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Influence of Switching Strategy on Capacitor Current in a Two Level Converter

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Abstract-DC-link capacitors are widely used in power electronic systems to supply instantaneous power imbalances and to filter harmonics arising from switching and voltage imbalances. However, these harmonics will shorten the life of the capacitors, making them a bottleneck for the system's reliability. This paper presents the impact of switching strategies and the converter configuration on the DC-link capacitor harmonics. It also presents the design and simulation of the Active Front End Converter (AFEC). Total Harmonic Distortion of capacitor current with AFEC is compared to that of a normal rectifier. The AFE converter achieves near-unity power factor, minimal harmonic distortion, enabling efficient bidirectional power flow, particularly beneficial for electric vehicle charging infrastructure and renewable energy integration into the grid. The simulation results show that this configuration has less ripple current in DC-bus capacitors.

Keywords :-Front End Converter, Sine PWM converter,DC link; dq control, PI controller, Clarke's transformation, Park's transformation, THD, Capacitor ripple, Harmonics.

1. INTRODUCTION

Two-level converter consisting of three-phase voltage-source back-to-back converters is shown in Fig. 1, where the rectifier and inverter are linked through a DC capacitor. It is also called as Active Front End Converter (AFEC).AFECs are used in various applications like industrial drives[1] , wind power generation[2], and electric transportation [3]. It's a more advanced type of converter compared to traditional passive front-end converters. The passive front-end converters comes with disadvantages of harmonic distortions and low power factor[4].

Converter topologies play a crucial role in power electronics, and the analysis of capacitor ripple current is essential for their efficient design and operation. This research paper explores the impact of different switching strategies, namely sinusoidal pulse-width modulation[5],[22]and space-vector pulse-width modulation[6],[24][25]on the capacitor ripple current in front-end converters. Additionally, the study investigates the influence of connecting a front-end converter to an inverter on the capacitor ripple current.

The capacitor bank in a front-end converter is typically formed by electrolytic capacitors due to their high energy density(Lei et al., 2017). However,current pulses will be injected into the dc link capacitor from both the rectifier and inverter sidesduring operation. These current pulses lead to high power losses in the dclink capacitor[7].Several methods, such as direct capacitor current control [1], active damping method [8], [9], and feedback linearization control [10], have been proposed to minimize ripple current in capacitor.

Switching strategies play a crucial role in determining the capacitor ripple current. Sinusoidal pulse-width modulation and space-vector pulse-width modulation are two widely used techniques in power electronics (Ki-wai, 1992; Lei et al., 2017). In sinusoidal pulse-width modulation, the output voltage is controlled by modulating the pulse width, while space-vector pulse-width modulation utilizes a mathematical representation of the voltage vectors to achieve a sinusoidal output (Ani, 2013; Ki-wai, 1992).

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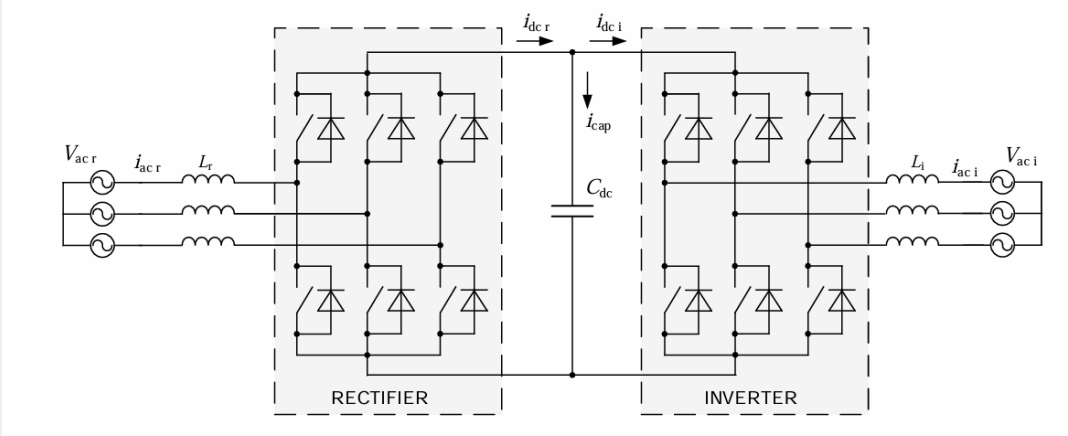

Fig.1: Active end front end converter system

The AFE converter system provides bi-directional power flow, unity power factor, low total harmonic distortion of line current[15].Core of an active front-end rectifier is its control system, which regulates the operation of power electronic devices to meet specific performance goal.

The analysis of sinusoidal pulse-width modulation, and space-vector pulse-width modulation done in[11]. This article [12]will discuss controlling methods of the Active Front End converter to improve electric power quality. The clark's and park's transformation discussed in[13] .

The papers[14],[21]investigates direct and quadrature axis current control method. In this paper[16],the control strategy of three level dc/dc converters are proposed for minimizing and balancing the capacitor ripple currents. The paper[17]is focused on the analysis of voltage imbalance calculation.[18]proposes a multicarrier PWM for three-phase AFE converters. Paper[19] presents an improved current balancing control methods for a high power parallel connected AFE for wind energy applications. The paper [20]presents a dynamic model of the active front-end (AFE) converter in the synchronous reference frame under balance input voltage condition. The concept of THD reduction of active frontend converter discussed in [23].

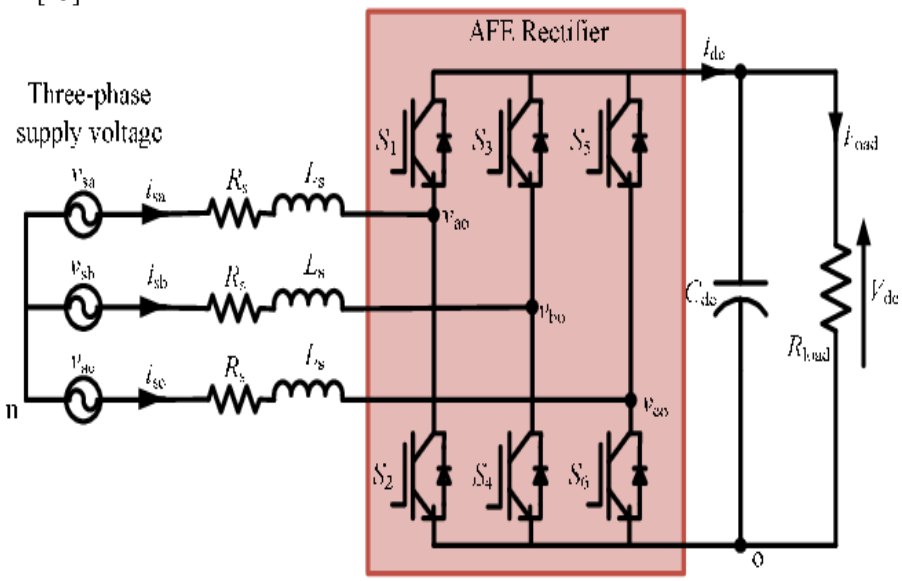

Fig.2: Active Rectifier

1.1. Review of literature:

The frequency of carrier wave is very high compared to that of sine wave. The frequency of carrier wave is called as "Switching frequency". The Reference wave and the Carrier wave are fed to the comparator and signal output is generated based on logic of the comparator. This comparison between a Sinusoidal wave and a triangular wave will give an output of pulsating wave of a constant magnitude and the frequency of this pulsating wave will be equal to the reference wave i.e. sinusoidal wave. The pulses generated has constant magnitude but different duty cycle.

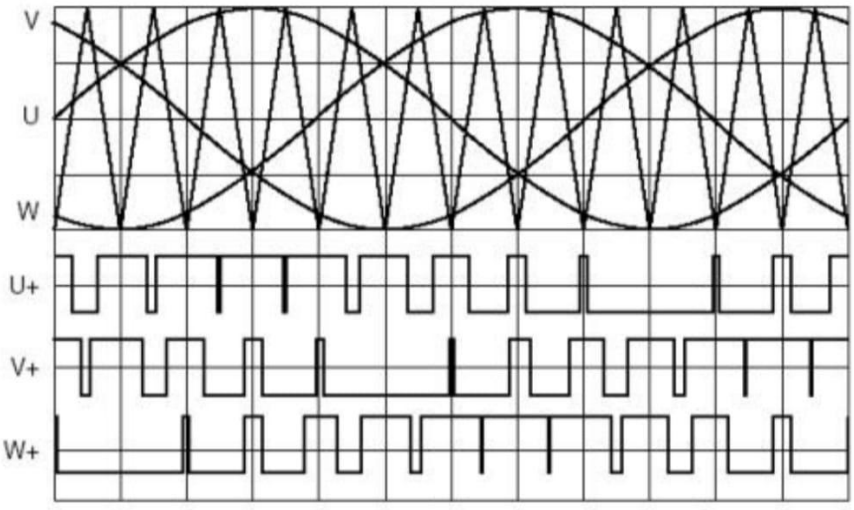

Fig.3: Sinusoidal Pulse Width Modulation (SPWM) technique

1.2. PWM generator:

In this project the three-phase voltage signals (Va, Vb, Vc) are used to as Reference signals and they are compared with a Carrier signal (triangular wave) to perform Sinusoidal Pulse-Width Modulation (SPWM) with the help of logical comparators as shown in fig.4.

The output signals of the comparators are taken as gate pulses for the Active Front End rectifier switches (i.e. PWM1–PWM6).

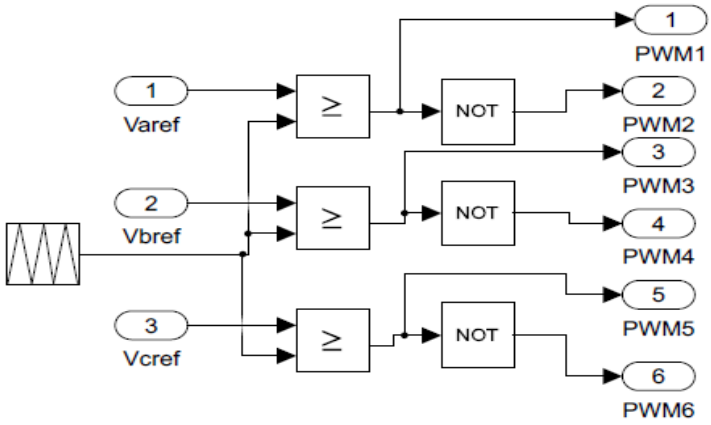

Fig.4: PWM generator

1.3. Control method:

The dq control theory is fundamental in power electronics for simplifying the control of three phase AC systems. This theory involves transforming the three-phase quantities into two orthogonal components (d and q axes) in a rotating reference frame. The primary advantage of this transformation is that it converts AC quantities, which are time-varying, into DC quantities that are easier to manage with standard control techniques such as PI controllers. The transformation from the three-phase abc frame to the $dq0$ frame (also known as combination of Clarke's and Park's transformation) is given by the following equations:

Clarke's transformation:

$$\begin{bmatrix}\alpha\\ \beta\\ 0\end{bmatrix} = \frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{bmatrix}\begin{bmatrix}a\\ b\\ c\end{bmatrix} \quad \ldots(1)$$

Park's Transformation:

$$\begin{bmatrix}d\\ q\end{bmatrix} = \begin{bmatrix}\cos(\omega t) & \sin(\omega t)\\ -\sin(\omega t) & \cos(\omega t)\end{bmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \quad \ldots(2)$$

Three-phase abc frame to the $dq0$ frame (Combination of clarke's and park's transformation):

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \sin(\omega t) & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \ldots (3)$$

Where: θ is the angular position of the rotating reference frame. a, b, c are the three-phase quantities. d, q are the direct and quadrature axis components in the rotating reference frame.

1.4. Phase Locked Loop:

A Phase-Locked Loop (PLL) is crucial in Active Front-End (AFE) rectifiers for synchronizing the rectifier's operation with the grid voltage. This synchronization ensures that the rectifier can perform functions such as harmonic reduction, power factor correction, and bidirectional power flow effectively.

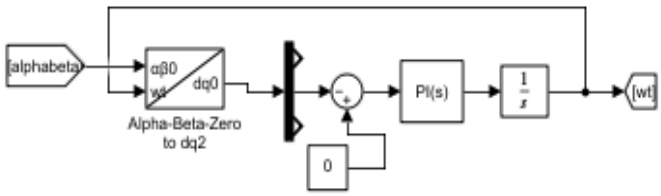

Fig.5: Phase locked loop

It consists of a PI controller that processes the error signal (difference between the q-component and the reference) to minimize it. It is a combination of both proportional and integral controller. It significantly reduces steady state error. It adjusts the phase and frequency of the PLL output to lock onto the grid phase and frequency.Ensure the q-component approaches zero.

The working of PLL includes the input grid voltage in the αβ frame is converted to the dq0 frame using the current estimate of ωt. The q-component of the dq0signal is used as the error signal. The PI controller minimizes the error by adjusting ω, ensuring that the PLL output frequency and phase (ωt) lock onto the grid frequency and phase. This process continues iteratively, ensuring tight synchronization even under dynamic conditions.

1.5. Closed Loop Voltage and Current Control:

The figure below shows a closed-loop control system, where both voltage control and current control loops are implemented. This system ensures proper regulation of the DC bus voltage and grid current synchronization while minimizing harmonics and controlling active/reactive power flow.

Regulating idin order to control the DC bus voltage and iqin order to regulate reactive power is how the Active Front End (AFE) rectifier is controlled in the dq reference frame. The control architecture is made simpler by decoupling the dq components, which makes it possible to independently tune the active and reactive power control loops. This technique improves the dynamic performance and stability of the rectifier by enabling precise control over its output.

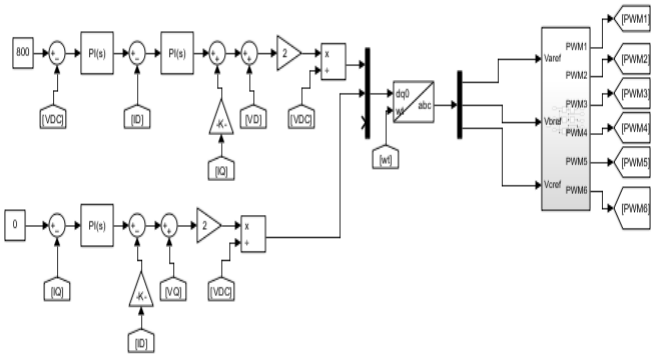

Fig.6: Closed Loop control system

1.6. Decoupling Control

In an Active Front-End (AFE) rectifier operating in a synchronous reference frame (d-q frame), the control of active and reactive power components (associated with d- and q-axes, respectively) can be coupled due to system dynamics. Decoupling ensures independent control of these components by compensating for cross-coupling terms.

A. Cross coupling terms:

The voltage equations in the d-q frame are:

$$V_d = RI_d + L\frac{dI_d}{dt} - wLI_q$$

$$V_q = RI_q + L\frac{dI_q}{dt} + wLI_d$$

B. Feed forward Decoupling

To decouple the system:

- The term LωIq is subtracted from Vd to eliminate the effect of the q-axis current on the d-axis control.
- The term LωId is added to Vq to eliminate the effect of the d-axis current on the q-axis control.

Thus, the decoupled voltage references become:

$$V_d^* = RI_d + L\frac{dI_d}{dt}$$

$$V_q^* = RI_q + L\frac{dI_q}{dt}$$

This feed forward decoupling ensures that the d-axis current only controls active power (real power) and the q-axis current only controls reactive power.

1.7. PI Controller Tuning

The PI controllers are used in both voltage and current control loops. Tuning of a PI controller means adjusting the K p and K I term to achieve the optimized controller output by minimizing error and avoid overshooting and oscillation. There are some rules that follows for tuning a PI controller. Here it is tuned using Trail and Error method .

- Start with initial guesses for K p and K I.
- Set K I value to '0'
- Gradually increase K p to achieve a fast response without excessive overshoot.
- Introduce K I and incrementally raise it to eliminate steady-state error.
- Continuously fine-tune K p and K I, considering their impact on overshoot, setting time and steady state error.
- Test the controller under various condition.
- Tuning is an iterative process, and optimal parameters may vary for different systems, requiring practice and experience to achieve stable and effective control.

2. SIMULATION SETUP &RESULTS

2.1. ACTIVE FRONTEND RECTIFIER

The testing and simulation of the 3-phase active rectifier is outlined in this section. The simulation is conducted using MATLAB/Simulink, the main aim is to analyze the performance of this active rectifier at different operating conditions.

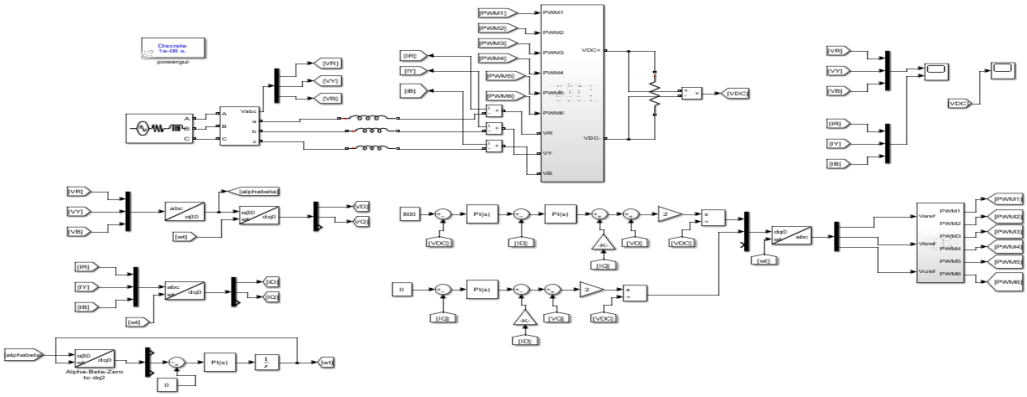

Fig.7: Active front end rectifier using MATLAB Simulink

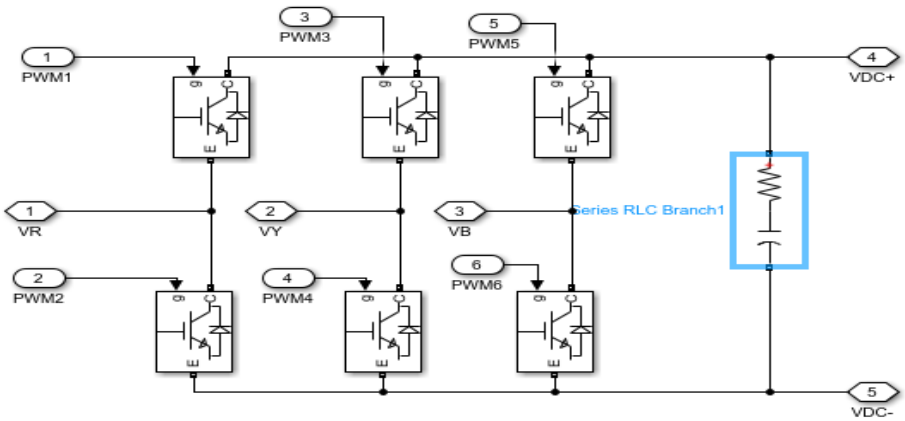

Fig.8: Rectifier Bridge circuit

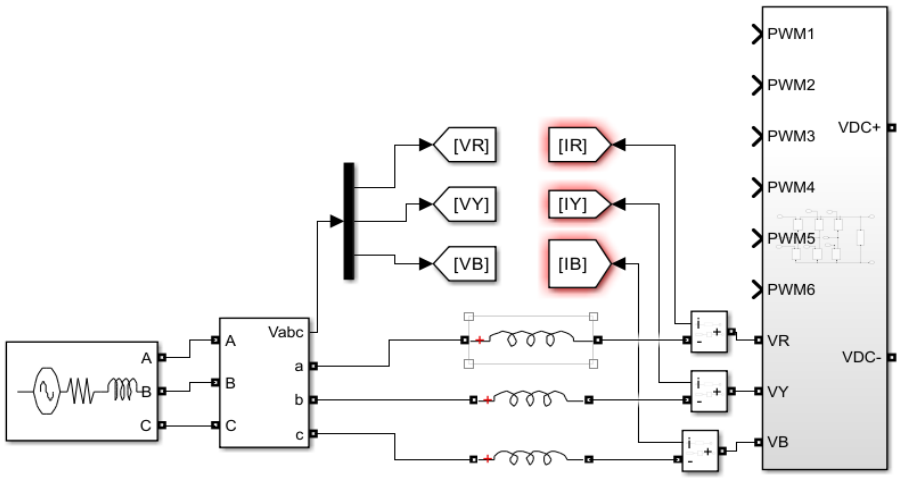

Fig.9: VR, VY, VB Voltages and IR, IY, IB Currents blocks

SIMULATION RESULTS OF ACTIVE FRONT END RECTIFIER:

Converter Specifications:

Rated Power: 100 kW
DC Voltage: 800 V
Grid Voltage: 415 V RMS (line-to-line)
Grid Frequency: 50 Hz
Switching Frequency: 10 kHz

1.Decoupling Control parameters:

Cross coupling terms:

The voltage equations in the d-q frame are:

$$V_d = RI_d + L\frac{dI_d}{dt} - wLI_q$$

$$V_q = RI_q + L\frac{dI_q}{dt} + wLI_d$$

Where:

For load of 6.4 ohms and Vdc = 800 V:

a. R: Resistance= 0.5 ohms
b. L: Inductance = 0.5 milli Henry
c. ω: Angular frequency = 2*3.14*50= 314 rad/sec.
d. I d, I q are currents in d and q-axes: I d = 227.6, I q=0.011
e. V d, V q are voltages in d and q-axes: V d = 586.6, V q =0.000012

2.Transfer Function of the Current Loop: The plant model for the current loop is:

$$(s) = \frac{1}{sCV_{dc}}$$

Where:

- C: DC-link capacitor

Here C= 5600 micro-Farad

- VDC : Nominal DC-link voltage

Here VDC=800V

3.PI Controller Design: The controller is:

$$G(s) = \frac{1}{sCV_{dc}}$$

Where:

$$K_p = \frac{2C\zeta\omega_n}{V_{dc}} \quad ; \quad K_i = \frac{C\omega_n^2}{V_{dc}}$$

ωn: Desired natural frequency of the voltage loop (lower than current loop bandwidth).
ζ: Damping ratio (commonly set to 0.7 for critically damped response).

Here we use two PI Controller:

Kp1= 0.5 Ki1=200
Kp2=25 Ki2=500

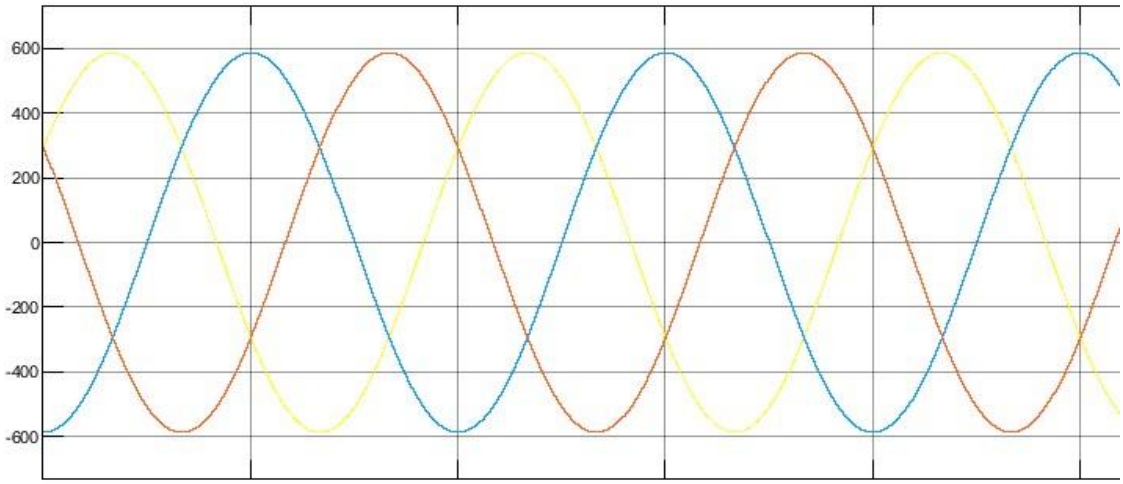

Fig.10: VR, VY, VB Voltage waveforms (for load of 6.4 ohms)

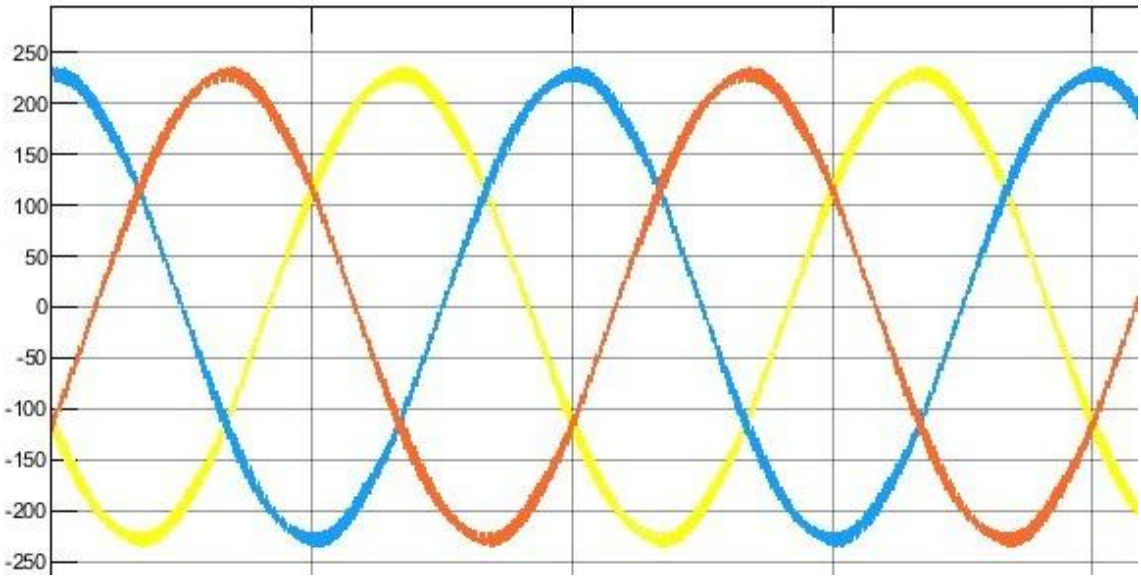

Fig.11:IR, IY, IB Current waveforms for (load of 6.4 ohms)

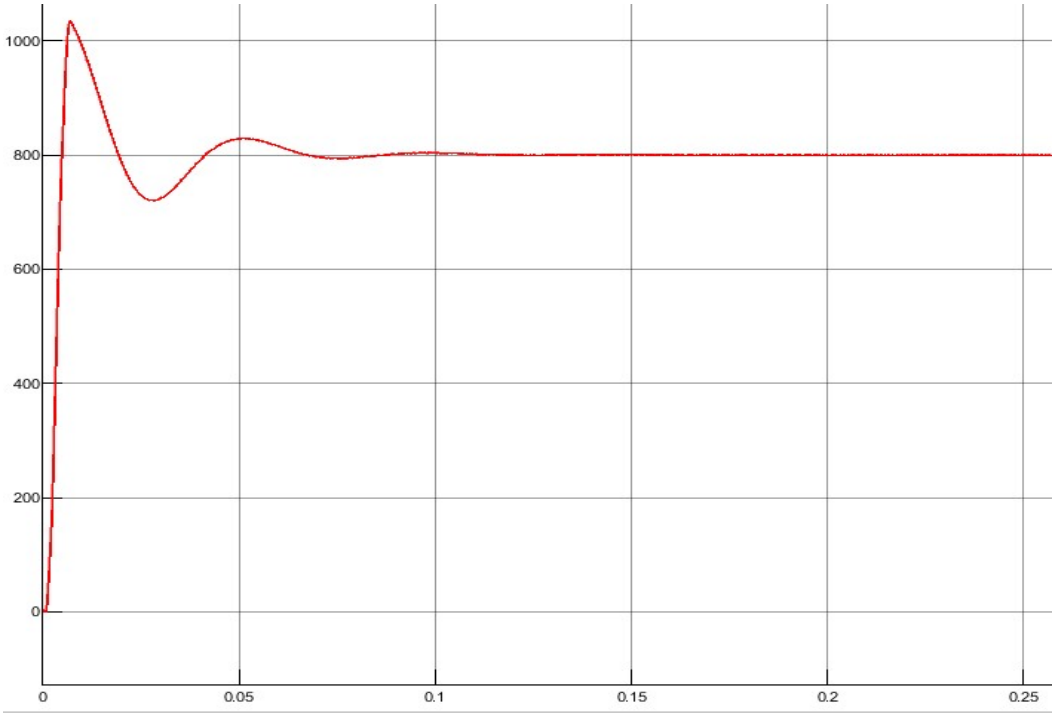

Fig.12: Output voltage (Vdc) waveform for (load of 6.4 ohms)

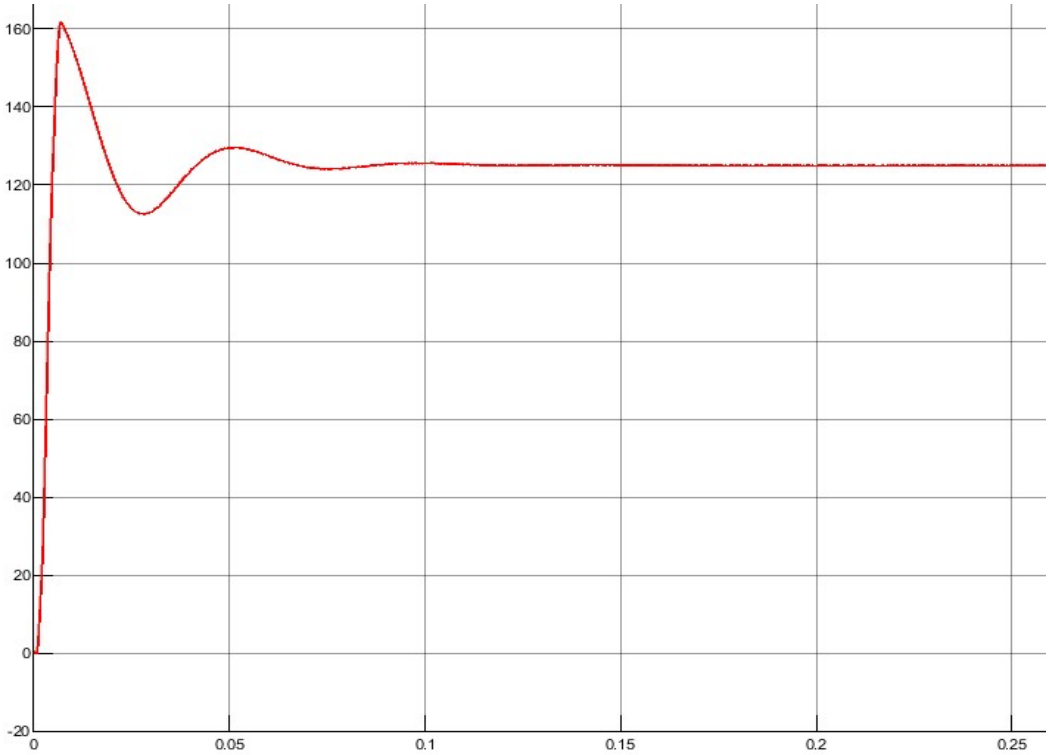

Fig.13: Output current (Idc) waveform for (load of 6.4 ohms)

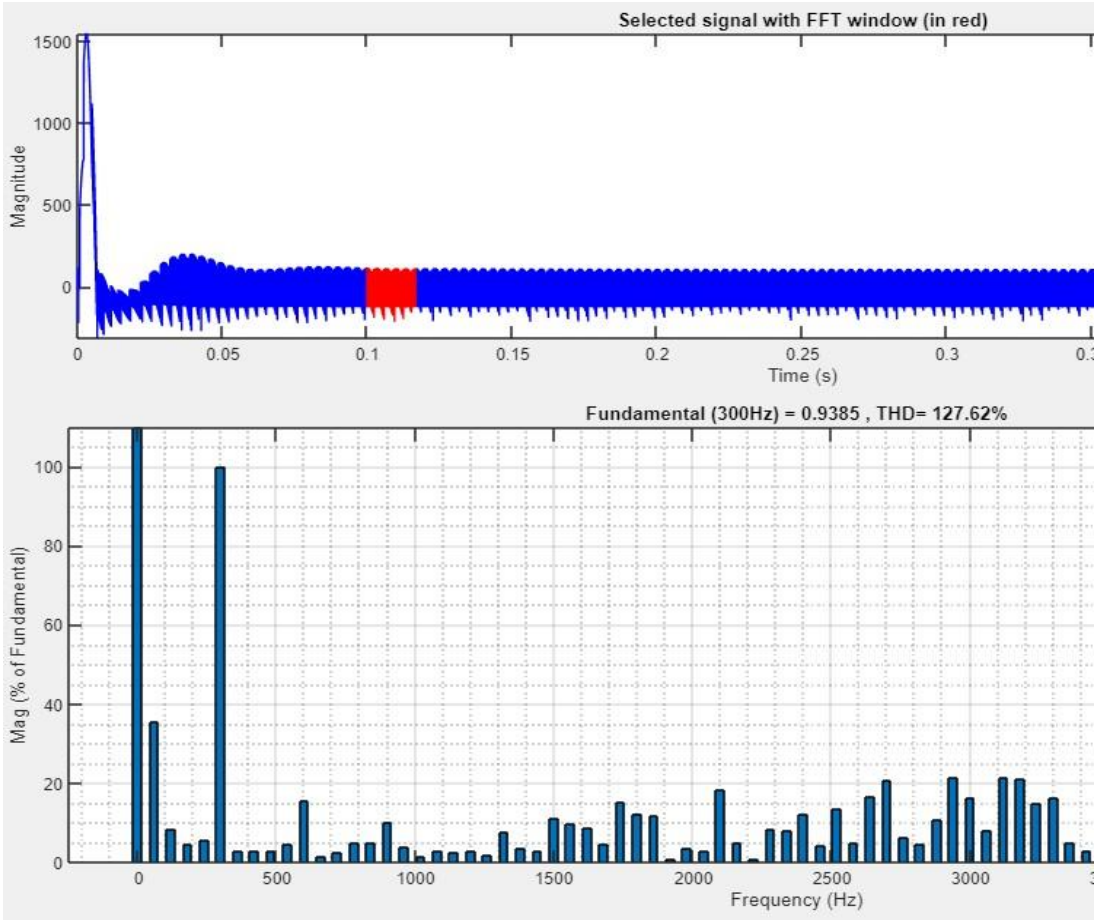

Fig.14:THD for DC link Capacitor current

As of the experimental results the figures show the waveforms of the source voltage and source current of the system and the output dc voltage respectively. The sinusoidal waveforms of the current and voltage is been observed. To validate the system more the dynamic response of the system for change of the load is been conducted for both increasing and decreasing of the load.The figure (15) shows the VI waveforms of the system for a decreased load to 2

ohms (referenceload is 6.4 ohms), in figure (16) the output dc voltage remains same reducing ripples and does not change which is a good result. It is seen that the system can withstand with dynamic change of the load and keeps the output same.

2.2. THREE PHASE INVERTER

A **Three-Phase inverter** is a power converter that converts DC into three phase AC. Inverters use Pulse Width Modulation (PWM) to regulate power conversion. The primary function is to convert DC voltage into AC voltage efficiently while maintaining a sinusoidal current waveform. The output of rectifier (DC) is connected to inverter's input and is transformed into AC by three phase inverter bridge. The gate pulses for the switches in the inverter bridge are generated by PWM strategy and reference signals are generated from control loops. The switching frequency is maintained at 10KHz.

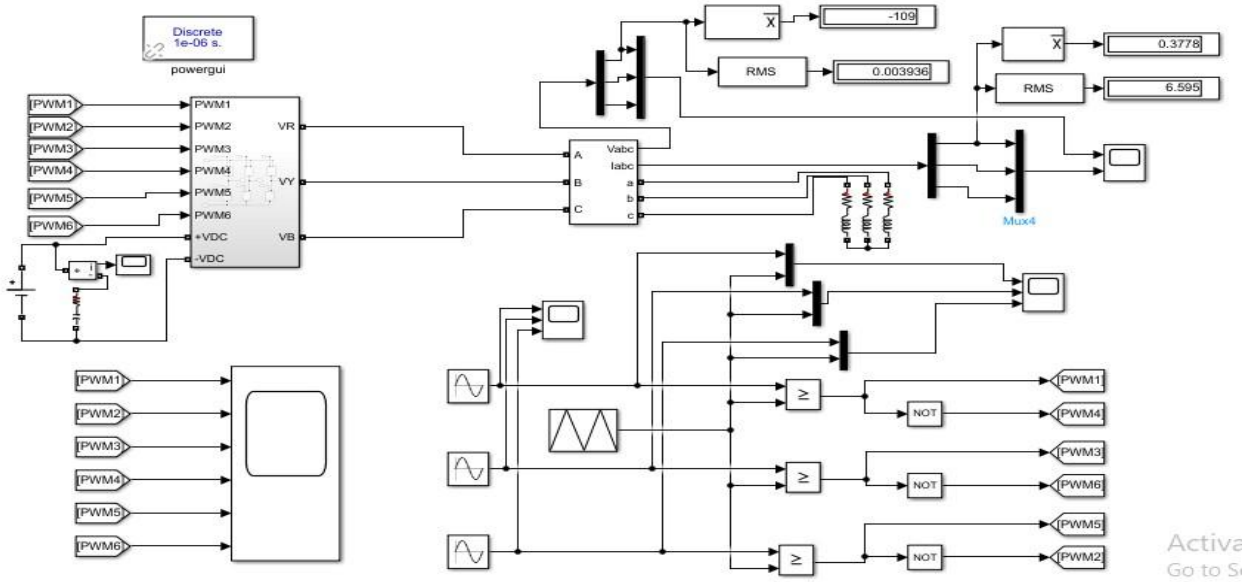

Fig.15: Three Phase Inverter Simulink model

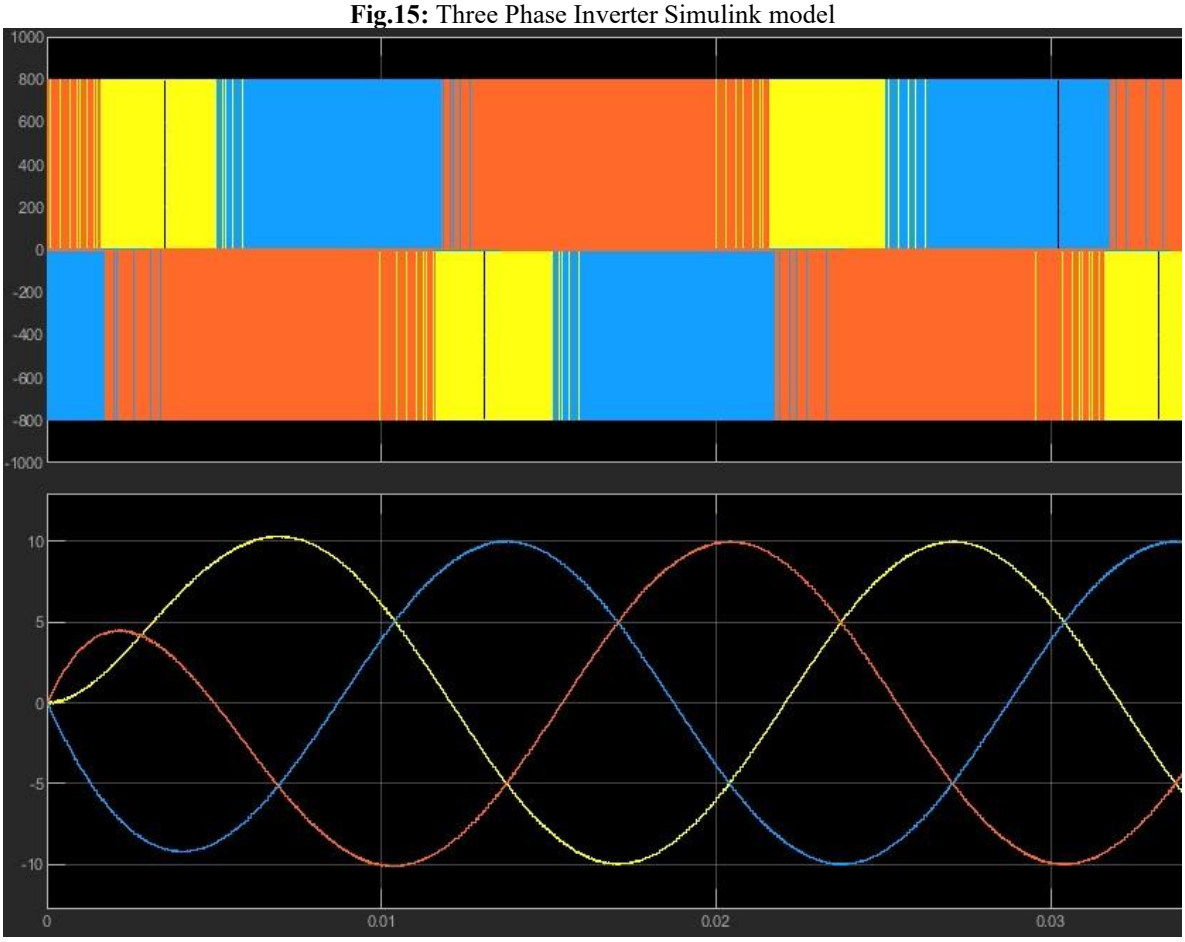

Fig.16: Output Voltages and Currents waveforms

2.3. ACTIVE FRONT END CONVERTER

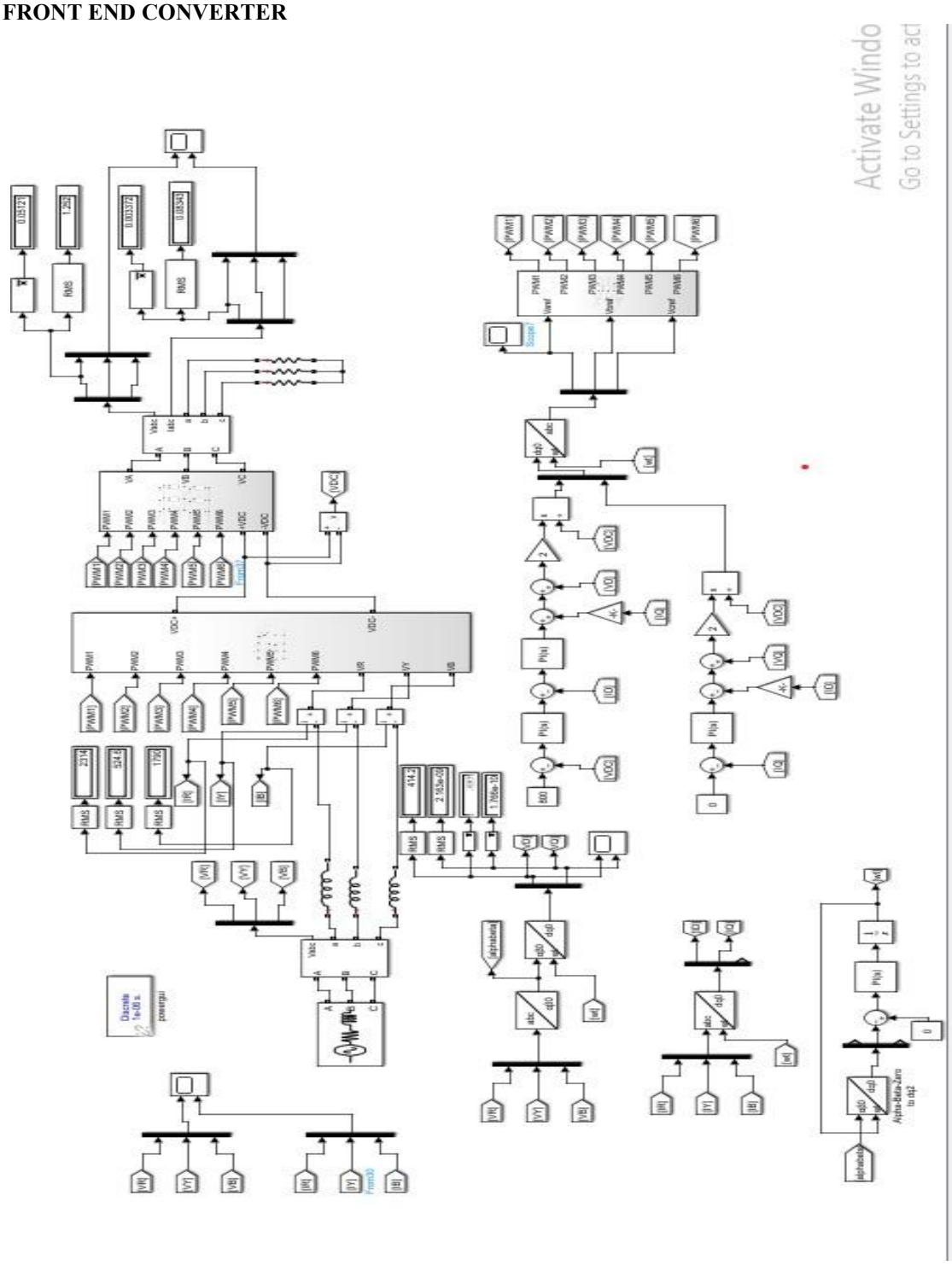

Fig.17: Active front end converter Simulink model

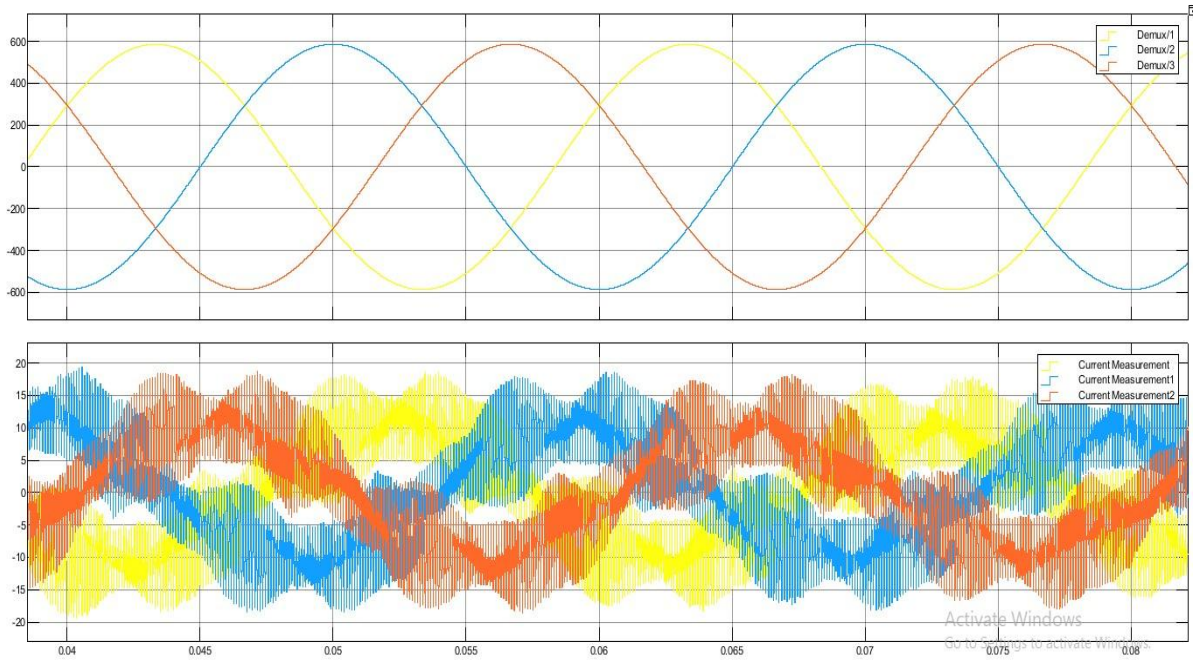

Fig.18: Input voltages and Currents waveforms

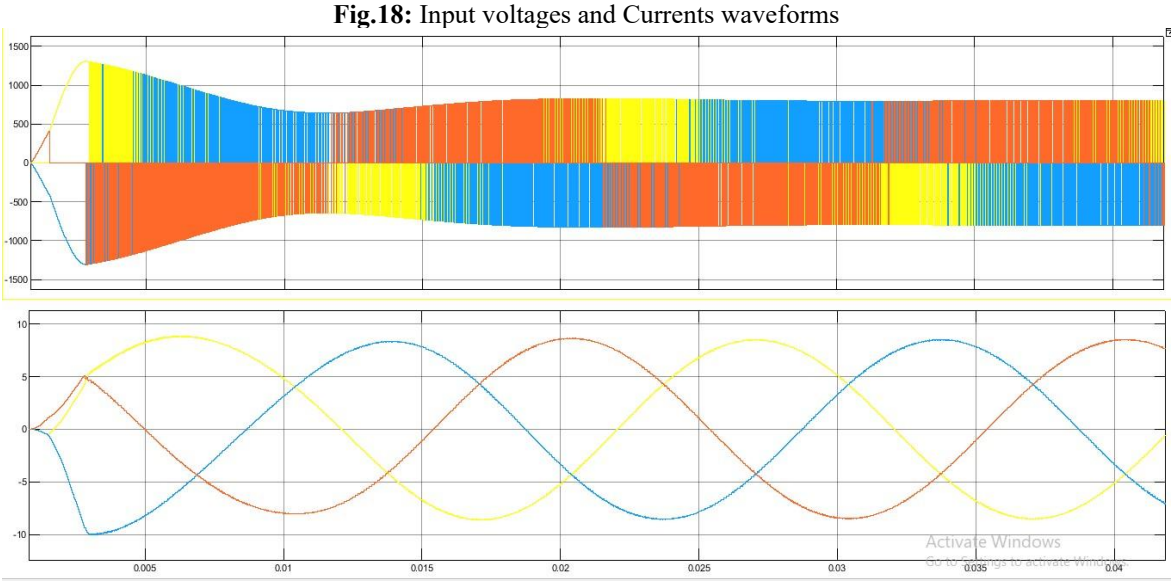

Fig.19: Output voltages and Currents waveforms

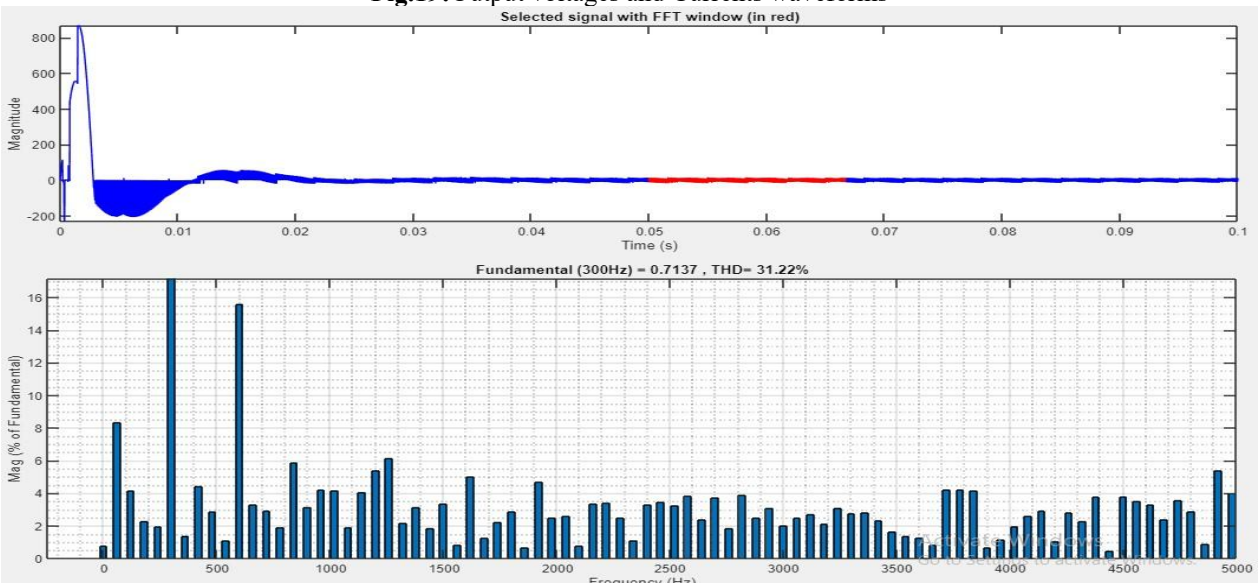

Fig.20:THD for DC link Capacitor current

2.4. SPACE VECTOR PWM strategy

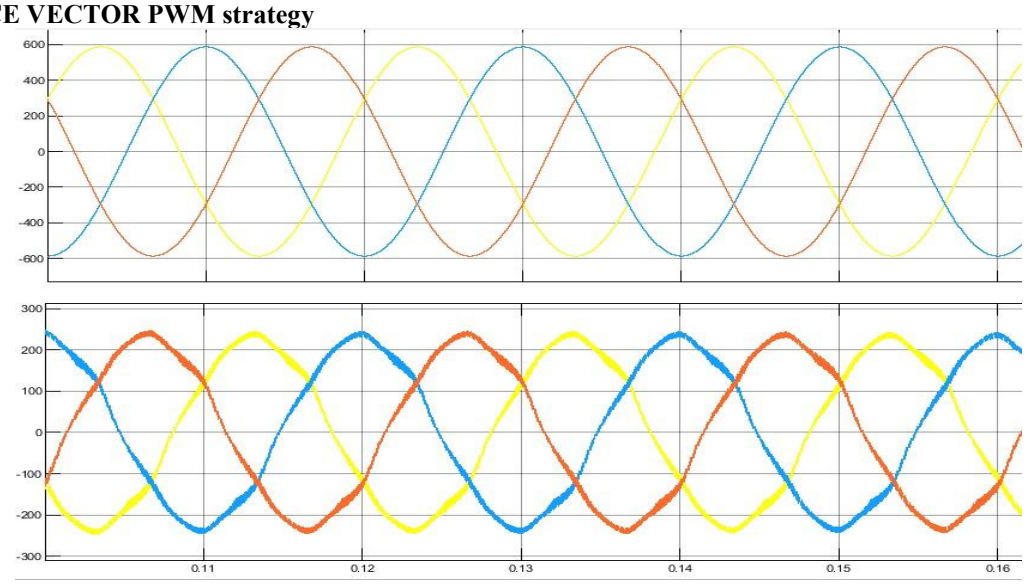

Fig.21: Input Voltages and Currents waveforms

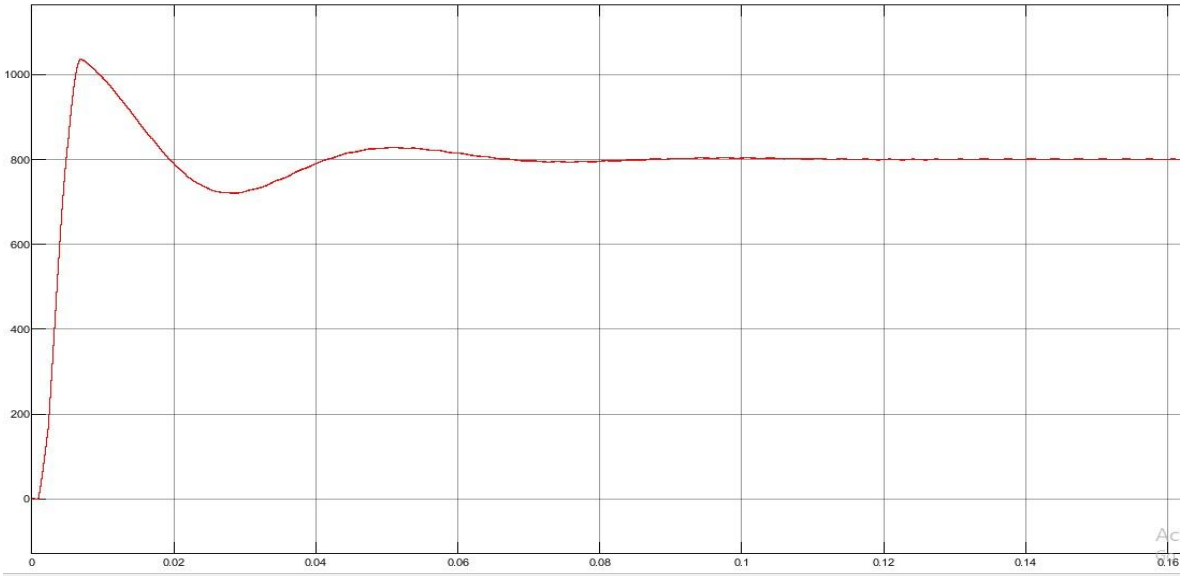

Fig.22: Output voltage waveform

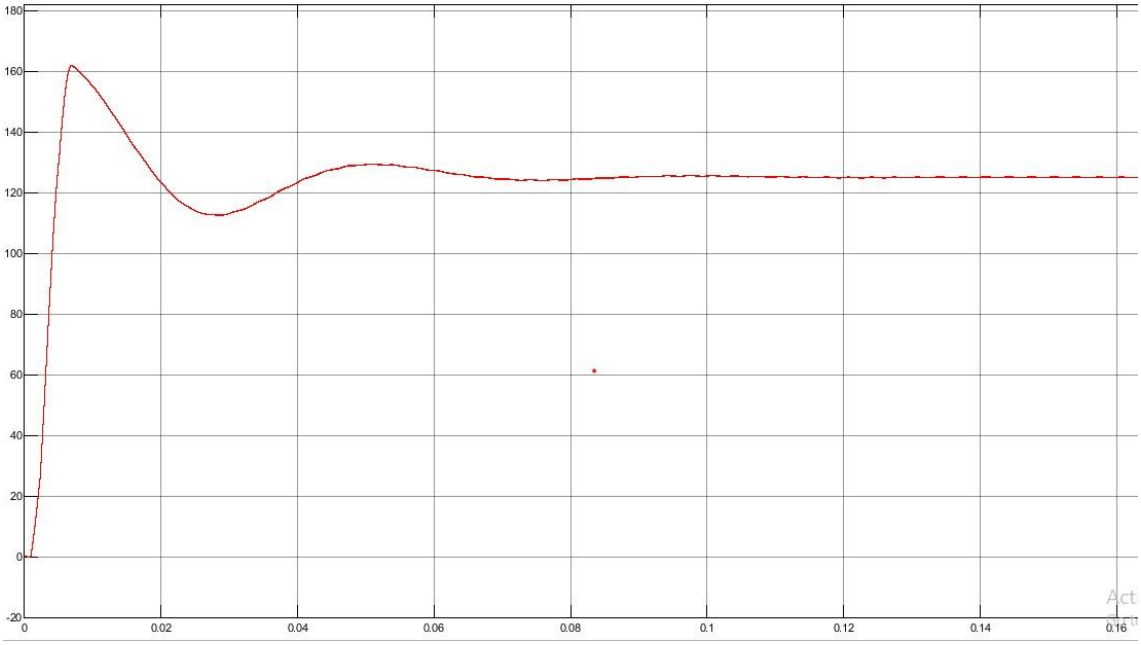

Fig.23: OutputCurrent waveform

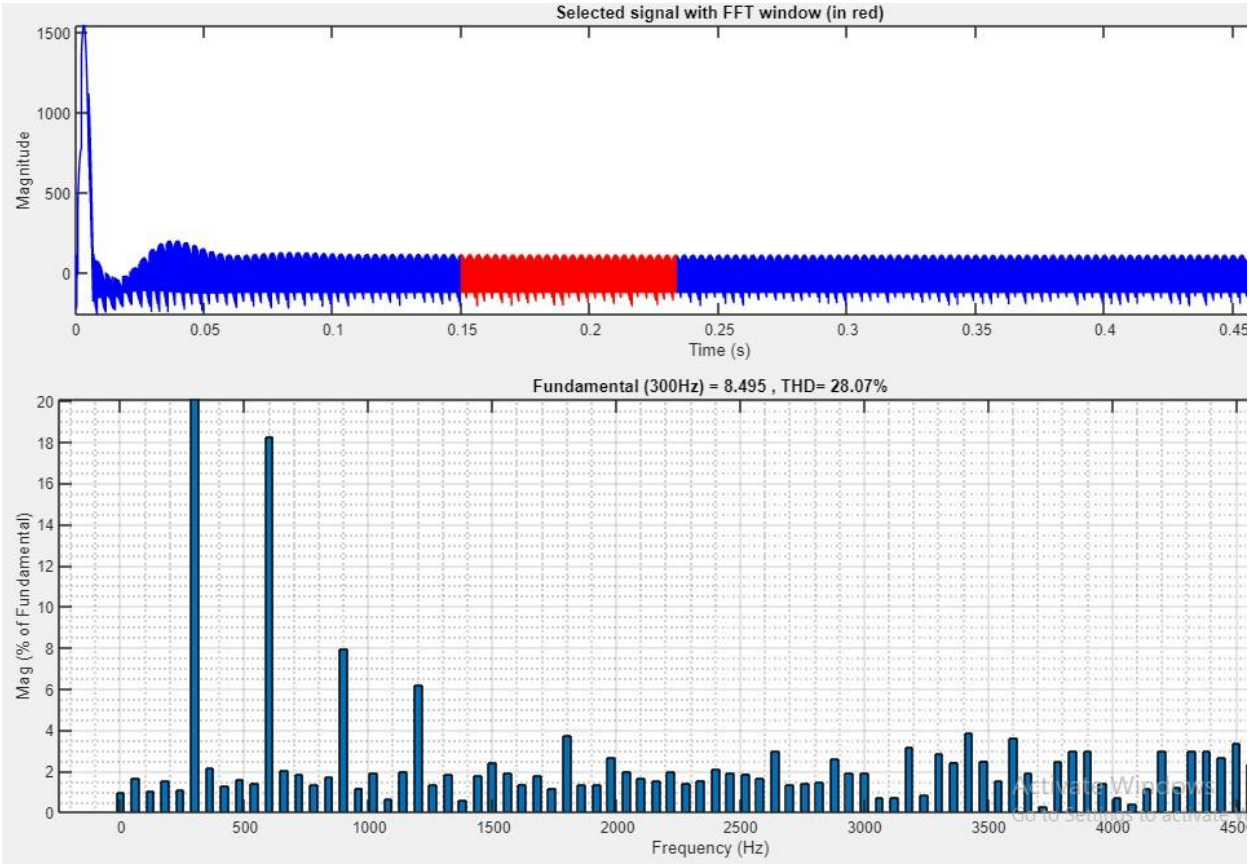

Fig.24: THD for DC link Capacitor current

3. RESULTS

Control strategy	THD for DC link Capacitor current
Rectifier	127.62 %
AFEC	31.22 %
Space vector PWM	28.07 %

4. CONCLUSION

This project investigates the control of a three-phase active front-end converter using Sinusoidal Pulse Width Modulation (SPWM). It was designed based on a detailed mathematical model to externally balance the generated active and reactive power. The implementation of the MATLAB/Simulink simulation system includes an L filter and a three-phase bridge rectifier. The L filter being connected is reducing the low-level harmonics in the current. The simulation results indicated that this control strategy could enable the system to working stably and efficiently in different ways. By using Sinusoidal Pulse Width Modulation (SPWM) technique and the control methodology, DC output of a three-phase controlled rectifier has lesser ripples. The Capacitor current and THD is obtained for AFEC and rectifier alone. By implementing techniques such as Sinusoidal Pulse Width Modulation (SPWM), L-filter the converter achieves reduced harmonic distortion and improved power quality.

The successful implementation of this converter will result in better power conversion and will contribute to energy efficient systems, reducing the losses. Although the model complexity, parameter selection and practical implementation introduce more challenges for this approach to be used as a standard method in power electronics, it did provide reasonable results to build some insights about future research or industrial applications. To improve the system performance further we can implement Space Vector Pulse Width Modulation (SVPWM) Techniques.

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