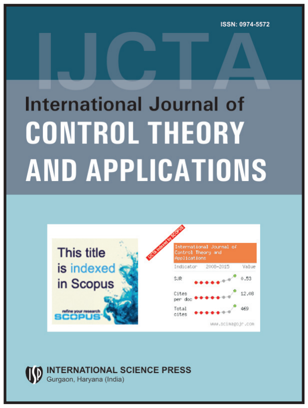

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3-Phase 3-Level Transformerless Neutral Point Clamped Inverter for Wind Energy System

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Abstract: The Multilevel inverters are highly being used in high-power medium voltage applications due to their better performance compared to two-level inverters. Among various types of multilevel inverters, neutral point clamped three-level inverter (NPCTLI) is suitable for a Transformerless grid-connected wind energy conversion system. As it avoids leakage currents, common mode voltage and capacitor balancing problems. Split inductor is used to interconnect inverter with grid connected system which avoids the usage of transformer. While using split inductor neutral point clamped multilevel inverter, shoot-through problems are producing in the bridge legs of an NPC-TLI. Space Vector pulse width modulation Control (SVPWMC) offers an excellent current control and improved voltage performance to NPCTLI, which reduced amount of total harmonic distortion present in system. The proposed topology guarantees for no shoot-through possibility and capacitor balancing problem. The new topology is referred to as split-inductor NPCTLI (SI-NPCTLI). Finally, the simulation results of a proposed SI-NPCTLI system verified using MATLAB SIMULINK.

Index Terms: Wind energy conversion system, PMSG, Space Vector pulse width modulation (SVPWM), Neutral point clamped three-level inverter (NPCTLI).

1. INTRODUCTION

Wind energy systems are in rapid use all over the world owing to technology advancements [1] which are the fastest developing in renewable energy sector [2]. Wind is available aplenty to be harnessed and environmentally viable. To further make it economically viable improvements in the electrical system efficiency [2] mainly in the power electronic converter control is discussed. A permanent magnet synchronous generator (PMSG) is favorable in comparison to a FESG (Field excited induction generator) for a wind turbine since it increases the system efficiency, reduces need for maintenance and the need for a gear assembly in a turbine can be eliminated as well [3].

Excitation losses are eliminated in PMSG, which are indispensable in an induction machine. Due to the absence of mechanical failure in PMSG based Wind energy conversion system (WECS) the system failure rate is reduced. The system is applicable for medium voltage and high power applications. The rectified dc voltage is fed to a boost converter, which boosts the input signal voltage and feeds an amplified dc voltage to the MLI. It consists of an inductor, a switch (IGBT), capacitor and diode. The energy stored in the inductor adds up with the input source voltage when the switch is turned on and the voltage across the capacitor is built up by quickly cycling the switch. This way more energy can be fed to the inverter. The blocking diode prevents reverse capacitor discharging through the switch.

A Multi Level Inverter (MLI) or specifically a three level inverter reduces the voltage stress on the switches [4] and also the Total Harmonic Distortion (THD).The multiple voltage levels with smaller voltage changes, closer in resemblance to sinusoidal waveform, reduces stress on the motor [5-8]. Only half the dc link voltage is available across the off state switches due to clamping diodes, thus facilitating high power output from a lower voltage rated inverter [5]-[8]. The additional level is introduced by the NPC (Neutral point clamped) topology where two clamping diodes are connected in parallel with the switches to the DC bus neutral point, which is connected to the output through the diodes [9].

A transformer based grid connected system is bulky, costly, cause grid current distortion and gives rise to leakage current [10] These problems are overcome in a Split inductor (SI) based system which is used. For controlling the Split Inductor-NPC-MLI Space Vector Pulse Width Modulation (SVPWM) technique is employed. It is advantageous as it increases output efficiency and minimizes the Total Harmonic Distortion. It uses redundant switching states which are not available in sinusoidal PWM. This technique is used to minimize total harmonic distortion in the power fed to the grid.

2. WIND ENERGY CONVERSION SYSTEMS (WECS)

Wind energy conversion systems have been in the global power scenario since more than a decade ago. Though fossil fuels still continue to be the chief energy sources worldwide, but they raise environmental concerns[11] and also their reserves are limited, On the other hand wind energy is practically unlimited and devoid of any harmful emissions.

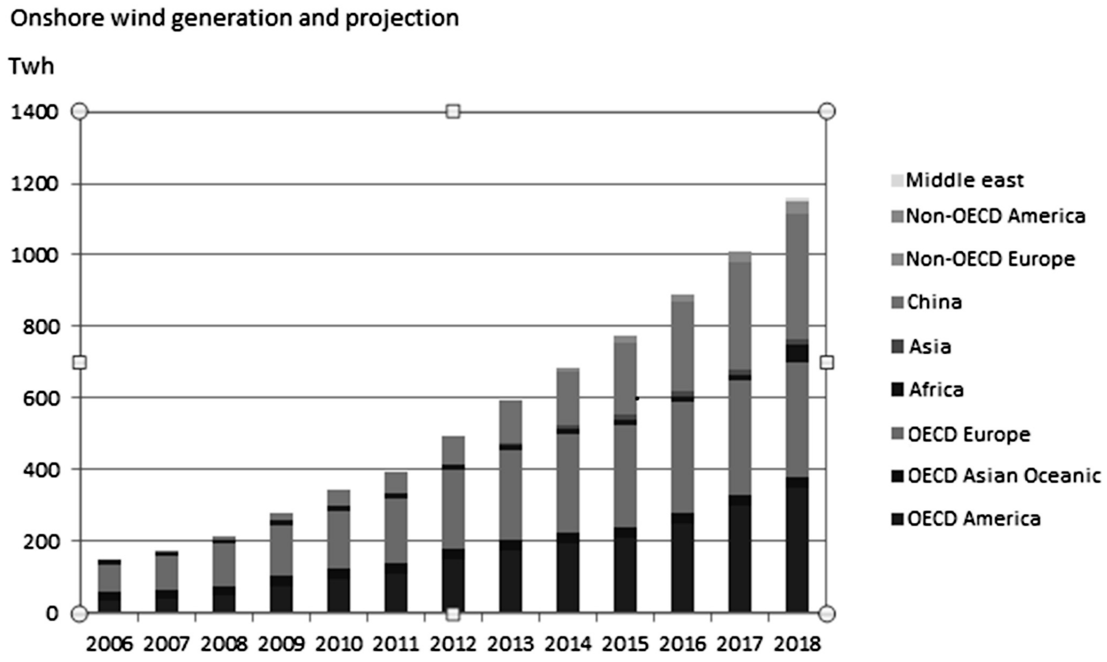


Figure 1

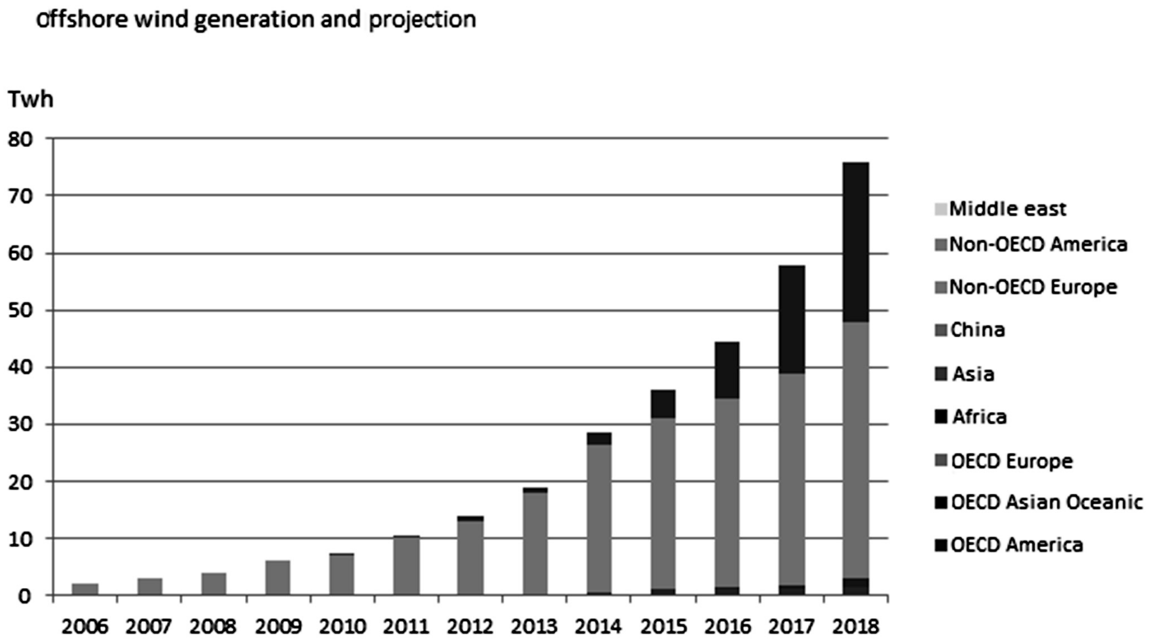


Figure 2

Figure 1 & 2 IEA(2013), Medium Term Renewable Energy Market Report 2013, OECD/IEA, Paris.

The Wind turbines are the first step in the conversion of mechanical wind energy to an electrical output. They have three blades designed to harness wind energy. The output torque of this turbine is fed to the PMSG (Permanent Magnet Synchronous Generator). A PMSG machine having large number of poles can also be used without a gearbox [12].

PMSG's are compact and tough, need less maintenance and eliminate the need for an excitation field [12]. Low cost permanent magnets for them are easily available [13]. These factors make PMSG's a feasible choice for MV-high power applications. But due to output voltage fluctuations in this tubine-PMSG system, it cannot be directly connected to the grid. For this, and to increase the power output of the wind energy system [14], power electronic converters are used.

A Split Inductor based NPC-MLI configuration of power converters can be used to connect the generator to the grid. But this topology has low efficiency [14]. SVPWM control technique for the power electronic switches solves this problem and also enhances the power quality fed to the grid.

3. NPC 3-LEVEL INVERTER

One of the multilevel arrangements that has gained much notice and widely used is the Neutral-Point-Clamped multilevel inverter or also known as Diode Clamped multilevel inverter. This structure was first proposed by Nabae [8]. Figure 3 shows the 3-level NPC inverter. Fundamentally, NPC multilevel inverters combine the small step of staircase output voltage from several levels of DC capacitor voltages. A k-level NPC inverter consists of $(k-1)$ capacitors on the DC bus, $2(k-1)$ switching devices per phase and $2(k-2)$ clamping diodes per phase. The DC bus voltage is split into 3 levels by using 2 DC capacitors, C_1 and C_2. Each capacitor has $V_{dc}/2$ volts and each voltage stress will be limited to one capacitor level through clamping diodes.

The number of levels can be comprehensive to a higher level by additional switching devices and with these additions, the inverter will be able to achieve higher AC voltage, producing more voltage steps that will be approaching sinusoidal with minimum harmonics distortion. During inverter operations, the switches near the centre tap are switched on for a longer period compared to the switches further away from the centre tap as given in the switching states in Table. As the switch is further away from the centre tap the switching time is shorter. Another difference between the conventional 2-level and multilevel NPC is the clamping diode. In case of 3-level NPC inverter, clamping diode, D_1 and D_4 clamped the DC bus voltage into three voltage level, $+V_{dc}/2$, 0 and $-V_{dc}/2$. The number of freewheeling diodes (d_f) per phase, the number of clamping diodes (d_c) and number of DC capacitance can be calculated by using Eqs. (1) and (2) respectively.

$$d_f = 2(k-1) \tag{1}$$

$$d_c = (k-1)(k-2) \tag{2}$$

$$c = k-1 \tag{3}$$

Table 1
Modes of Operation of SI-NPC-MLI

Modes	*Leg 1*	*Leg 2*	*Leg 3*	*Inverter Output*
Mode 1	S2a, S3a	S2b, S3b	S2c, S3c	0
Mode 2	S3a, S4a	S3b, S4b	S3c, S4c	–3Vdc/2
Mode 3	S3a, S4a	S1b, S2b	S3c, S4c	–Vdc/2
Mode 4	S3a, S4a	S2b, S3b	S2c, S3c	–Vdc/2

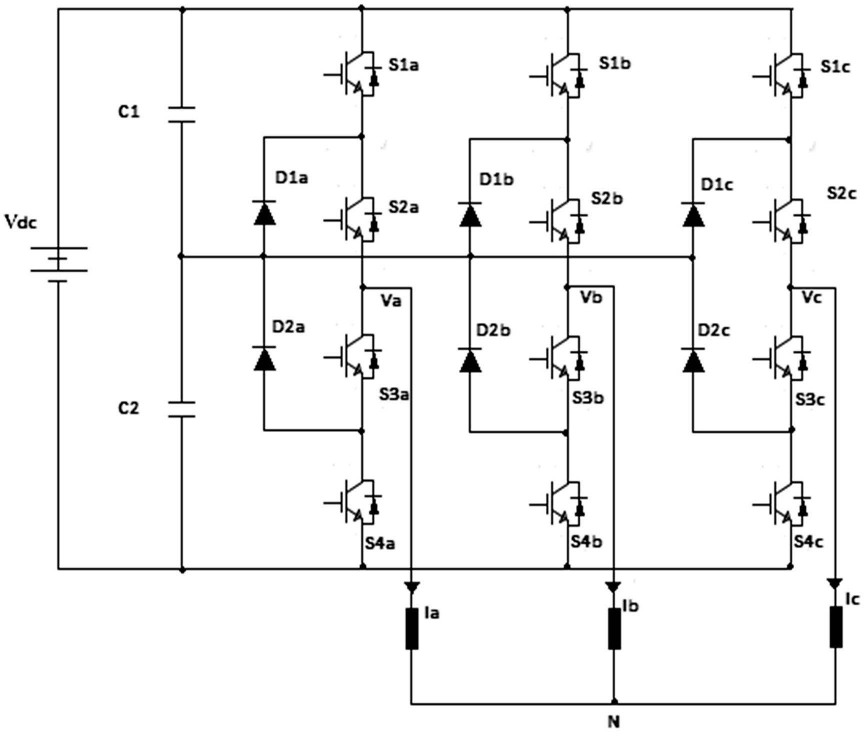


Figure 3: Three level NPC inverter

The NPC multilevel inverter includes the advantages are for a high *m*-level, the distortion level of the harmonics content is so low that the use of filter is redundant. Constraints obligatory on the switches are low because the switching frequency may be lower than 500Hz. Reactive power flow can be prohibited and the efficiency is high because all devices are switched at fundamental frequency.

4. SPLIT INDUCTOR BASED NPC-MLI

Transformers are required for synchronizing the inverter output with the grid requirements. But these systems are complex and costly. They increase leakage current in the system causing grid current distortion and safety problems [15]. Transformerless systems reach an efficiency upto 97% [15] and are ideal for Distributed Power Generation Systems (DPGS). In addition, they reduce the size, complexity, weight of the inverter [10].

I. Takahashi at. el., [16] neutral point clamped three-level inverter (NPCTLI) topology is widely applied in transformerless systems. It reduces the dc component injected to the grid. Transformerless systems use split inductors between the dc link of the inverter and the neutral point of the grid.

A. Modes of Operation of Switches

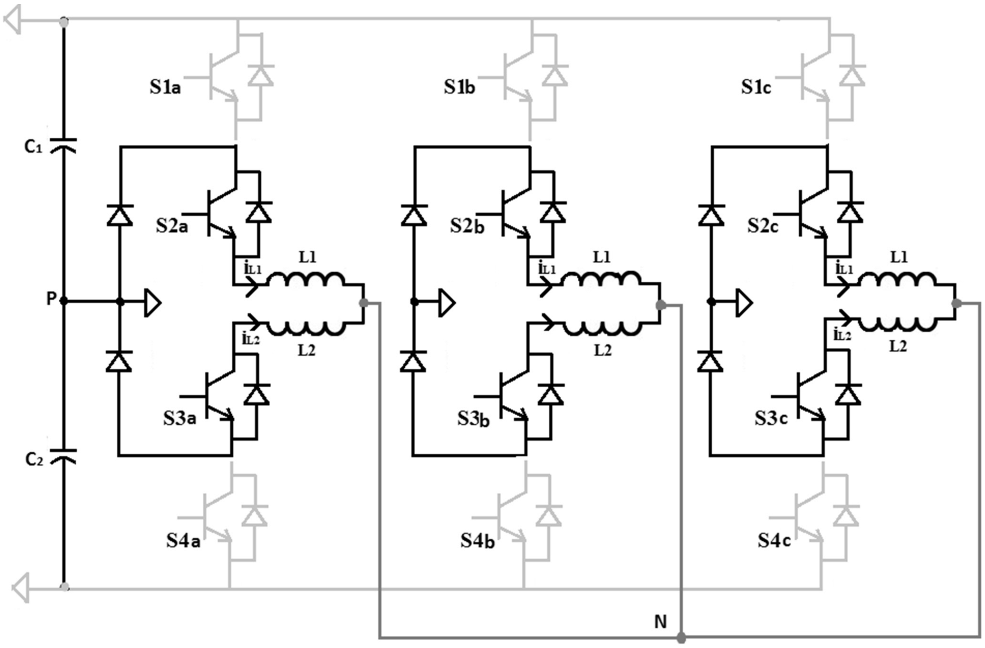
In mode 1, the switches S2a, S3a of leg 1; S2b, S3b of Leg 2; S2c, S3c of leg 3 are in ON state and other switches are turned OFF. The bridge output voltage is zero is shown in Figure 4(a).

In mode 2, the switches S3a, S4a of leg 1; S3b, S4b of Leg 2; S3c, S4c of leg 3 are in ON state and other switches are turned OFF. The bridge output voltage is –3Vdc/2 zero is shown in Figure 4(b).

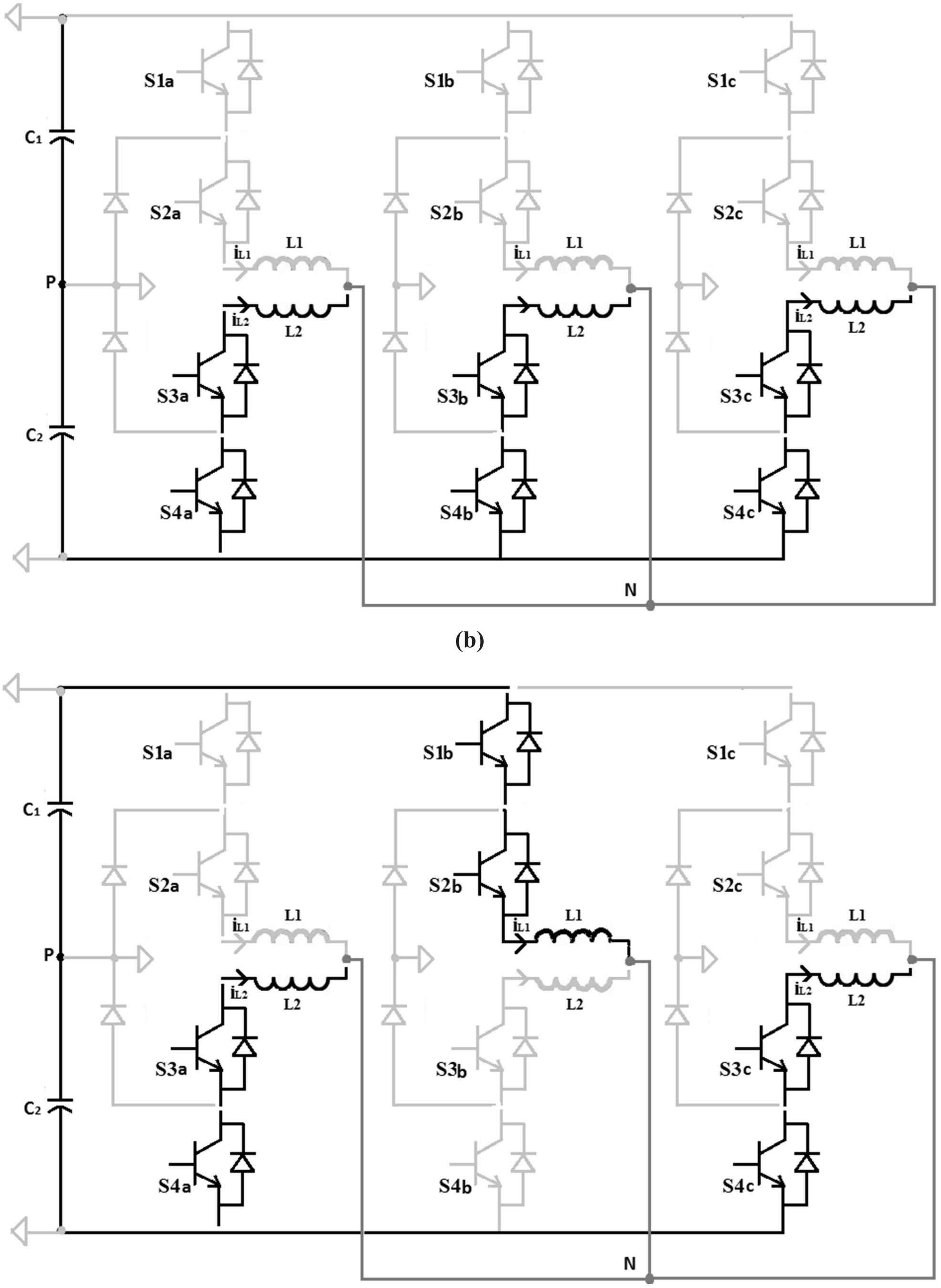
In mode 3, the switches S3a, S4a of leg 1; S1b, S2b of Leg 2; S3c, S4c of leg 3 are in ON state and other switches are turned OFF. The bridge output voltage is –Vdc/2 zero is shown in Figure 4(c).

5. SVPWM (SPACE VECTOR PULSE WIDTH MODULATION)

For an MLI to operate properly, proper selection of switching states and their sequence is essential. In SPWM technique, only half of dc link voltage can be obtained as the peak for fundamental component [17]. In comparison, SVPWM gives more fundamental voltage and better harmonic reduction. In an NPC inverter, due to current at neutral [18], the voltage across the capacitors is not divided equally which compromise the output voltage waveform and produces unequal stress on the power electronic devices [18].



(a)



(b)

(c)

Figure 4: Modes of Operation (a) Mode 1 (b) Mode 2 (c) Mode 3

Neutral point balancing needs proper selection of switching states and utilization of on times for the switches. SVPWM technique can be used to achieve that. It is also suitable for DSP [19] implementation and improved dc link utilization. SVPWM deals directly with switching states and their sequence. The space vector diagram of a three level inverter consists of six sectors, each having four triangles. [20] For an *n*-level inverter, *n* switching states are possible. Hence there are twenty seven switching states for a three level inverter. The tip of switching vector is located in the triangles as a point in the complex space (α, β).

The following are the salient features of the proposed scheme:

1. The on-time calculation is simple due to the use of two levels SVPWM. The on-time calculation equations do not change with the position of reference vector like the traditional approach. So there is no need for any lookup tables as well.
2. In the space vector diagram of an n-level inverter, the triangle where the reference vector is located is identified as integer j using a simple algebraic expression. We call j as triangle number, it implies the j^{th} triangle among the $(n-1)^2$ triangles in a sector. Any switching sequence can be executed with respect to triangle j, leading to a simplicity and flexibility of optimizing the switching sequence.
3. The proposed scheme can be used for any n-level ($n \geq 3$) inverter without any significant increase in computations.
4. The proposed method can be easily implemented using a commercially available motion-control DSP or microcontroller, which normally supports only two-level modulation. The scheme is explained for a three-level inverter and then generalized to include any level. Experimental results are provided for three-level and five-level inverters.

A. Switching Time Calculations

SVPWM is to compensate the required volt-seconds using discrete switching states and their on-times.

Traditionally, in order to determine the on-times for a triangle of an n-level inverter, three simultaneous equations are solved. However, classical two-level space vector geometry can be used for on-time calculation for a multilevel SVPWM. Figure shows the space vector diagram of a two-level inverter. Every sector is an equilateral triangle of unity side and ($h = \sqrt{3}/2$) is the height of a sector. On-time calculation for any of the six sectors Si, $i = 1, 2, \ldots, 6$ is same, so let us consider the operation in sector 1. On-time calculation is based on the location of the reference vector within a sector. For the sector 1 in Figure 5, the volt-second balance is given by,

- The nearest three vector (NTV) scheme is used for the capacitor balancing.
- The reference can be located in the any of the sub triangle $\Delta_1(V_{Z0}V_{SI}V_{S2})$, $\Delta_2(V_{S1}V_{MI}V_{S2})$, $\Delta_3(V_{S2}V_{MI}V_{L2})$, $\Delta_4(V_{SI}V_{MI}V_{LI})$.
- The duty ratios are

$$\delta_a = V_\alpha - V_\beta/\sqrt{3} \tag{4}$$

$$\delta_b = V_\beta/m \tag{5}$$

$$\delta_0 = 1 - \delta_a = \delta_b \tag{6}$$

The nearest vector redundancy scheme is the proposed technique used to obtain the capacitor balance in the modulation index below ($0 < m < 0.6$). Depend upon the point the participation of the switching vector can be utilized. By the redundant state in (SV) the positive and negative phase currents cancelled. Due to that the capacitor balance can be achieved.

These three vectors could be used to synthesis the sampled reference voltage vector.

$$V^*\,\delta_{S1} + V^*\,\delta_{S2} + V^*\,\delta_{M1} = V^* \tag{7}$$

$$\delta_{S1} + \delta_{S2} + \delta_{M1} = 1 \tag{8}$$

And duty cycles calculations.

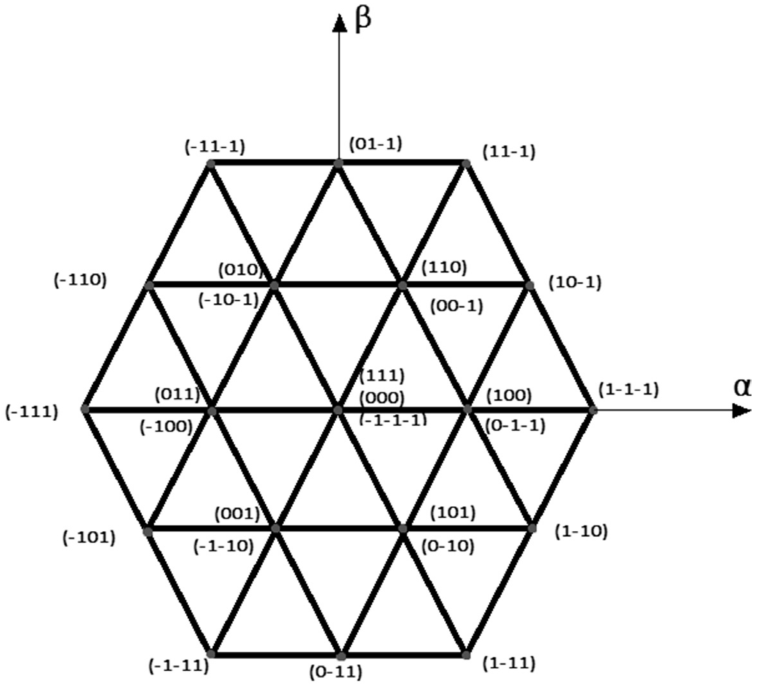


Figure 5: SVPWM Switching States

6. CONTROL STRATEGY

The entire wind energy conversion system is as shown I Figure 6 above. The blades of the turbine capture wind energy and transfer energy to the turbine rotor which is connected to a common shaft connecting the PMSG.PMSG converts this mechanical energy to three phase ac voltage which fluctuates according to the wind speed. This three phase ac voltage is converted into dc by a three phase rectifier. Output dc voltage is fed to a boost converter which boosts the input signal voltage and feeds an amplified dc voltage to the MLI. The NPC topology of the MLI blocks the dc component from entering the grid and provides feasible application of control technique for the switches.

SVPWM technique uses redundant switching states to locate a switching vector corresponding to a reference vector in α, β plane. It is highly efficient and it reduces Total Harmonic Distortion in the output. The inverter output is a three level stepped wave which is converted to a sinusoid by using split inductors. They omit the need for a transformer and reduce the circuit complexity, size, cost and accurately synchronize the inverter to the grid. The output waveform obtained is a pure three phase sinusoid with negligible THD is shown in the Figure 6.

7. SIMULATION RESULTS

The simulation system was setup in Matlab11.b. The motor is a 1HP induction motor with a rated voltage of 300V and current of 5A. An open loop constant V/f control is used to regulate the motor speed and the dc-link voltage is set at 300V. The performance of wind turbine system is tested and is shown in Figure 7 shows the output three phase voltage waveform of PMSG. The voltage generated by it is 260V.The dc voltage output of rectifier is 295V as shown in Figure 8.Using boost converter, the voltage was increased to 600V as shown in Figure 9.The three level step voltage of the NPC inverter is as obtained in Figure 10.The three phase inverter current waveform is also shown. Final Output Grid voltage and current is as shown in Figure 11. It can be seen that the stepped voltage is fully converted to sinusoidal waveform and the grid current waveform is also shown. Figure 12 shows two phases of split inductor current. Each phase is at an angle of 120 degrees from the other. The Total Harmonic Distortion in the output grid voltage waveform is 0.00% as shown in Figure 13. Total Harmonic Distortion in the output grid current waveform is 5.9% as shown in Figure 14.

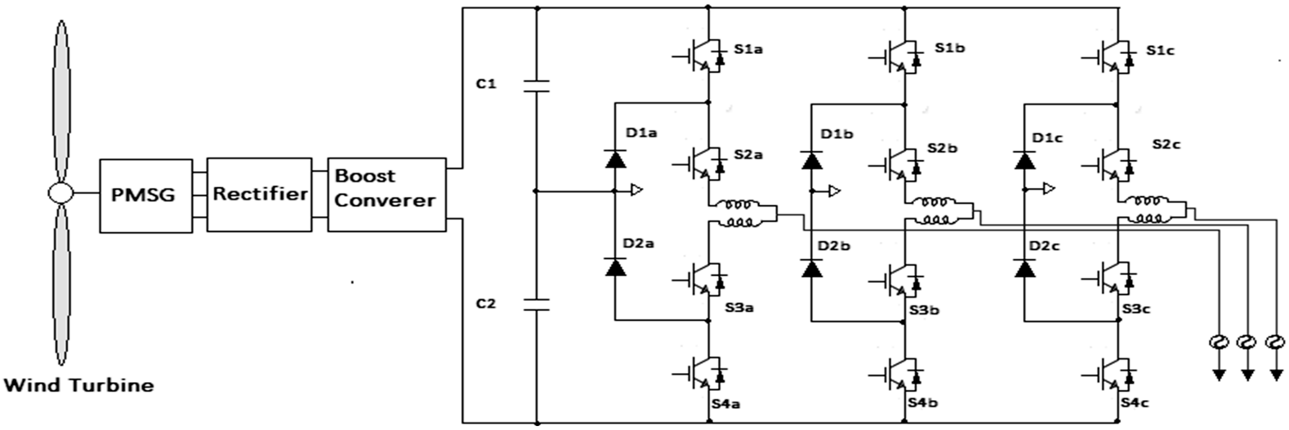


Figure 6: Control Strategy for the WECS

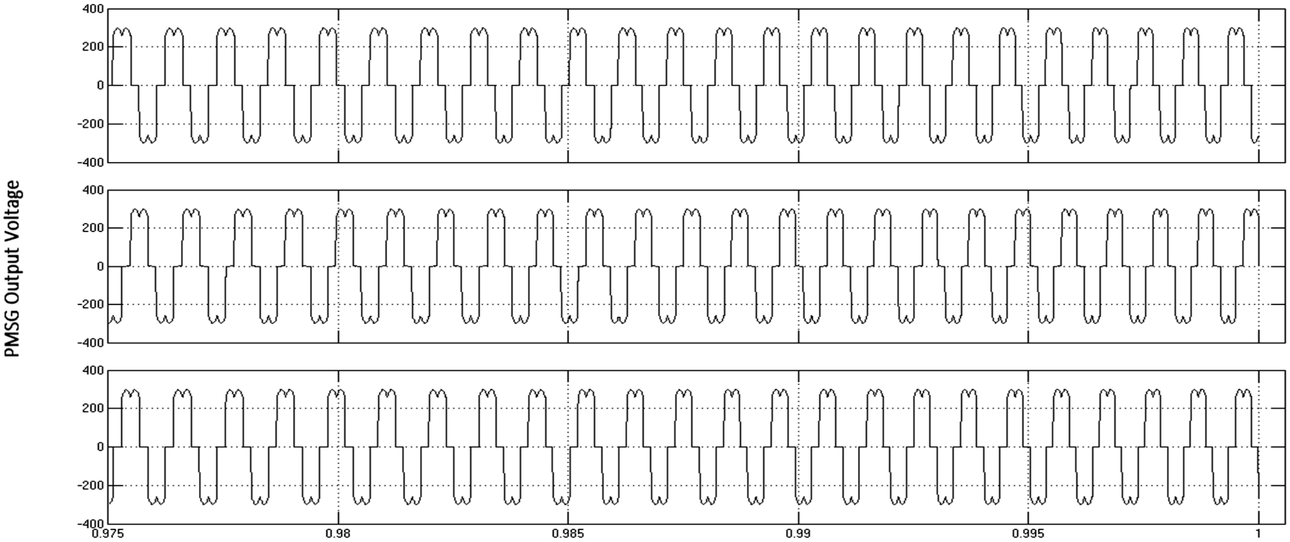


Figure 7: Three Phase Output Voltage of PMSG

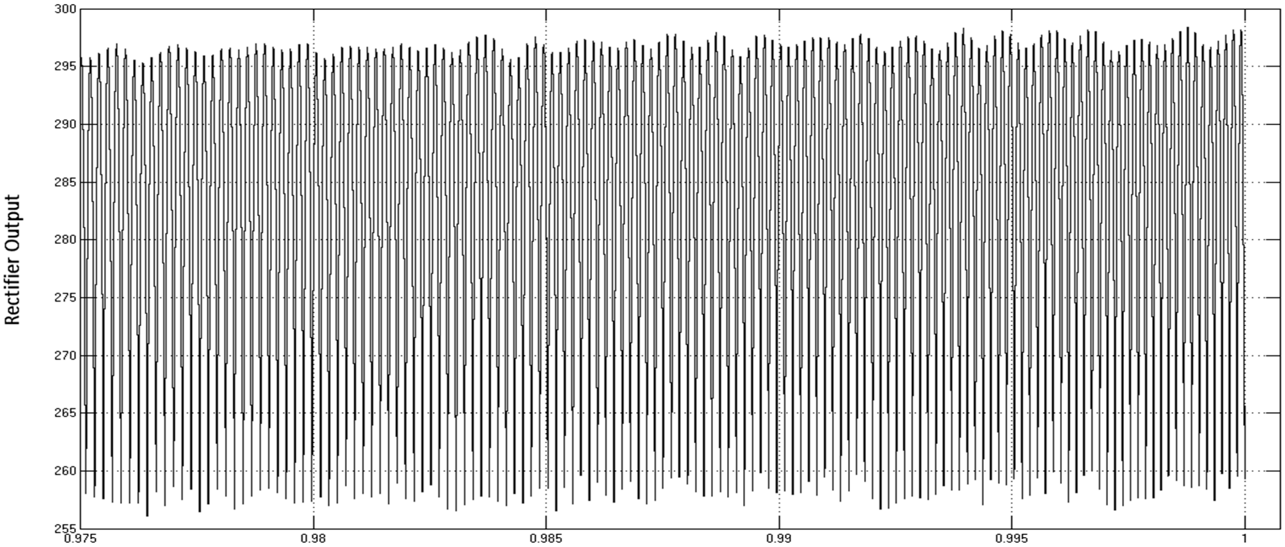


Figure 8: Rectifier Dc output Voltage

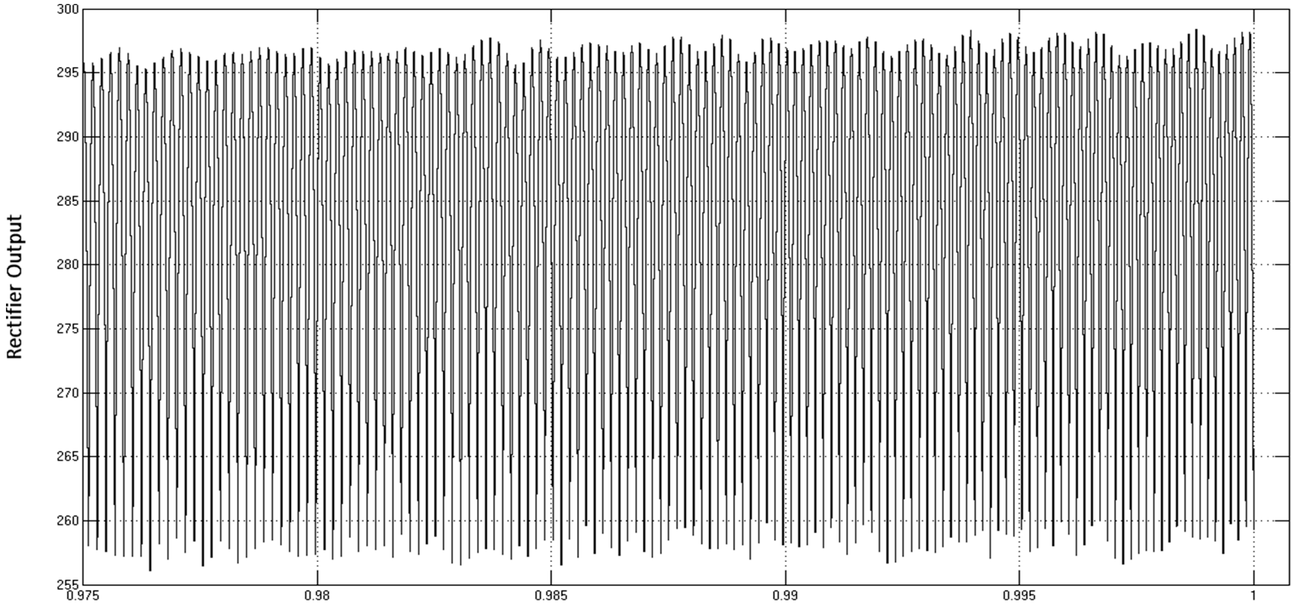


Figure 9: Boost Converter Output

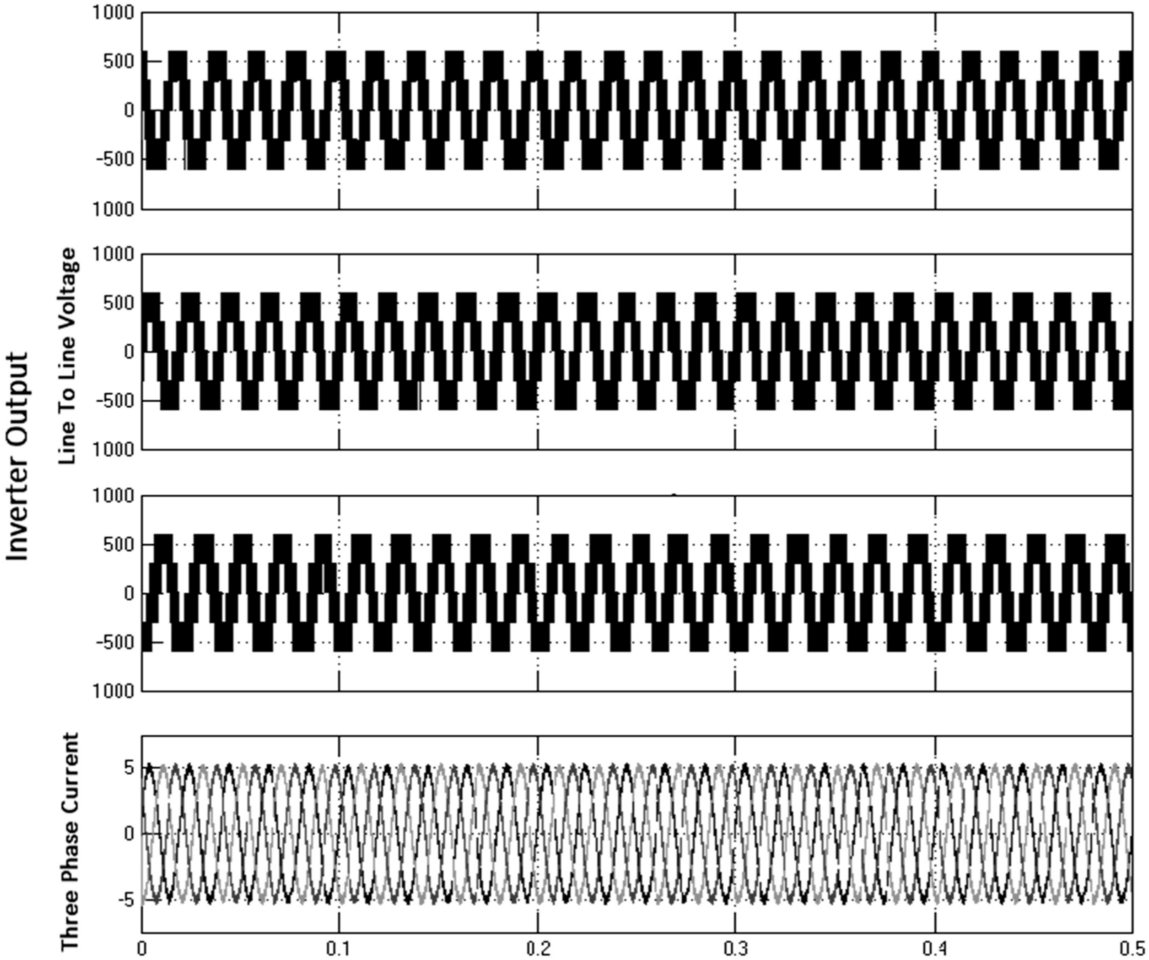


Figure 10: Output voltage & current of NPC inverter

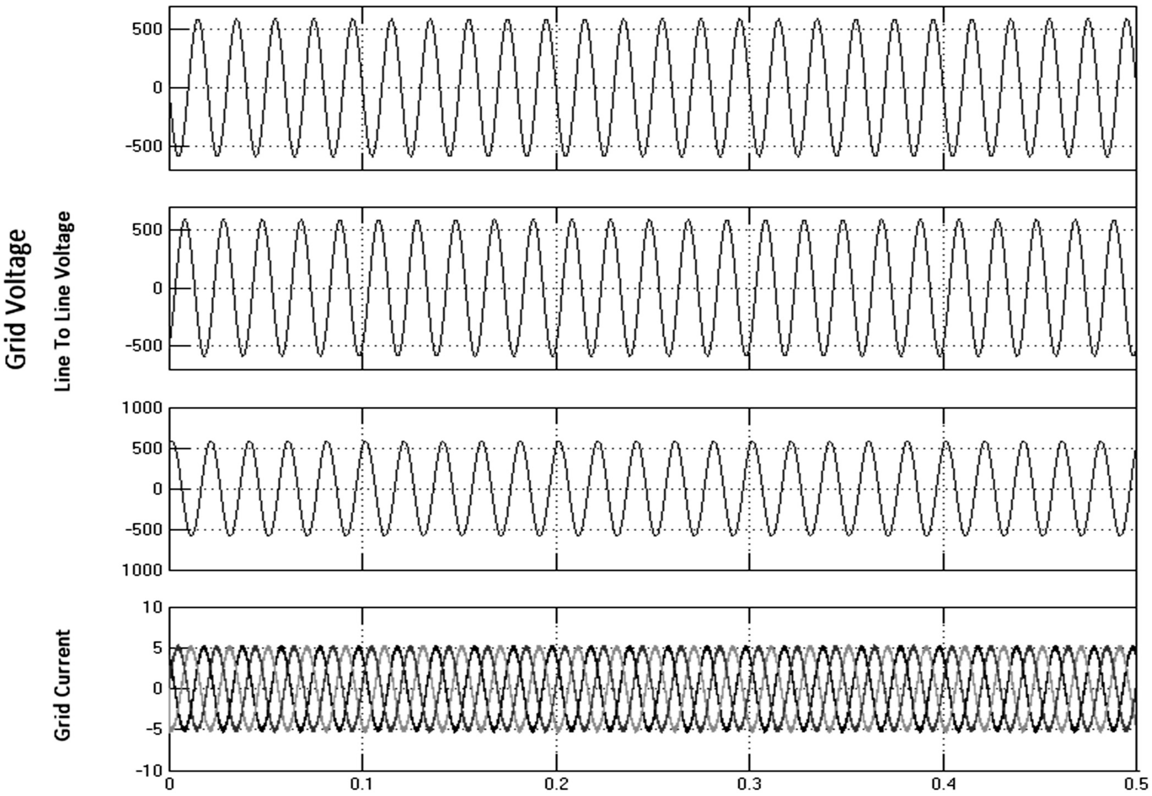


Figure 11: Output Grid Voltage and Current

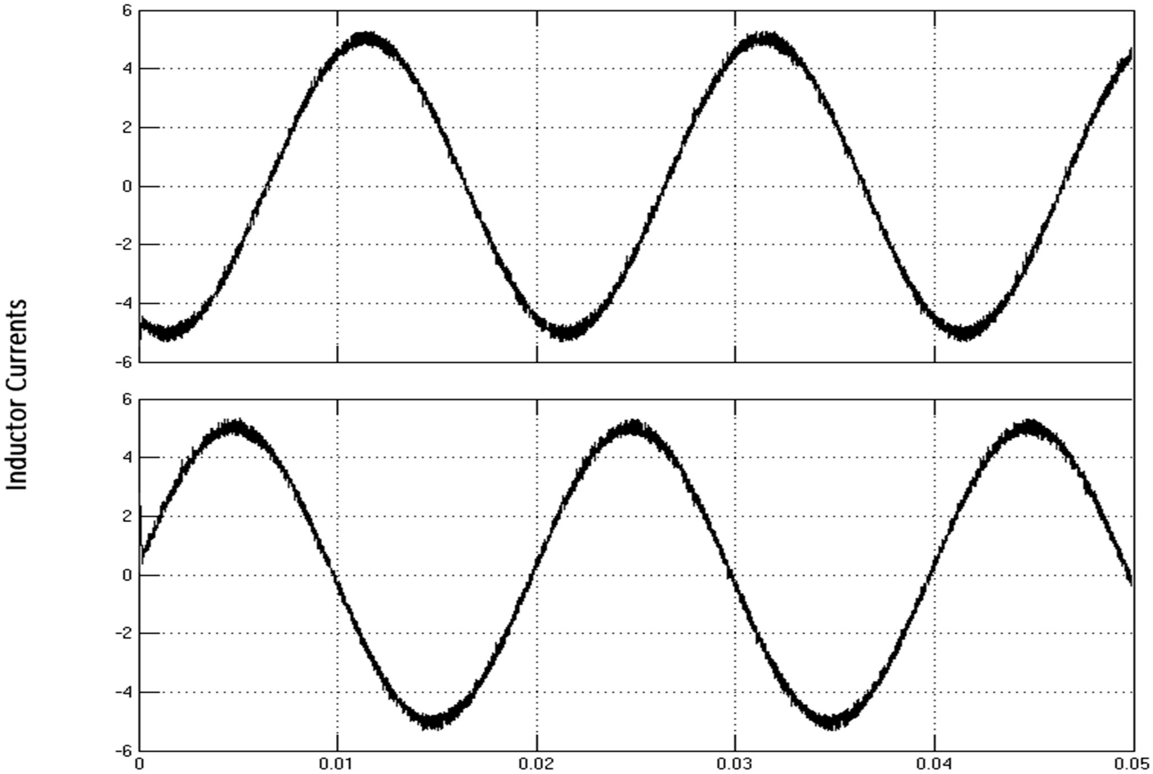


Figure 12: Split inductor current

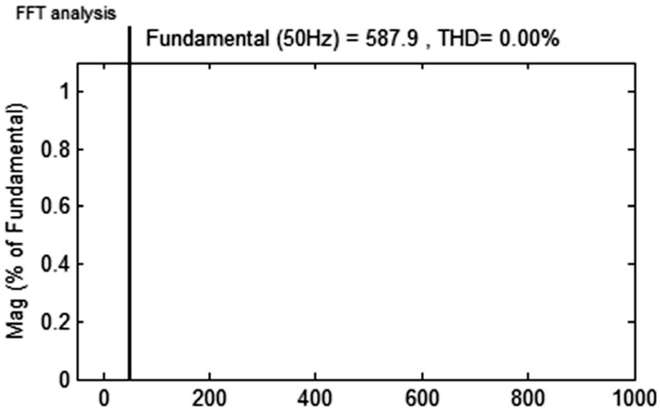


Figure 13: Total Harmonic Distortion in output voltage

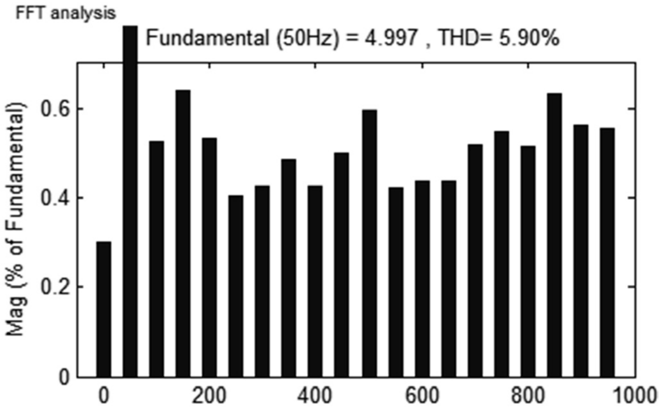


Figure 14: Total Harmonic Distortion in output current

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