PROJECT NUMBER-1

3-LEVEL NEUTRAL POINT CLAMPED CONVERTER AS RECTIFIER WITH HYSTERESIS CONTROL

Team Members

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1. Introduction

Many inherent benefits of multilevel converters have led to their increased interest amongst industry utilities. At present, the two most commonly used multilevel topology are the 3-level neutral-point-clamped (NPC) and cascaded topology.

The control of multilevel power converters has been widely studied since they can achieve high power using mature medium-power semiconductor technology and present more advantages compared with conventional ones. These advantages are improving the waveform quality, reducing voltage stress on the power devices and a nominal power increase in the converter.

2. 3-Level Neutral Point Clamped Converter as Rectifier

2.1. Origin of NPC converter

This Neutral-Point-Clamped pulse width modulation inverter is proposed in 1981 by Akira Nabae, Isao Takahashi and Hirofumi Akagi in the paper 'A New Neutral-point-clamped PWM Inverter'. It is composed of main switching devices which operates as switches for PWM and auxiliary switching devices to clamp the output terminal potential to the neutral point potential has been developed. This converter was proposed in-order to rectify the problems or the drawbacks which the conventional converters had i.e more harmonics in the output. This converter output contains less harmonic content as compared with that of a conventional type.

2.2. 3 Level NPC converter

A three-level neutral point clamped converter as rectifier converts a three-phase AC voltage at the input end to a DC voltage at the output end.

When power is flowing from the DC source to the converter, this circuit acts as a inverter and converts DC voltage into 3-phase AC voltage and supplies the grid. When the power flows in the reverse direction the converter will operate as an rectifier, thus taking power from the grid and supplies the battery.

One major advantage of such a converter is the bidirectional of power flow and ability to control the active and reactive power of the Grid. It is to be noted that for satisfactory operation of the converter the output voltage must be maintained 1.5 times higher than the peak of input line voltage.

The control technique used for the controlled rectifier in this project is the abc model and hysteresis control.

Circuit Diagram of 3 Level NPC is given in Fig. 1:

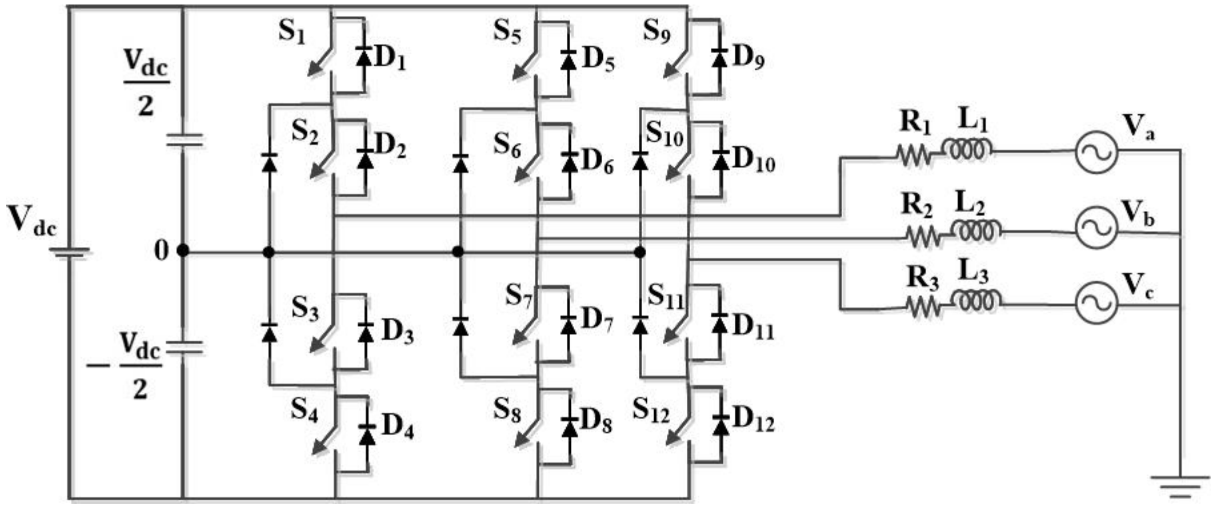

Fig. 1: 3-Level Neutral Point Clamped Converter as Rectifier

$$v_{AB} = \frac{V_{LLPeak}}{\sqrt{3}} cos(\omega t) \tag{1}$$

$$v_{BC} = \frac{V_{LLPeak}}{\sqrt{3}} cos(\omega t - \frac{2\pi}{3}) \tag{2}$$

$$v_{CA} = \frac{V_{LLPeak}}{\sqrt{3}} cos(\omega t - \frac{4\pi}{3}) \tag{3}$$

2.3. Basic operation of 3-Level NPC Converter

A three level neutral point clamped inverter which converts DC input to 3 phase AC output. Considering a leg of the converter which is shown in the fig. 2:

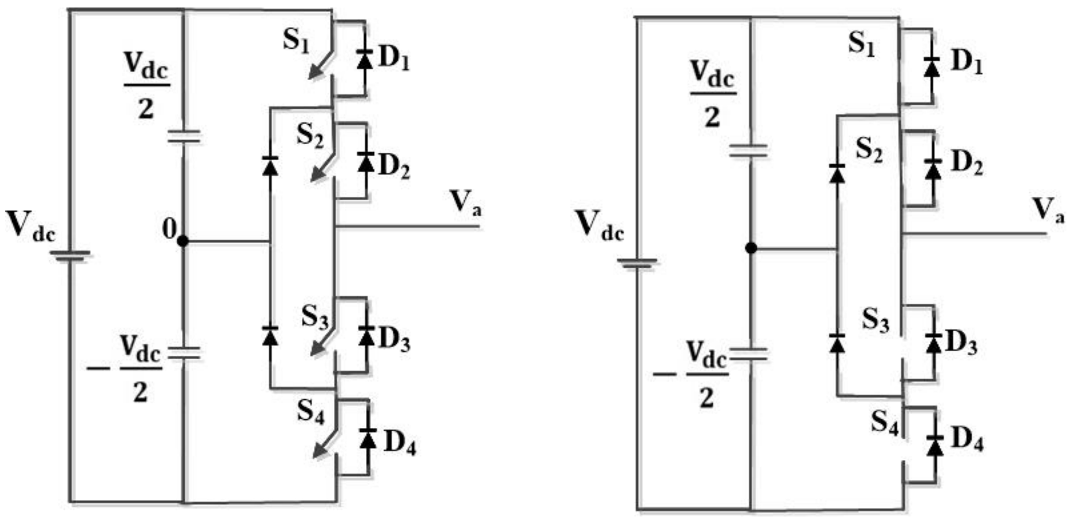

Fig. 2: Phase a of converter and case 1

With different arrangements of switches we can get different voltages at the output V_a.

For case 1 (fig.2) when S1 and S2 are ON and S3 and S4 are OFF, we get $V_{dc}/2$ at the output.

For case 2 (fig.3) when S2 and S3 are ON and S1 and S4 are OFF, we get 0 voltage at the output.

For case 3 (fig.3) when S3 and S4 are ON and S1 and S2 are OFF, we get $-V_{dc}/2$ at the output.

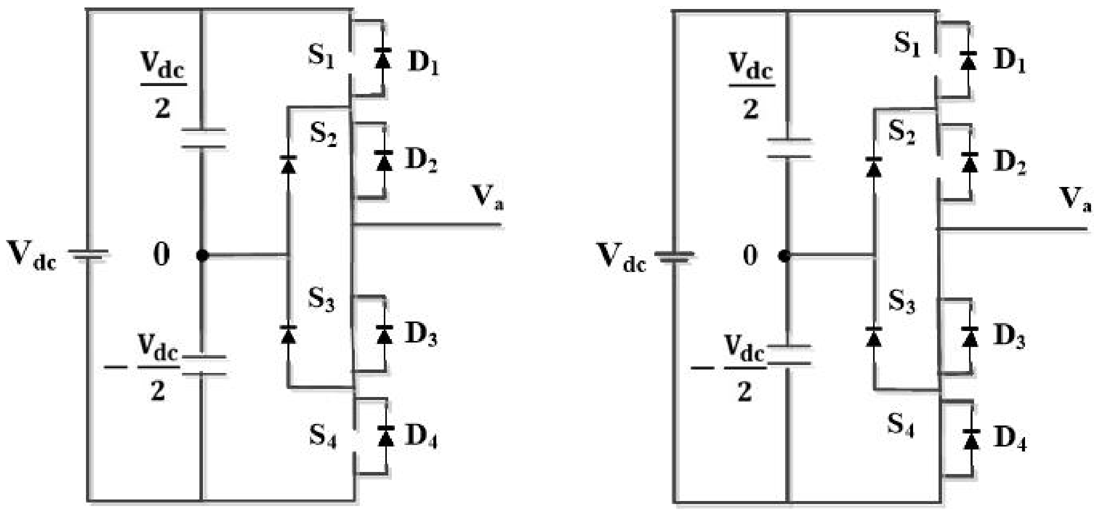

Fig. 3: Case 2 and Case 3 for Phase a of converter

Three levels in the voltages are $+V_{dc}/2$, 0 and $-V_{dc}/2$.

In the fig.4, S1 and S4 are the main switches and S2 and S3 are the auxiliary switches. So in the first cycle S2 is ON and S3 is off and according to the current variation the S1 operates giving us the voltage. In the next cycle S2 is OFF and S3 is ON and according to variations in current S4 operates giving us the voltage. Similarly for 2^{nd} leg we get V_b which is 120° lagging with respect to V_a and from 3^{rd} leg we get V_c which are 240° lagging with respect to V_a.

When negative power flows in the circuit, the converter acts as rectifier.

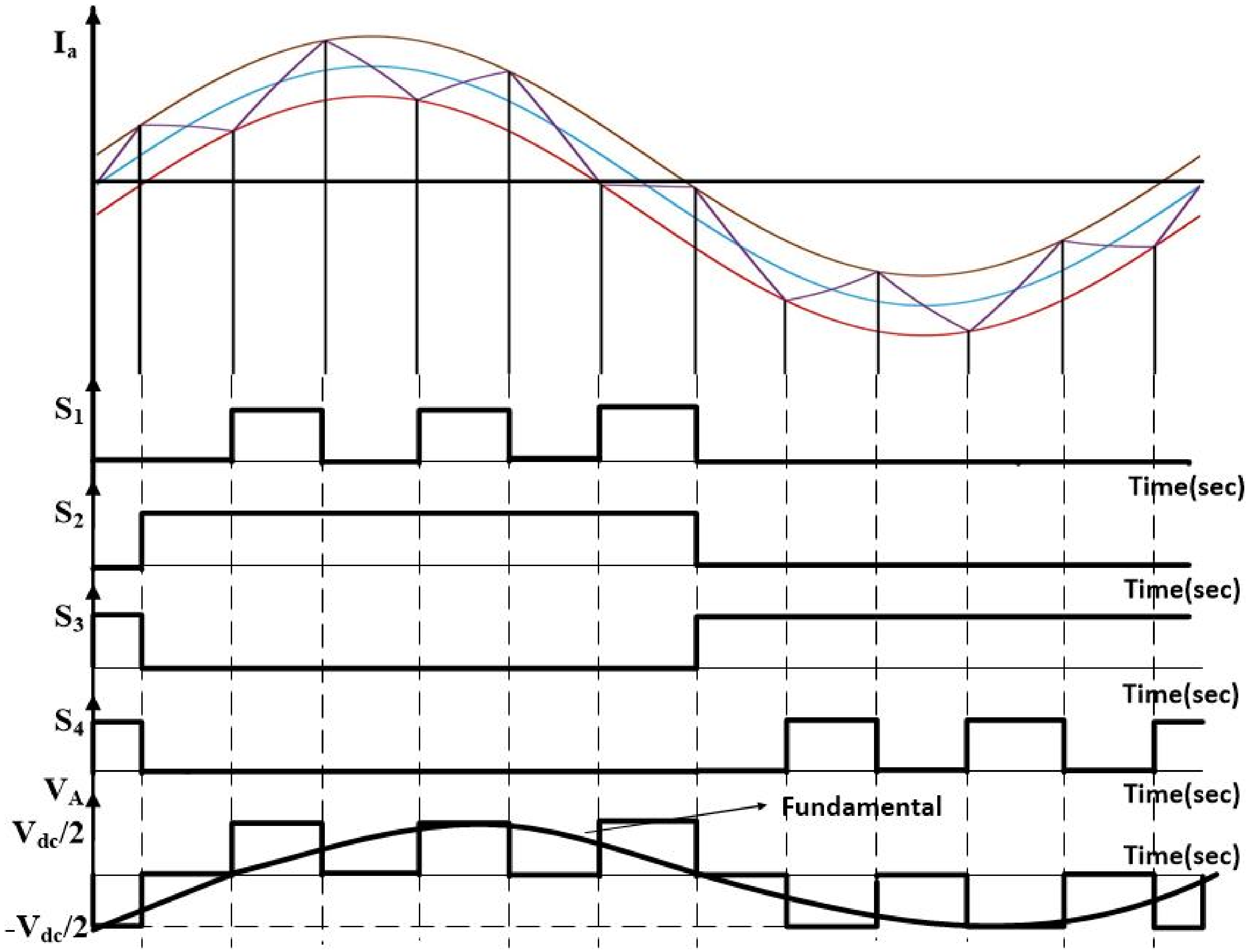

Fig. 4: Switching pulses and voltage

3. Control of converter

We will be using abc model with hysteresis current control to control the converter.

3.1. Grid synchronisation

The three phase 3-level converter is connected to the grid, it is controlled using hysteresis current control. Such that, output voltage of the converter cannot be controlled, only the current injected or absorbed from the grid can be controlled. So, the converter should act as grid following converter. And the power injected or absorbed from the grid is controlled by controlling the current injected by the converter.

The angle θ is the angle between voltage and current. In the Reference current I_a^*,I_b^* and I_c^* is obtained from Eq.(11) and mentioned in Eq.(12). Now to synchronise the converter and grid, reference currents are converted from abc reference frame to dqo reference frame using Eq.(13). And again converted

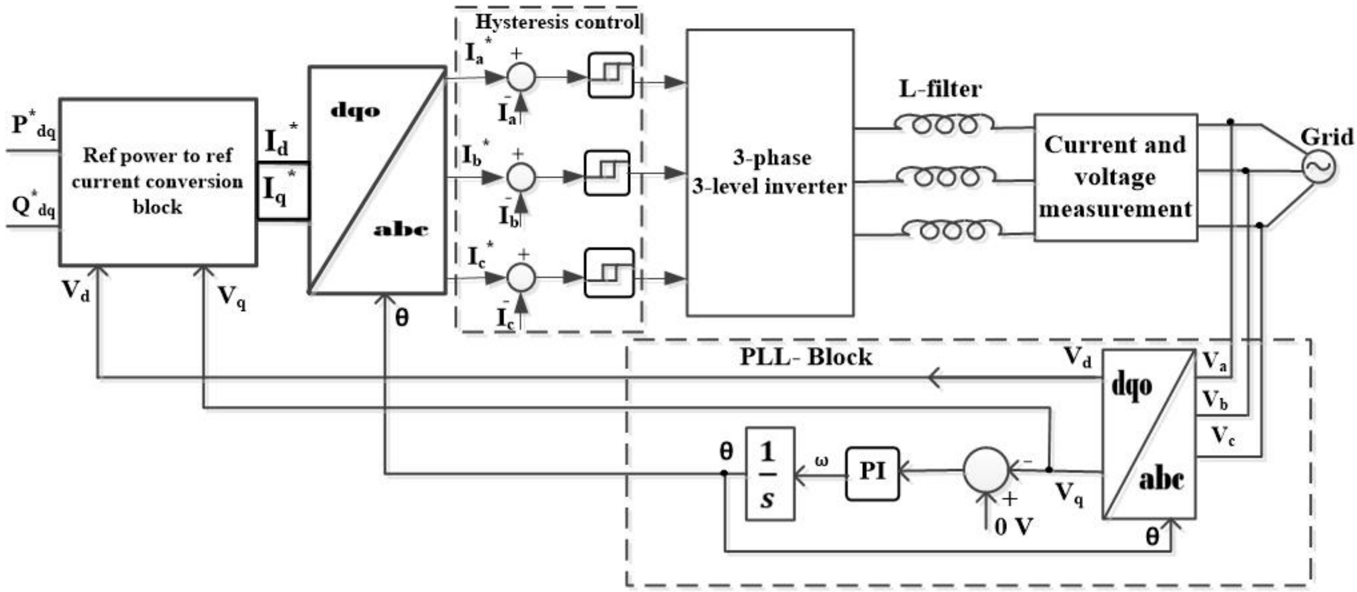

Fig. 5: Grid synchronisation

from dqo to abc reference frame using Eq.(14) by taking θ from the PLL block connected to the grid voltages mentioned in [6]

The values which are given to us are Active power=10 kW and Reactive power=0 kVAr.

3.2. PLL - Phase locked loop

Phase locked loop (PLL) is one of the most necessary strategy used in grid connected converters. It is used to synchronise, grid connected converters with the grid. Power system has many uncertainties, such that the grid phase angle may vary. PLL uses a PI controller to actively track the phase angle of the grid. It is achieved by making $V_q = 0$, the PI controller will generate such a way that V_q is maintained zero. One of the advantage of making $V_q = 0$ is, active power of the converter is controlled only by I_d and reactive power of the converter is controlled by I_q only.

3.3. Hysteresis current control topology

When a converter is connected to a grid and operated in a current control mode, hysteresis current control technique can be used. In this technique, a hysteresis band is created over the reference signal and the controller will try to maintain the actual signal within that band.

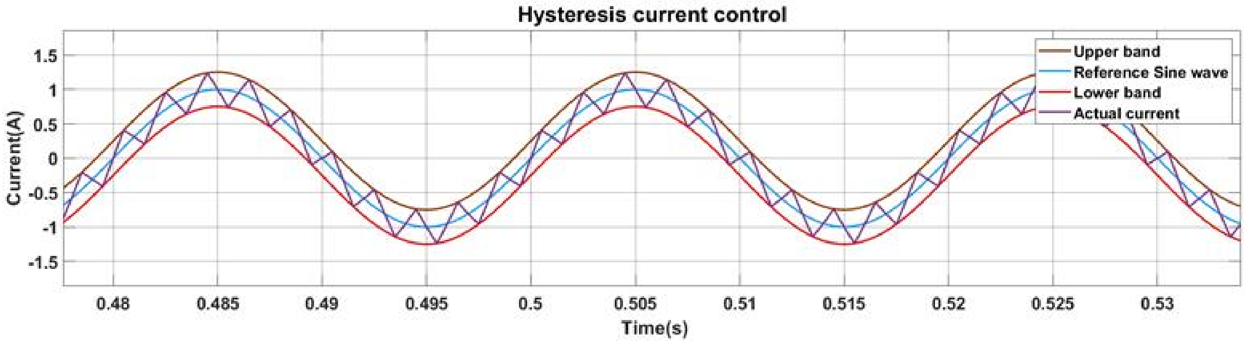

Fig. 6: Hysteresis Current Control

In fig:7, there is a reference sine wave and a band of error, upper band and lower band is given. And comparison in done between actual current in the ac side and reference current.

When the reference current is greater than zero and the actual current is within the band, S1 & S2 is turned on and S3 & S4 is turned off, and it remains off until reference current reaches below zero. Similarly, S2 remains on until reference current reaches below zero. When the actual current touches the upper band, switch S1 is turned off such that the current decreases, as it further decrease and touches the lower band switch S1 is turned on. And the current raises, this process is repeated until the reference current is lesser than zero.

When the reference current is lesser than zero and the actual current is within the band, switch S3 & S4 is turned on, S1 & S2 is turned off and it remains off until reference current reaches above zero. Similarly, S3 remains on until reference current reaches above zero. When the actual current increases in the negative direction and touches the lower band S4 is turned off such that the current decrease and when it touches the upper band, S4 is again turned on. And the current raises, this switching cycle is repeated until reference current is greater than zero.

3.4. Reference parameters calculations

The given power is 10 kW and the line-line rms voltage is 415 V. Phase voltage is $\frac{415}{\sqrt{3}} = 239.6V$
The values of V_d and V_q can be found using following matrices.[8]

$$V_a = 239.6\angle 0^\circ V, V_b = 239.6\angle -120^\circ V, V_c = 239.6\angle 120^\circ V \tag{4}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5}$$

The values of $V_d = 293.44\angle 0°$ V and $V_q = 293.44\angle 90°$ V and $p_{dq0} = 10000$ W and $q_{dq0} = 0$ VAr

We can determine I_d and I_q as following equations[8]

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{1}{V_d^2 + V_q^2} \begin{bmatrix} V_d & V_q \\ -V_d & V_q \end{bmatrix} \begin{bmatrix} p_{dq0} \\ q_{dq0} \end{bmatrix} \tag{6}$$

The values of $I_d = 17.03\angle 0°$ A and $I_q = 17.03\angle 90°$ A Also the value of I_0 is 0 for a balanced system. The values of I_a, I_b and I_c can be found from I_d and I_q which is given below[6]:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \text{-}\sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & \text{-}\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & \text{-}\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \tag{7}$$

$$I_a = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \text{-}\sin(\theta) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

considering $\theta = 0°$

$$I_a = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(0) & \text{-}\sin(0) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

$$I_a = \sqrt{\frac{2}{3}} * (I_d - 0 * I_q - \frac{1}{\sqrt{2}} * I_0)$$

So, the Value of I_a is found out to be $13.09\angle 0°$ A

Similarly for I_b current

$$I_b = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta - \frac{2\pi}{3}) & \text{-}\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}}) \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

$$I_b = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(0 - \frac{2\pi}{3}) & \text{-}\sin(0 - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

$$I_b = \sqrt{\frac{2}{3}} * (-\frac{I_d}{2} + \frac{I_q}{2} + \frac{1}{\sqrt{2}} * I_0)$$

And the value of I_b is found out to be $13.09\angle -120°$ A

And similarly for I_c current

$$I_c = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta + \frac{2\pi}{3}) & \text{-}\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}}) \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

$$I_c = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(0 + \frac{2\pi}{3}) & \text{-}\sin(0 + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

$$I_c = \sqrt{\frac{2}{3}} * (-\frac{I_d}{2} - \frac{I_q}{2} + \frac{1}{\sqrt{2}} * I_0)$$

And the value of I_c is found out to be $13.09\angle 120°$ A

In MATLAB, this generation of reference current is created by making a ideal three phase voltage source supply power to the three phase programmable load. The current supplied to the programmable load is measured and used as the reference signal to the converter. Which is shown in the block diagram (fig.6).

3.5. Filter Design

Since, the inverter current produced by the converter will have harmonics, which will disrupt the grid voltage and cause noises. A suitable filter to should be designed to filter out the harmonics from the currents from the inverter. The inductor value is given by Eq.(15) mentioned in [7].

$$L = \frac{V_{dc}}{4 * h * f_s} \tag{8}$$

The value of h=10% of $I_L(peak)$=2 A, V_{dc} = 600 and f_s = 9.3 kHz

$$L = \frac{600}{4 * 2 * 9.3 * 10^{-3}}$$

$$L = 8.06mH$$

Where,

h is tolerance in hysteresis band.

V_{dc} is DC side voltage.

f_{SW} is converter switching frequency.

The value of L is found out to be 8.06 mH

3.6. DC link capacitor

On the DC side, DC link capacitor is required to maintain the voltage. Ideally, very high value of capacitor is required to maintain a constant voltage. But, practically having such high value is not possible. So, 10% of DC voltage is taken as tolerance. And capacitor value sufficient enough to maintain this voltage is selected. In this, there are two cases, a.V_{dcH} given by C_1 Eq.(16) and b.V_{dcL} given by C_2 Eq.(17). The higher capacitor value is chosen, between these two capacitor values.

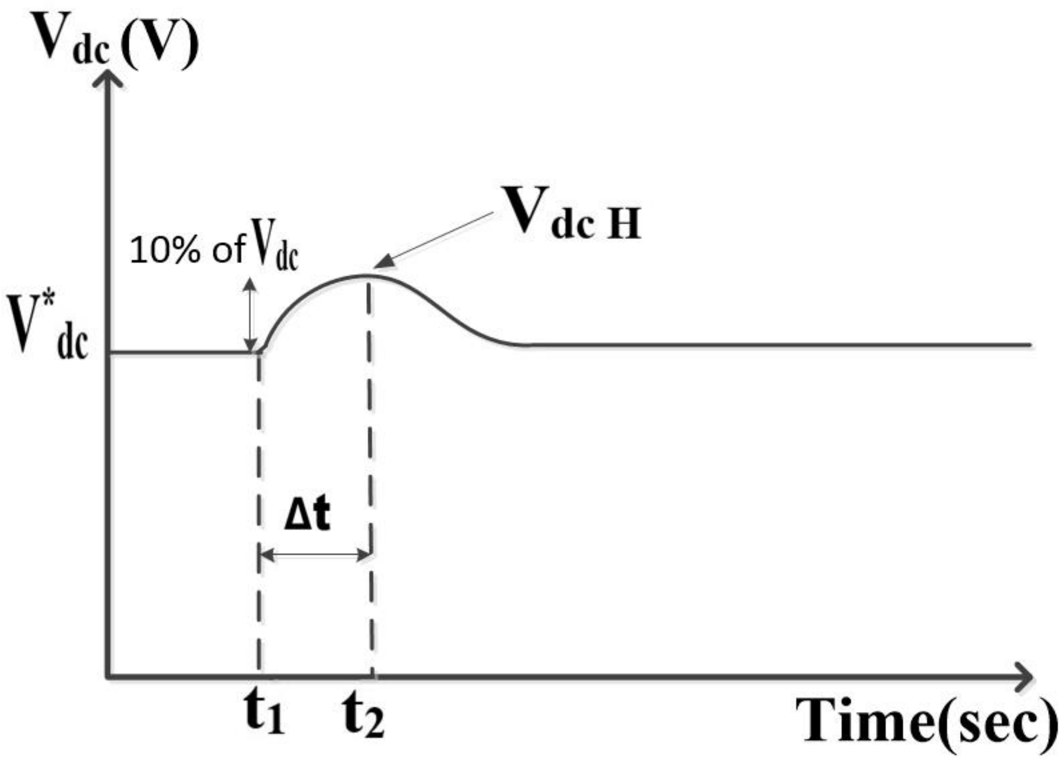

Fig. 7: Voltage variation graph

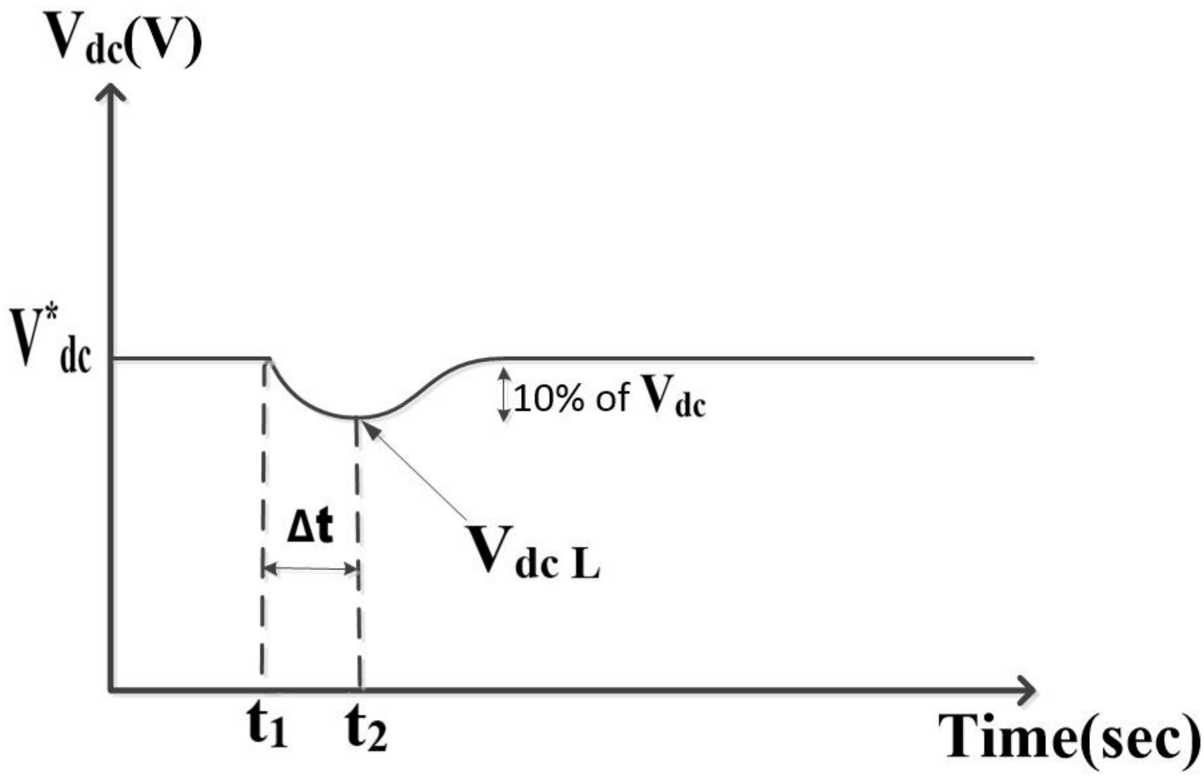

Fig. 8: Voltage variation graph

$$C_1 = \frac{t_1 * \Delta P}{0.5 * (V_{max}^2 - V^2)} \tag{9}$$

$$C_1 = \frac{13.68 * 10^{-7} * 0.05 * 10000}{0.5 * (660^2 - 600^2)}$$

$$C_2 = \frac{t_1 * \Delta P}{0.5 * (V^2 - V_{min}^2)} \tag{10}$$

$$C_2 = \frac{13.68 * 10^{-7} * 0.05 * 10000}{0.5 * (600^2 - 540^2)}$$

The value of C_1 = $10.8\mu F$ and C_2 is $11.9\mu F$

So the value of DC link capacitance is taken as C_2 is $11.9\mu F$

4. Three phase 3-level Converter Simulation Results

Now we will extend our analysis to Three phase 3-Level Converter which is controlled using hysteresis current control. Here it will operate as rectifier means power will flow from AC side to DC side with reference current is taken as negative value. Simulations results for three phase 3-level NPC converter given in Fig.(5) performed in MATLAB Simulink are given in Fig.(12) to Fig.(18).

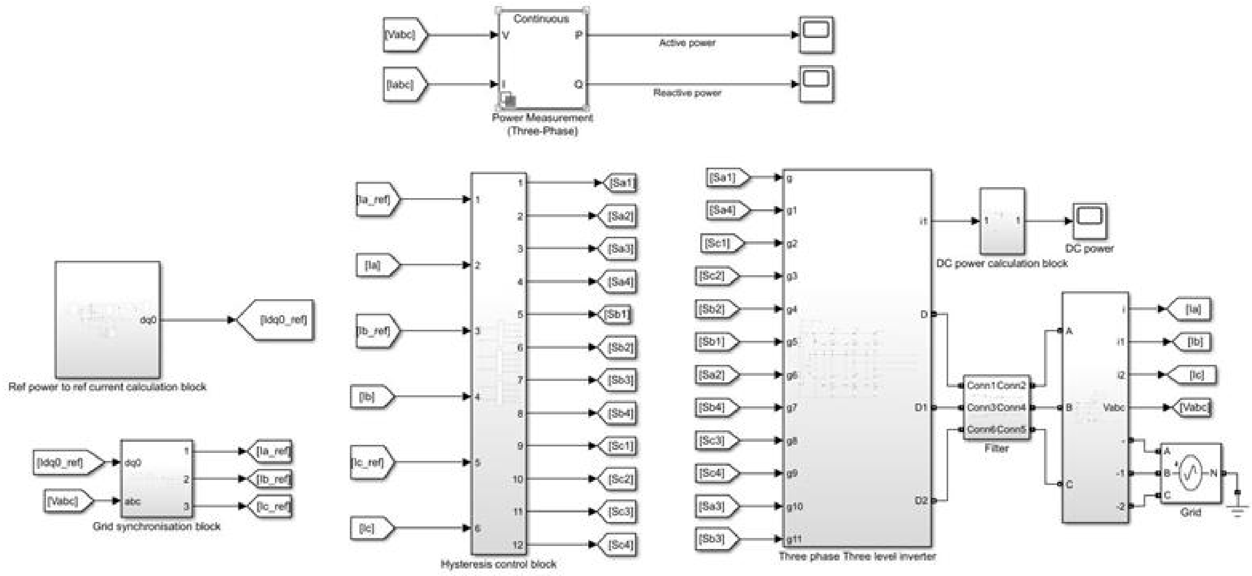

Fig. 9: Simulation block diagram

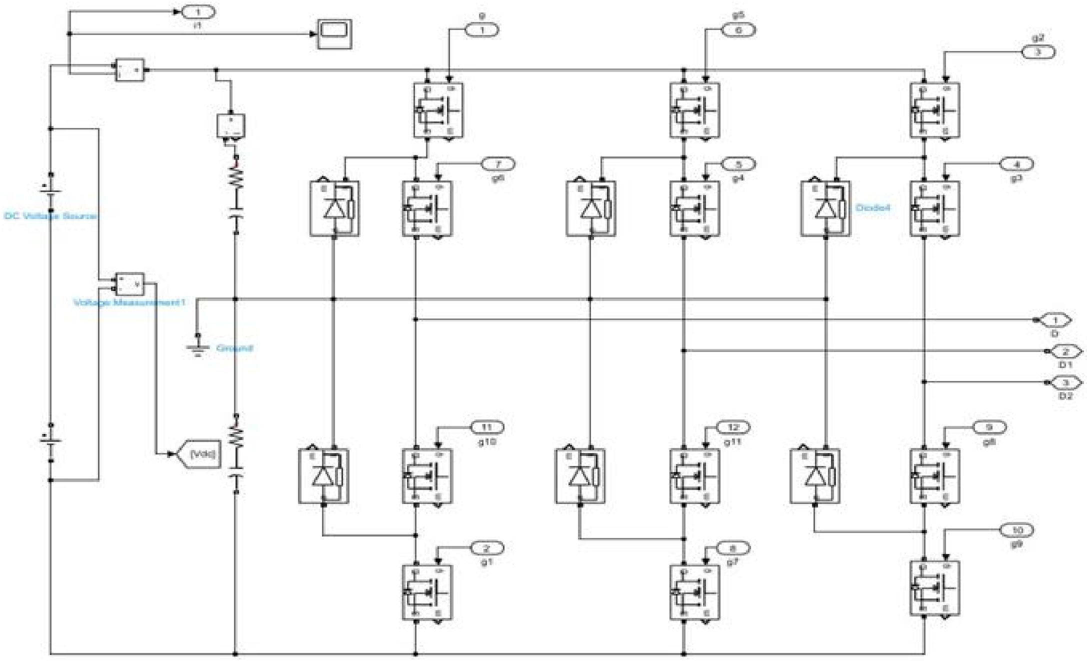

Fig. 10: Subsystem for inverter in simulation block diagram

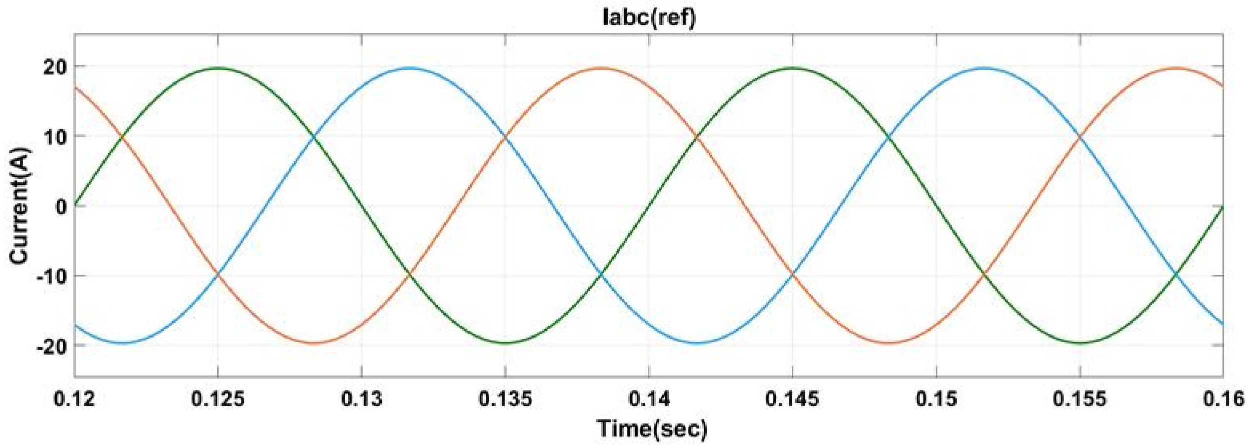

Fig. 11: Reference Currents

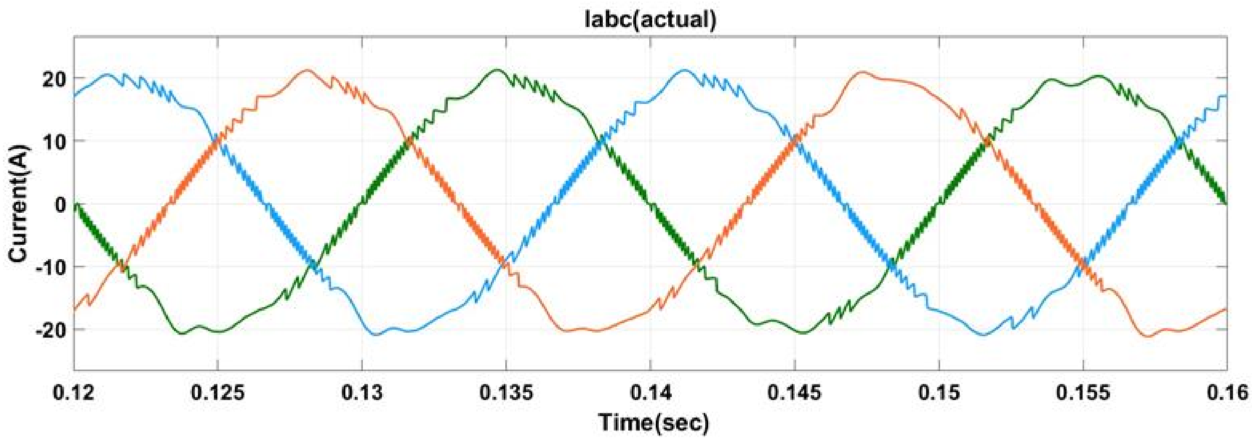

Fig. 12: Actual currents

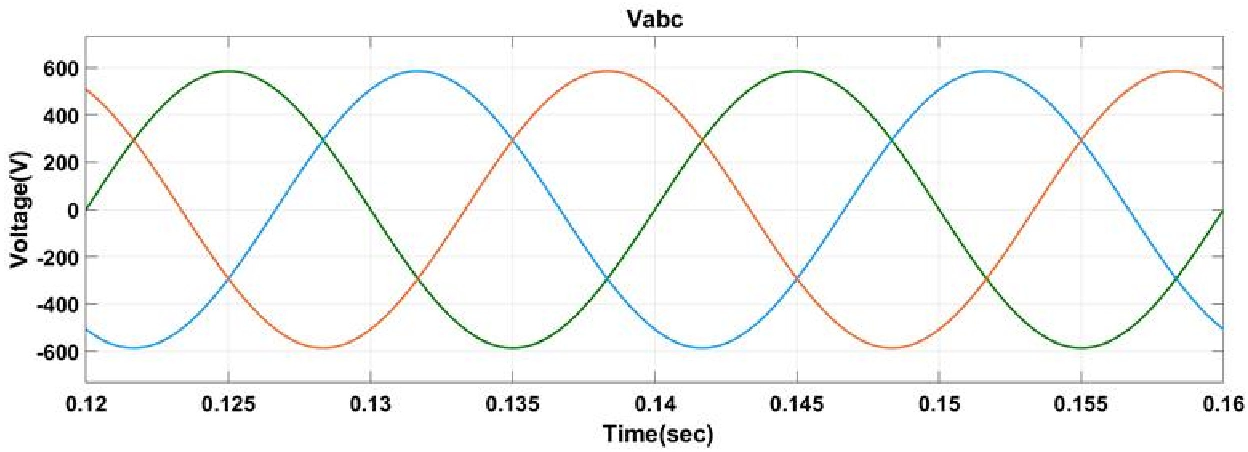

Fig. 13: Voltages

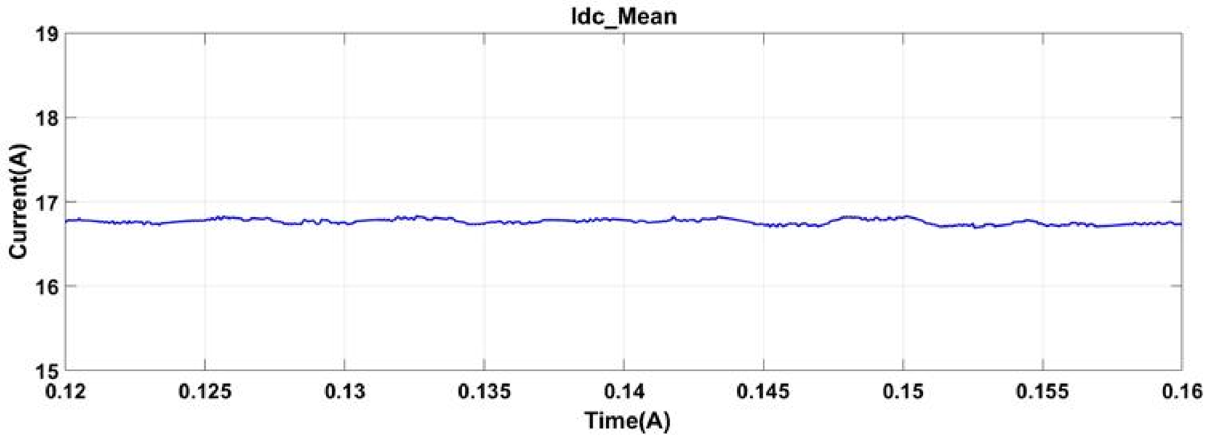

Fig. 14: DC side mean current

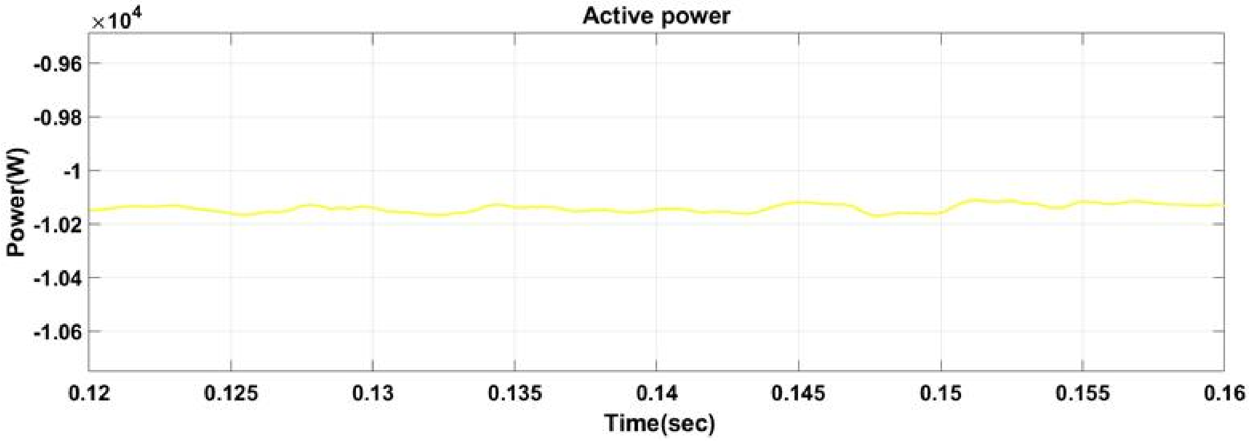

Fig. 15: Active Power

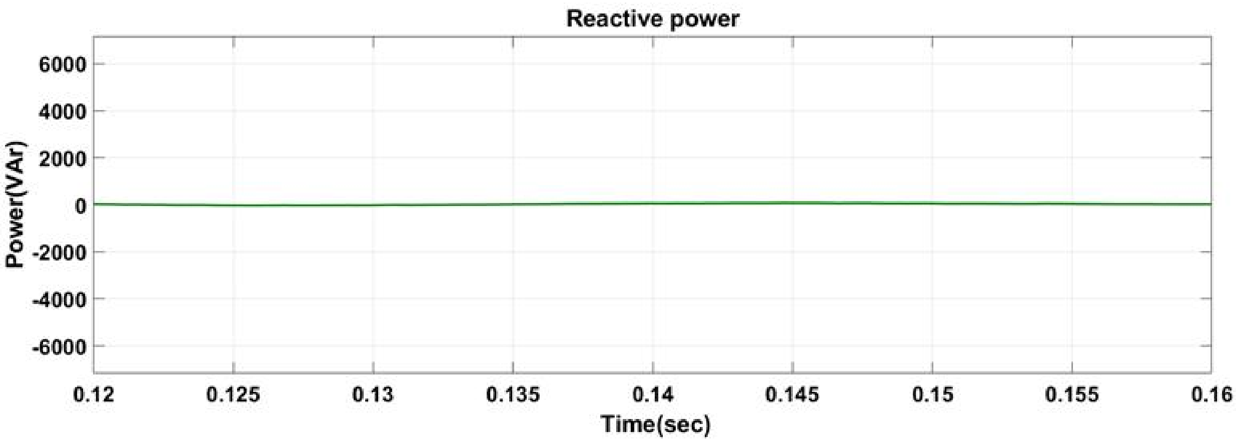

Fig. 16: Reactive Power

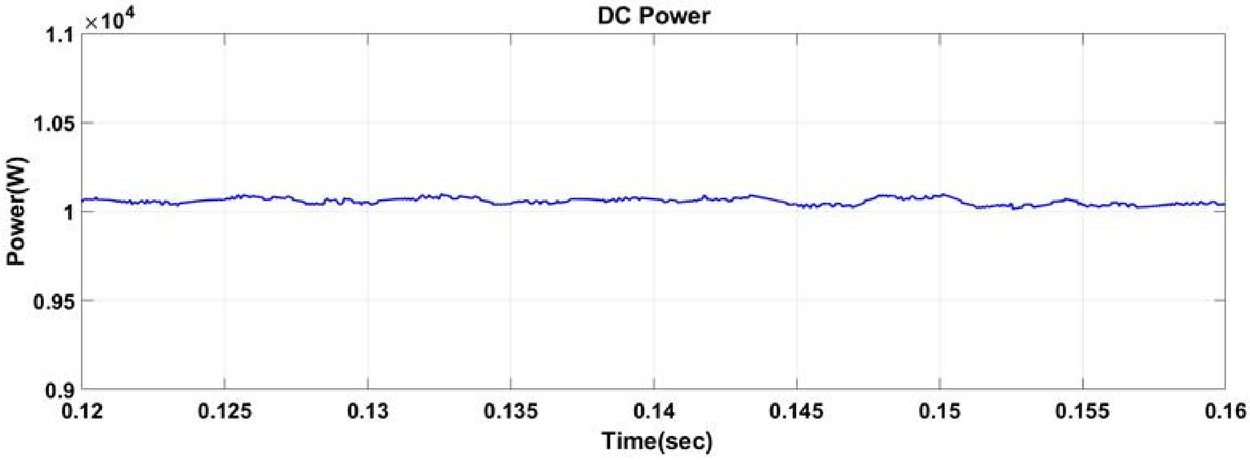

Fig. 17: DC Power

5. Results

The values obtained are mentioned in the table 1:

Table 1: Results

Results and Converter Parameters	
Parameters	Values
I_{abc} ref(rms)	13.91 A
I_{abc} actual(rms)	13.91 A
$V_{abc(L-L)}(rms)$	415 V
I_{dc} mean	16.8 A
Filter Inductance L	8.06 mH
DC link capacitance C	11.9 μF
Active power	10.17 kW
Reactive power	0 VAr
DC Power	10 kW

6. Conclusion

Three level NPC converter is designed and operated as a rectifier using hysteresis current control in abc model, with ac side line to line input voltage as 415 V and dc side output voltage as 600 V. Using this converter 10 KW power is drawn from the grid and supplied to the dc side. Three phase reference current for the hysteresis current control is found using reactive power theory form the given power. Three phase reference current is converted to dq0 frame and then converted into abc frame using ωt, calculated from the PLL loop of the grid voltage. L filter is calculated to reduce harmonics injected in the grid and dc link capacitor is calculated to maintain voltage with 10% of V_{dc}. This converter can be used to charge battery of electrical vehicle.

7. References

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