techniques to get the six pulses required to drive the transistors in the inverter section

After sensing the three-phase grid voltages $V_{R,}V_S, and\ V_T$, and the three-phase inverter currents I_R, I_S, I_T , the abc to alpha-Beta principle is implemented as shown in figure (5)

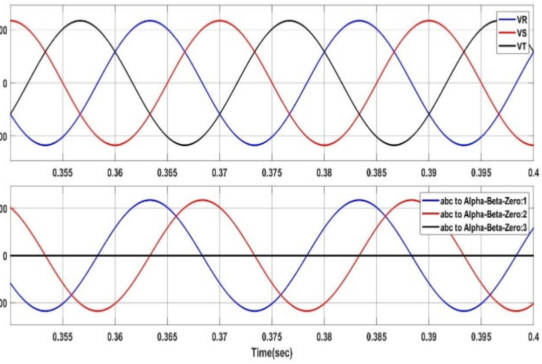

Fig. 5 Abc to Alpha-Beta principle

Then the d-q frame is obtained from the Alpha-beta as shown in figure (6)

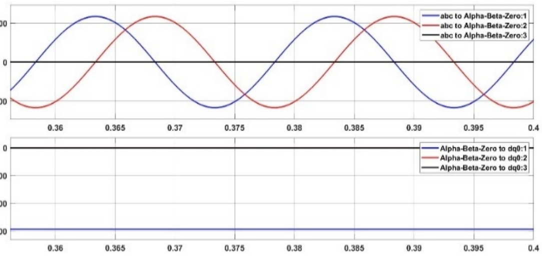

Fig.6. Alpha-Beta to d-q frame

The references RefD and RefQ are obtained from the d-q frame and then transformed to the final there-phase references that are used for the SPWM and SVPWM techniques as shown in figure (7).

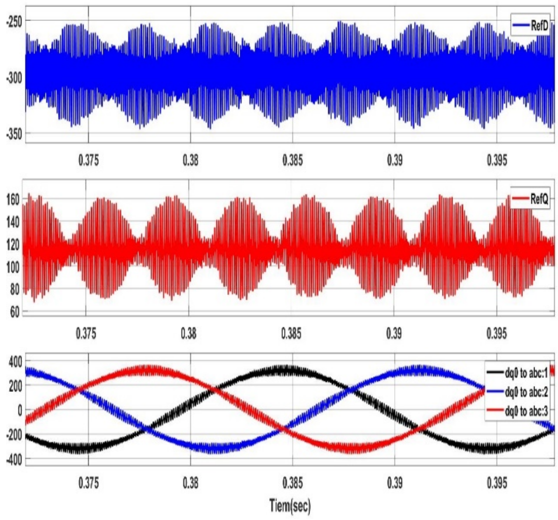

Fig. 7. RefD and RefQ to three-phase references transformation

These 50Hz references are compared with triangular carrier signal of 10KHz in the SPWM circuit and an output pulse is generated each time when the reference voltage is greater than the carrier signal. Figure (8) shown the three-phase voltage references and the carrier waveforms.

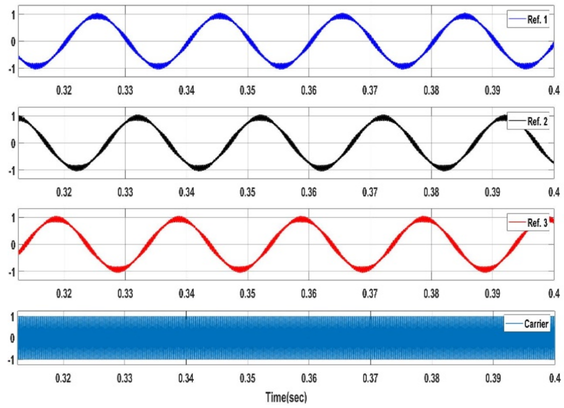

Fig. 8. Three-phase and carrier waveforms for SPWM

All the above are synchronized operation controlled by the (wt) linear region shown in figure (9). The (wt) signal is generated from phase locked loop PLL which is connected to the voltage control circuit.

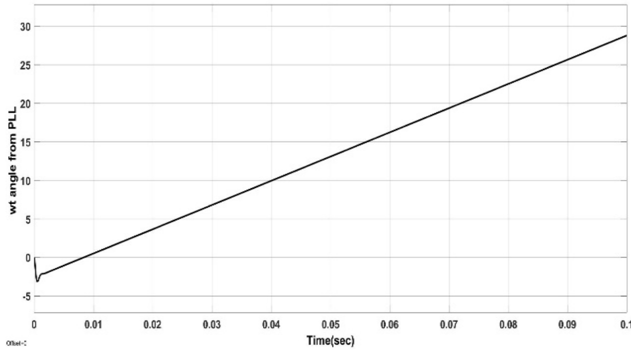

Fig. 9. The (wt) synchronized signal

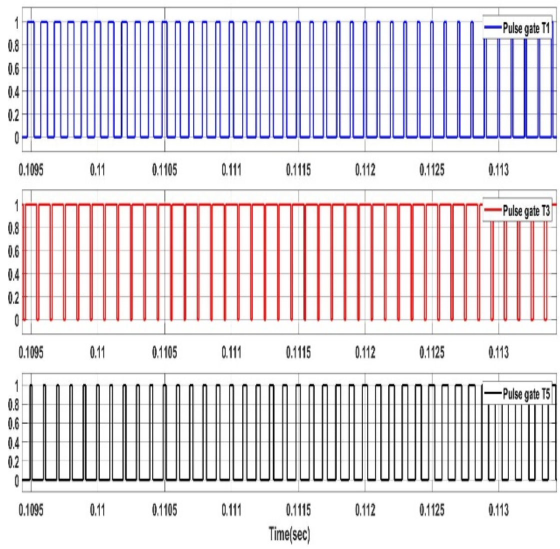

Fig.10.Three-phase pulses for switching operations

SVPWM and SPWM are two modulation techniques commonly used with power converters. The purpose of a modulation scheme is to translate a voltage reference into a sequence of switching signals, to produce that reference at the output of the converter. While both techniques share similar acronyms, they have different approaches.

The SVPWM technique represents each switching state of the converter by a space vector in the Clarke reference domain. Then, the desired output voltage is synthesized on average, by alternating between multiple space vectors over each switching period. On the other hand, SPWM is a Carrier-Based PWM scheme. After the implementation of the SPWM technique by logical operations of the 50Hz reference signal with 10kHz carrier signal, the required three-phase pulses are supplied to the gates of the appropriate transistors in the three-phase-inverter circuit as shown in figure (10).

The three-phase inverter output voltage unipolar output is shown in figure (11) using a DC supply of 800V.

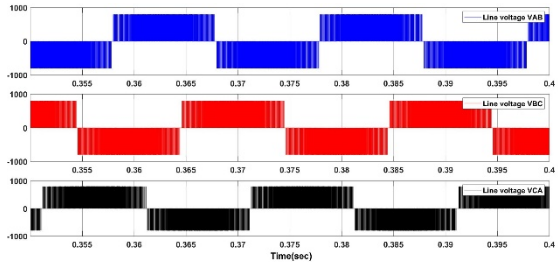

Fig. 11.Three-phase pulsating inverter output

The injection of active current into the grid is shown in figure (12). It is obvious that the phase difference between the grid voltage and the injected current is zero as expected. The value of the injected current is set to the desired value by a constant Simulink block in the current control section.

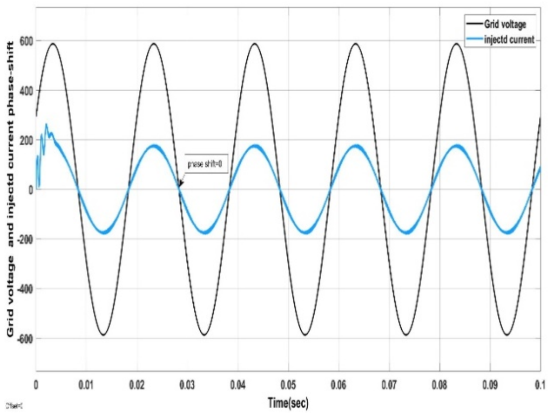

Fig. 12. Active current injection

Figure (13) shows the injection of reactive current into the grid. The angle between the grid voltage and the injected current is almost 90^0 .

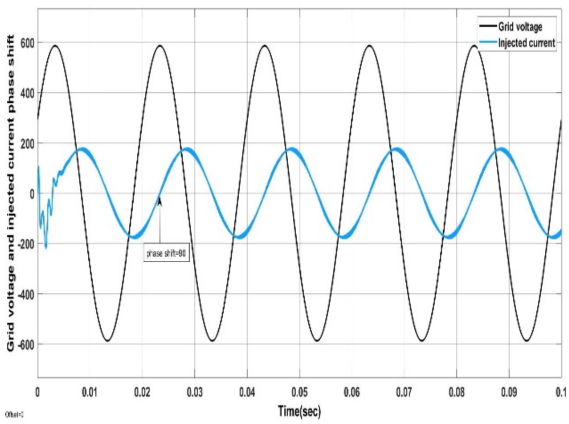

Fig. 13 Reactive power injection

The three-phase grid line voltages along with the injected inverter three phase currents after filtering by the LCL filter for active power are shown in figure (14).

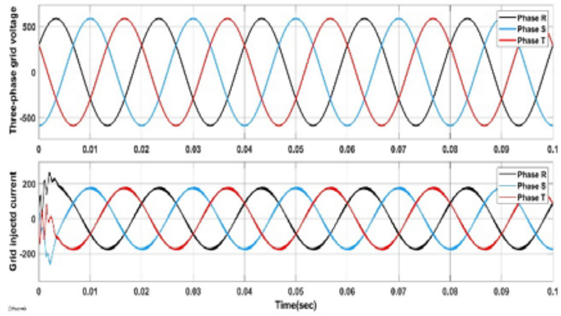

Fig. 14. Grid voltages and active injected currents

The capacitor current of one of the phases is shown in figure (14) . The LCL filter is subjected to high frequency switching operation which explains the ripple contents of the capacitor current.

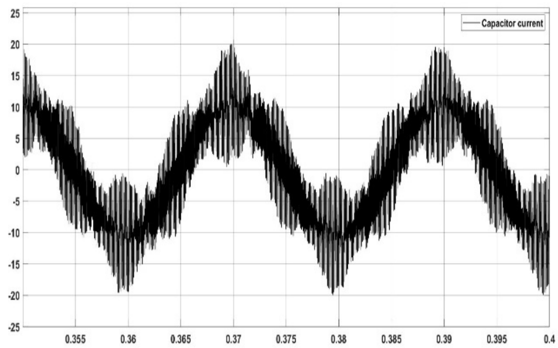

Fig. 15. Capacitor current of one of the phases

The frequency spectrum of the active injected current for one of the phases using SPWM technique is shown in figure (16). The THD is recorded as 3.45% which is within IEEE standard.

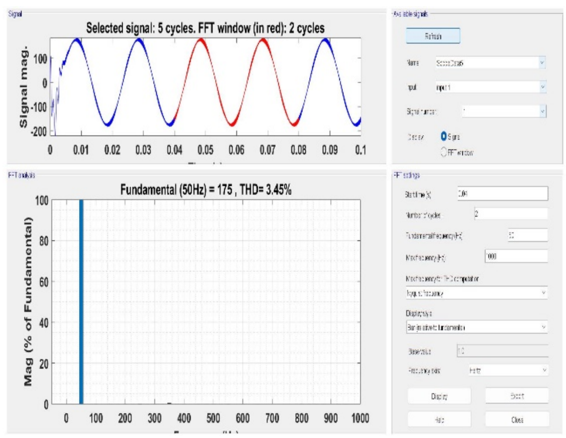

Fig. 16. Frequency spectrum of the active injected current using SPWM

All the mentioned analysis are implemented again but for the SVPWM technique for the sake of comparison. The three-phase references signal for SVPWM technique are shown in figure (17).

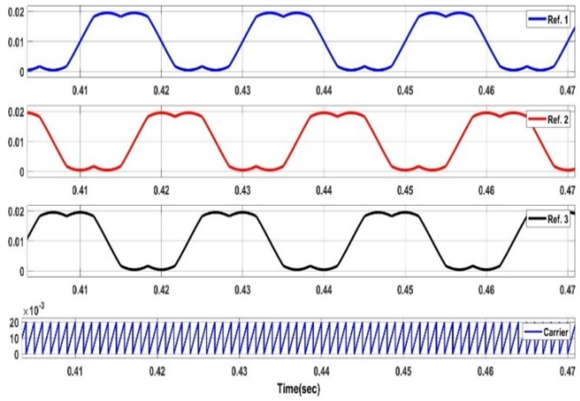

Fig. 17. three-phase reference signals for SVPWM

T Six sectors each of 60^0 span is shown in figure (18). In each sector the required triggering pulses are generated and fed to the gating of the switching transistors in the inverter section.

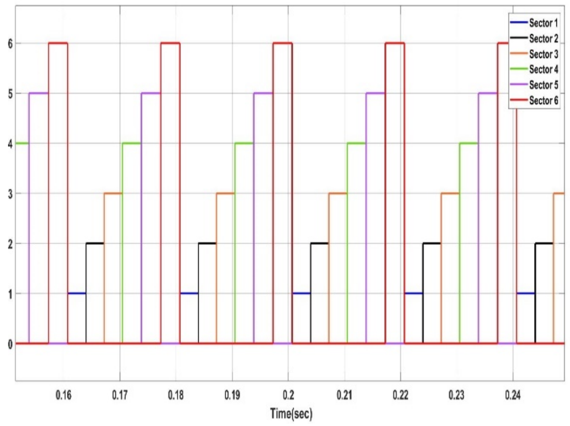

Fig. 18. Six sectors' regions generated in SVPWM

The triggering pulses for the MOSFET switches in the three-phase inverter for SVPWM technique are shown in figure (19)

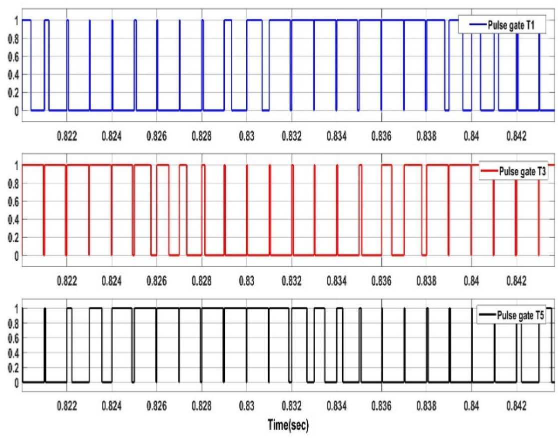

Fig. 19. Triggering pulses fed to the switches for SVPWM

The frequency spectrum for one of the line active injected currents for SVPWM is shown in figure (20). The THD is shown to be 1.66% which is about 50% less than the THD for active injected current for the SPWM.

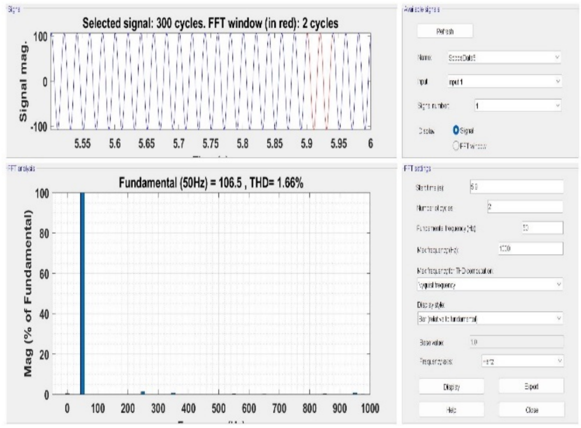

Fig. 20 Frequency spectrum for the active injected current for SVPWM technique

5. Conclusion:

In this paper, an active current and a reactive current were injected from a three-phase inverter to the grid of 200KVA via LCL filter. The inductors and capacitors to build a three-phase filter were calculated for the purpose of removing a lot of high-frequency harmonics that negatively affect the efficiency of the system. The control work starts by sensing the voltages of the grid and the three-currents of the phase inverter and then transforming them into two-dimensional references synchronized with the grid frequency of the system (50Hz). The concept of Clark transformation is used to build the reference signals and it is found that the phase difference between the grid voltage and the inverter current is 0 degree when injecting the active current and 90 degrees when injecting the reactive current. The gating signals for the six electronic switches in the three-phase inverter circuit (MOSFETS) were controlled using SPWM technology first and then the SVPWM technique is used. When comparing the frequency spectrum of the inverter current for SPWM and SVPWM it is found that the value of THD is 3.45 and 1.66 respectively, which shows the superiority of SVPWM techniques over SPWM.

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