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Design and Simulation of Space Vector Pulse Width Modulation Inverter based Transformer-less in small Wind Turbines

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***Abstract*—** For variable speed applications, an inverter with a voltage source is typically used to provide a three-phase induction motor that has a variable frequency as well as a changeable voltage. Among the several distinct varieties of multilevel inverters, a neutral point clamped three-level inverter (NPCTLI), which is appropriate for transformer-less grid-side wind turbines, is used in this work. Additionally, to gain a high level of power quality and low-pass passive filters, low distortion with two series of inductors and capacitors (LCL) filters are used. The LCL filter is used to link an inverter to a grid-connected system, eliminating the need for a transformer Problems with shoot-through are caused in the bridge legs of an NPC-TLI when an LCL filter and a neutral point clamped multilevel inverter are used. Output voltage suitably in the line side of the inverter is gained using an appropriate pulse width modulation (PWM) approach. PWM generation can be separated into two categories: triangle comparison based PWM (TCPWM) and space vector based PWM (SVPWM). SVPWM control scheme for NPC inverter gives higher reliability and outstanding dynamic performance as compared to other techniques. In order to address this issue, a space vector pulse width modulation control (SVPWMC) is used for great current control and enhanced voltage performance for NPCTLI. The results demonstrated that this kind of filter reduces the level of harmonic distortion at the lowest switching frequencies. This structure permits the basic waveform component to be sent to the output when the harmonic components are filtered away. The proposed control method greatly improves output efficiency and reduces total harmonic distortion in wind turbines, according to the findings.

***Keywords*—** Wind Turbine, Harmonics, Three-level inverter, SVPWM

I. INTRODUCTION

To fulfill human requirements, a wind turbine is able to convert wind kinetic energy into sustainable electrical energy. Enhancement of the quality of electrical systems [1], particularly controlling electronic converters are critical to making them economically viable. In a wind turbine, a permanent magnet synchronous generator (PMSG) is preferable to a field excited induction generator (FEIG) because it improves system efficiency, decreases servicing, and eliminates the needs for a gear assembly [2]. Due to its superior performance, the diode-clamped three-level neutral-point clamped (NPC) topology has been the most extensively utilized of all multilevel inverter topologies proposed [3],[4]. The reduction of harmonic content in inverter circuits is one of the key issues that power electronic design engineer encounter. Lower order harmonics in the output voltage are a serious shortcoming of the standard square wave inverter, which is often used in low or medium power applications. PWM control techniques are one of the ways to improve the harmonic-free environment in high-power converters. To acquire the needed output voltage on the line side of the inverter, an appropriate pulse width modulation (PWM) strategy is required for this design [5]. The output performance of a multilevel inverter is determined by the modulation algorithm, and several PWM algorithms have been created. The two most triangle comparison prevalent PWM generating methods for multilevel inverters (SVPWM) is space vector PWM and PWM (TCPWM). Three phase modulating reference signals are evaluated against a common triangular carrier in TCPWM methods, sine-triangle PWM for instance, to create PWM signals for the three phases. Instead of three phase modulating waves, revolving reference voltage vector is used as a voltage reference in SVPWM approaches. SPWM algorithms have been used in engineering applications in a long run[6],[7], but with growing microcontrollers, SVPWM became more popular because of its easy implementation, better harmonic proficiency, dipped in switching losses, high DC voltage usage ratio, and easiness in balancing of capacitor voltage. On the line side, the magnitude and frequency of the fundamental component are controlled by a reference vector [6]. When compared to space vector PWM, the highest attainable peak phase fundamental is much lower with sine triangle PWM. For the regulation of permanent magnet synchronous motors, the space vector modulation (SVM) technique has become a significant PWM technique for three-phase voltage source inverters. When compared to sinusoidal PWM (SPWM), the analysis of space vector modulation technique demonstrates that uses DC bus voltage more efficiently and brings about less harmonic distortion [7],[8].

The purpose of this article is to bring forth the system to meet the needs of small wind turbines, which are particularly susceptible to harmonics. This system uses a multilevel NPC inverter controlled with SVPWM. This design reduces the amount of harmonic distortion and makes the system more efficient. This design features fewer switches than other MLIs, resulting in a higher-quality waveform for the voltage and current. A filter is still necessary for efficient functioning, though, so we applied a LCL filter, which helps reduce harmonics at lower switching frequencies. The filter allows the output to carry the fundamental waveform while reducing the passage of harmonics. This power system allows wind turbines to generate energy more efficiently and with less damage to the overall system. Remarkably, this design allows the PMSG to be connected without a transformer, making it easier for consumers to deploy wind turbines at smaller locations, such as individual households or businesses.

II. RELATED WORK

The lack of mechanical failure in PMSG-based on wind energy conversion systems (WECS), which are essential in an induction machine, eliminates excitation losses. The system is enforceable for high power applications and medium voltage. The rectified DC voltage is fed to a boost-chopper, which increases voltage input and feeds an amplified DC voltage to the multi-level inverter (MLI). For variable speed applications, a multi-level inverter is typically used to an induction three-phase motor with variable voltage and frequency. It includes an inductor, a switch insulated-gate bipolar transistor (IGBT), a diode, and a capacitor. When the connection is switched on, in the inductor the energy stored is added to the input source voltage, and across the capacitor voltage is built up by cycling the switch. The blocking diode also stops the switch from discharging the reverse capacitor. More energy can be sent into the inverter this way.

Multilevel inverters have made their route into many disciplines of power system study, including wind and solar energy systems, where the widespread usage of multilevel inverters in high power and high voltage applications has piqued the interest of researchers because of their remarkable performance. When compared to two-level inverters, multi-level inverters provide a number of benefits. reducing voltage stress across switching devices, lower output voltage and current harmonics, lower DV/DT, and improved output wave form quality[6],[7],[8].

III. METHODOLOGY

In this part a control strategy and other ingredients of the designed control system for wind turbines was discussed.

3.1. Control tactics

Figure 1 shows the total wind energy conversion system. The turbine blades interact with the wind energy and impute energy to the rotor in the generator, which is linked to the PMSG by a shared shaft [8]. PMSG transforms mechanical energy into three phase electrical energy in varying wind speed. A rectifier converts the three phase ac voltage to dc. The output DC voltage is routed into a boost-chopper, which raises the input voltage and feeds it to the MLI as an increased DC voltage. The NPC topology of the MLI prevents the dc component from accessing the grid and allows for switch control approaches [9]. SVPWM technique uses a switching vector that corresponds to a reference vector using redundant switching states in α and β plane. It decreases Total Harmonic Distortion (THD) on the grid side. The output of the inverter is a three level stepped wave which is transformed to a sinusoidal waveform by using the LCL filter. At lower switching frequencies, the LCL filter reduces harmonic distortion. They do away with the requirement for a transformer, reducing circuit intricacy, size, and expense while precisely synchronizing the inverter to the grid [10].

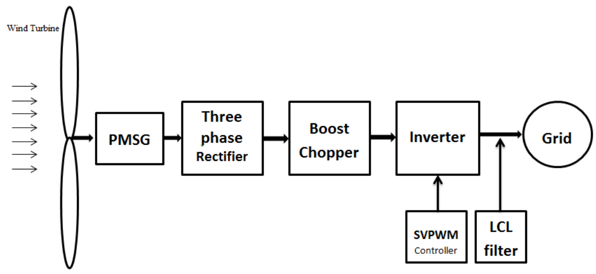

Figure 1. Small wind turbine diagram

3.2. PMSG Model

Permanent magnet synchronous generators play a vital role in wind power generation systems by generating electrical power from mechanical power. These generators are considered self-excitation generators since the excitation field is created by permanent magnets on the rotor. Equations (1) and (2) [10],[11] show the relationship between torque (T) and the resulting induced voltage (E):

$$T = K_t I_a \quad (1)$$

$$E = K_e w \quad (2)$$

where T, K_t, K_e, I_a, w are torque, machine constant, machine constant, stator current, and angular rotor speed, respectively.

On the other hand, it is clear that:

$$E = V_t + I_a(R_a + jX_s) \quad (3)$$

PMSG equivalent circuit for one phase where V_t is terminal phase voltage as shown in Fig 2.

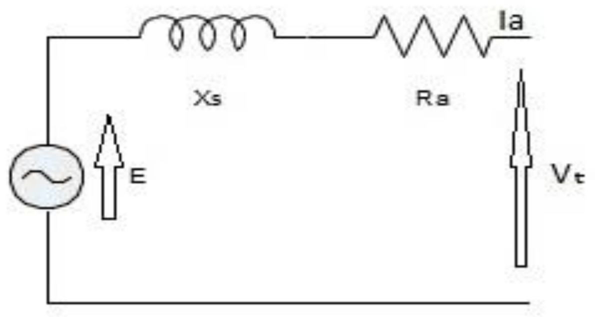

Figure 2. Equivalent circuit of PMSG for one phase

PMSGs are small and durable, require little maintenance, and do not require an induction field [12]. For them, cheap permanent magnets are readily available [13]. Because of these qualities, PMSGs are a viable option for MV-high power applications. PMSG, however, are unable to be connected to the network directly due to output voltage changes. Power electronic converters are utilized for this, as well as to boost the output power of the wind turbine system [14].

3.4. Three Phase Full Bridge Rectifiers:
The topology of the diode rectifier is used in power electronic applications to convert the output ac voltage into the dc voltage, and its average output voltage is obtained as follows [15]:

$$V_{rect} = \frac{3\sqrt{2}}{\pi} V_{LL} \quad (4)$$

where V_{rect} is input DC voltage for the set up boost chopper, and V_{LL} is the PMSG line-to-line voltage.

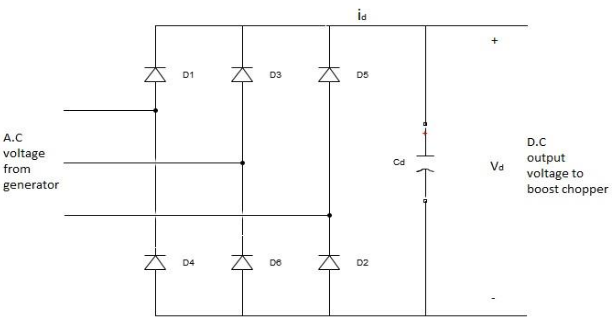

Figure 3. Full bridge three phase rectifier

To eliminate the significant ripple voltage component, a DC link capacitor (Cd) is used at the output stage of the rectifier [16].

$$Cd = \frac{V_m}{6fr\, V_{r(pp)}} \quad (5)$$

where V_m, f, R, $V_{r(pp)}$ are the peak value of the phase voltage, frequency of the source, load resistance, and peak to peak ripple voltage, respectively.

3.5. Boost (Step-Up) Chopper:
On board the Boost Chopper As the title indicates, the output voltage is always larger than the input voltage. Equations (6) represents the relationship between input and output voltage of the boost-chopper [15]:

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad (6)$$

Where
V_o: Boost-chopper output dc voltage.
V_{in} : Input dc voltage of boost chopper.
D: Duty cycle of boost chopper.

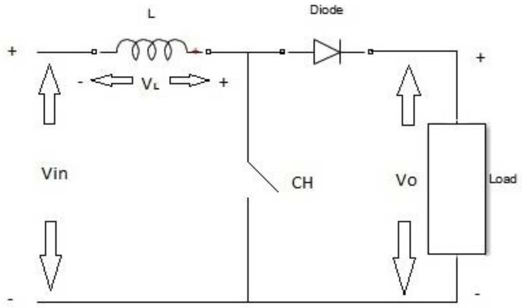

Figure 4. Equivalent circuit of step up chopper

Figure 4 represents the equivalent circuit of a step-up chopper. A step-up chopper is a static device that improves the average output DC voltage compared to the input DC voltage. By looking at the circuit diagram of the step-up chopper, we can see that the operation of this chopper is in two steps: the switch ON and the OFF period of the chopper. Current flows via the closed route established by the supply source Vs, inductor L, and chopper CH when the chopper (CH) is turned on. There is no current flowing through the load during this time. The source current is flowing and the value of load current i_o will be zero during the ON period. During the ON time, energy is also stored in the inductor L. Saving energy in L is critical for increasing the load output voltage. The current via the L does not dissipate quickly when the CH is switched off; instead, it decays exponentially [15],[16].

As a result, it will force current through the diode D and load for the duration of the time period OFF. In this model, the boost is controlled to get a constant output D.C voltage by modifying the duty cycle (D) in response to variations in input voltage. Figure 5 shows block diagram of PID controller model in MATLAB. The conventional single-loop feedback control is achieved by controlling the duty cycle of the boost chopper [16].

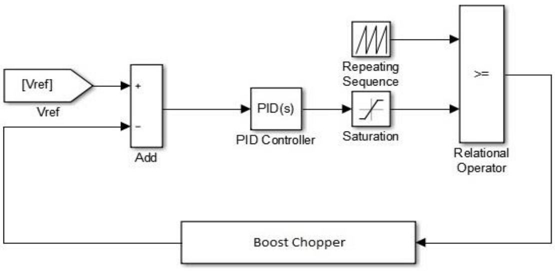

Figure 5. Block diagram of PID control model

3.6. NPC three-level inverter

The NPC multilevel inverter is one of the multilevel arrangements that attracted attention to be used widely [17]-[18]. Figure 6 demonstrates the NPC 3-level inverter. NPC multilevel inverters combine many levels of DC capacitor voltages into a single short step of output voltage. (k-1) capacitors on the DC bus, 2(k-1) per phase switching devices, and 2(k-2) per phase clamping diodes make up a k-level NPC inverter. Two DC capacitors, C_1 and C_2, split the DC bus voltage into three levels. Each capacitor has a voltage of Vdc/2, and each voltage stress will be restricted to one capacitor level via clamping diodes[18]. Additional switching devices can increase the number of levels available, allowing the inverter to get higher ac voltage and produce high voltage periods that are closer to sinusoidal with less harmonic distortion. The switches near the center tap are connected for a longer time during inverter operations than the switches further away from the middle tap, as shown in table 1. The connection time is reduced as the switch is moved further away from the center tap. The clamping diode is another variation between the conventional two-level and multilevel NPCs. Clamping diodes D_1 and D_4 clamped the DC bus voltage into three voltage levels, +Vdc/2, 0 and -Vdc/2, in the case of a three-level NPC inverter. The proportion of freewheeling diodes (df) per phase, the proportion of clamping diodes (dc), and the amount of DC capacitance can be calculated by using equations (7) and (8), respectively [7].

$$d_f = 2(k-1) \quad (7)$$

$$d_c = (k-1)(k-2) \quad (8)$$

$$c = k-1 \quad (9)$$

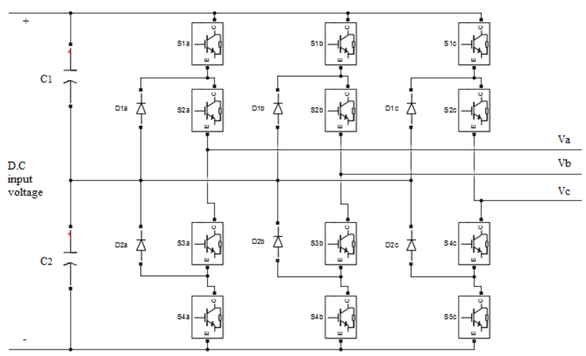

Figure 6. Three level NPC inverter

Table 1. Switching functions of operations of inverter

Switching	Leg1	Leg2	Leg3	Output
Function1	S_{2a}-S_{3a}	S_{2b}-S_{3b}	S_{2c}-S_{3c}	0
Function2	S_{3a}-S_{4a}	S_{3b}-S_{4b}	S_{3c}-S_{4c}	-3Vdc/2
Function3	S_{3a}-S_{4a}	S_{1b}-S_{2b}	S_{3c}-S_{4c}	-Vdc/2
Function4	S_{3a}-S_{4a}	S_{2b}-S_{3b}	S_{2c}-S_{3c}	-Vdc/2

3.7. SVPWM

For an MLI to function successfully, the right option of switching states and their subsequence is important. Only half of the dc link voltage may be acquired as the fundamental component peak in SPWM [18]. SVPWM, on the other hand, provides a higher fundamental voltage and superior harmonic suppression. The voltage across the capacitors in an NPC inverter is not divided evenly due to current at neutral [19], which compromises the output voltage waveform and causes unequal stress on the power electronic devices [19]. The utilization of switch on times and the proper selection of switching states are required for neutral point balancing. This may be accomplished using the SVPWM approach. It is also efficient for DSP [20] implementation and enhanced dc link utilization. SVPWM is focused with switching states and their order. There is six sector for space vector three level inverter, each with four triangles [21]. For an n-level inverter, there are n switching states. As a result, a three-level inverter has twenty-seven switching states. The apex of the switching vector is located in the triangles as a spot in the complex space (α, β).

3.7.1. The key characteristics of the proposed plan are as follows:

- The on time computing is simple because of the use of 2-levels of SVPWM. Unlike the old approach, the on time calculation equations do not vary with the position of the reference vector. As a result, no lookup tables are required.
- Using a simple algebraic equation, the triangle where the reference vector is positioned in the space vector diagram of an n-level inverter is designated as integer j. We call j as triangle number, it indicates the j^{th} triangle among the $(n-1)^2$ triangles in a sector. Because any switching sequence can be done with regard to triangle j, optimizing the switching sequence is simple and flexible.
- Without significantly increasing calculations, the suggested approach may be used to any n-level (n ≥ 3) inverter.
- An existing microcontroller, that typically only supports two level modulation, may simply implement the suggested approach. The technique is described in detail for a 3-level inverter before being generalized to any level. For 3-level and 5-level inverters, experimental findings are reported.

3.7.2 Switching Time Calculations

SVPWM uses discrete switching states and associated ON times to compensate for the required volt-seconds. Three simultaneous equations are traditionally solved to calculate the ON times for a triangle of an n-level inverter. However, for on-time calculation of a multilayer SVPWM, traditional two-level space vector geometry can be used. A two-level inverter's space vector diagram is shown in Figure. Every sector is a one-sided equilateral triangle and (h = √3/2) is the height of a sector. On-time computation for any of the 6 sectors S_i, i = 1, 2, ..., 6 is the same, So, let a 's have a look at the operation in sector 1. ON time calculation is based on the location of the reference vector within a sector. The volt-second balance for sector 1 in Figure 5 is provided by,

- The capacitor balancing is done using the closest three vector (NTV) approach.

- Any of the sub triangles can be used as a reference $\Delta_1(V_{Z0}V_{S1}V_{S2})$, $\Delta_2(V_{S1}V_{M1}V_{S2})$, $\Delta_3(V_{S2}V_{M1}V_{L2})$, $\Delta_4(V_{S1}V_{M1}V_{L1})$.
- The duty ratios are

$$\delta_a = V_\alpha - V_\beta/\sqrt{3} \quad (10)$$
$$\delta_b = V_\beta/m \quad (11)$$
$$\delta_0 = 1 - \delta_a = \delta_b \quad (12)$$

The proposed technique for obtaining capacitor balance in the modulation index below (0 < m < 0.6) is the nearest vector redundancy scheme. The switching vector's involvement can be employed depending on the point. The positive and negative phase currents were cancelled by the redundant state in (SV). The capacitor balance can be obtained as a result of this. [22].
The sampling reference voltage vector might be synthesized using these three vectors.

$$V^*\delta_{S1} + V^*\delta_{S2} + V^*\delta_{M1} = V^* \quad (13)$$
$$\delta_{S1} + \delta_{S2} + \delta_{M1} = 1 \quad (14)$$

SVPWM is a multi-level inverter switch control approach that recognizes switching sequences by placing a switching vector in d-q space. It is better to reduce harmonics and increase the output voltage value, compared with SPWM, which is generally used [7]. It decreases the common mode voltage, which is the difference between the vector sum of the potential at the inverter output and the potential at ground. Therefore, it improves inverter efficiency. The voltage should ideally be equally divided between two dc link capacitors, However, due to capacitor leakage current, there is a voltage imbalance that causes stress on the switching [23]. To solve the switching state problem, the space vector diagram is a better choice. A switching state is represented by each coupling point. For a three level inverter, twenty seven switching states are shown in Figure 7.

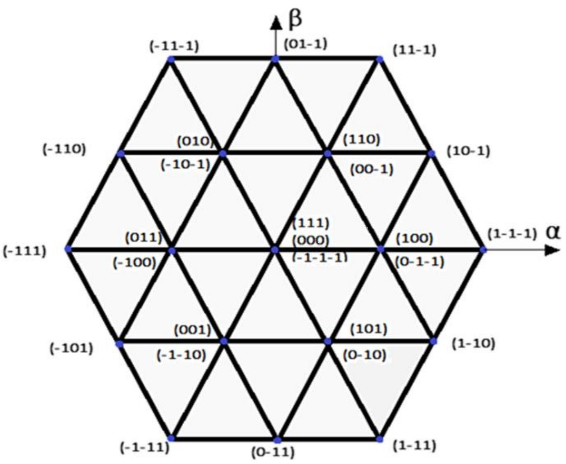

Figure 7. Switching states for SVPWM

3.8 LCL filter
The attenuation of the L filter is -20dB/decade throughout the whole frequency range. As a result, the inverter's switching frequency is increased. The attenuation of a second order filter, such as an LC filter, is about -40 dB/decade. The operating switching frequency elements will be further attenuated by this LC shunt component. As a result, it must be constructed to generate lower reactance but larger impedance magnitude while staying within the specified limitations [24],[25]. The load impedance across the filter capacitor must also be sufficient. LCL Filter: This is a third-order filter that attenuates at -60 dB per decade. At lower switching frequencies, this sort of filter can minimize harmonic distortion levels [7].

The abandonment of power electronic converters in grid side system applications opens the door to serious injected harmonics. Two series inductors and a capacitor known as LCL filter are commonly used so as to minimize current harmonics around the switching frequency. As a result, in the current scenario, the use of filters becomes an important factor. Because of its lower cost and size, a higher order passive filter is most commonly used in this application. The goal of this study is to construct an LCL filter for reducing injected harmonics [7],[25],[26].

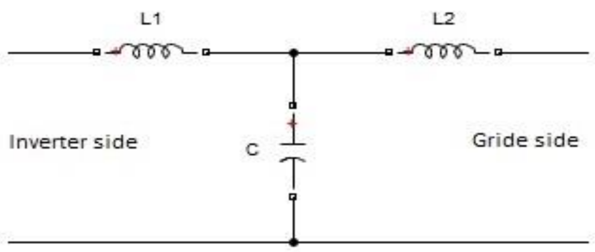

Figure 8. Per phase T filter

IV. Results and Discussion

In this part, the results were implemented by the MATLAB/SUMULINK so as to present the proposed system.

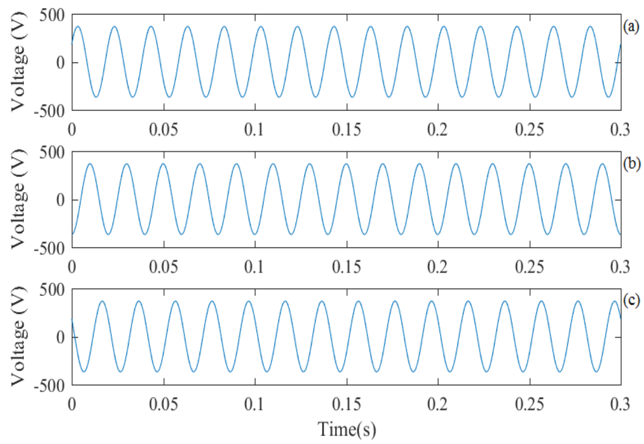

Figure 9. Output PMSG voltage: A phase(a), B phase(b), C phase(c)

The motor is a 3 phase AC 1 HP induction motor with 300V voltage and 5A current, which has high reliability and is convenient to operate. The DC link voltage and motor speed are set at 300V by an open loop constant V/f control. Figure 9 is shown generator output voltage. It can be seen that 260V of voltage has been generated by PMSG.

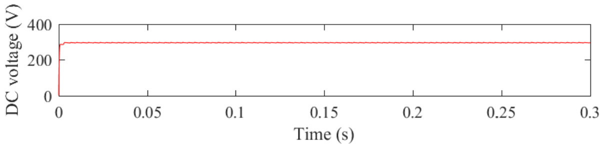

Figure 10. Rectifier output DC voltage

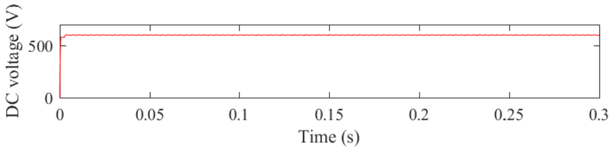

Figure 11. Boost chopper output DC voltage

AC voltage was transformed to DC voltage by rectifier. The capacitor in the rectifier improved the voltage from 260V to 295V as demonstrated in figure 10. Moreover, the Boost (Step Up) Chopper helped the voltage climb to 600V, as demonstrated in Figure 11.

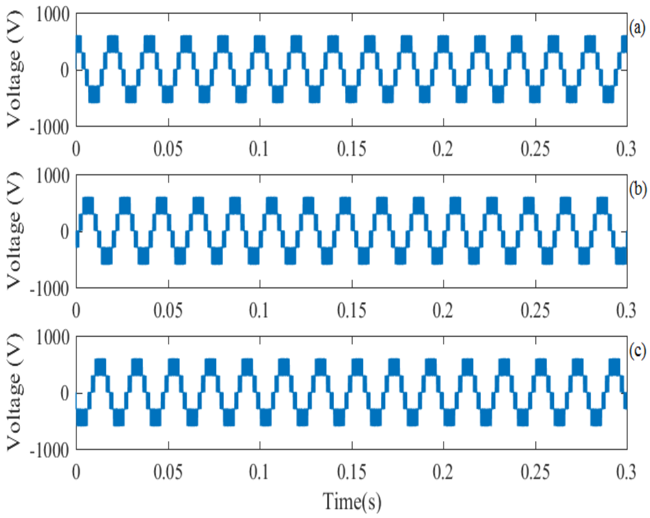

Figure 12. NPC output voltage: A phase(a), B phase(b), C phase(c)

In figure 12 three-level step NPC inverter was obtained 600V. Each 3-phase is at a 120-degree angle to the other.

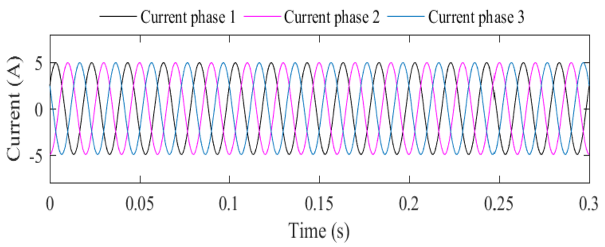

Figure 13. Output current of NPC inverter

The frequency spectrum of the current output of a 3-phase 3-level NPC inverter is demonstrated in figure 13. The current ripple on the inverter side is sinusoidal, as can be seen.

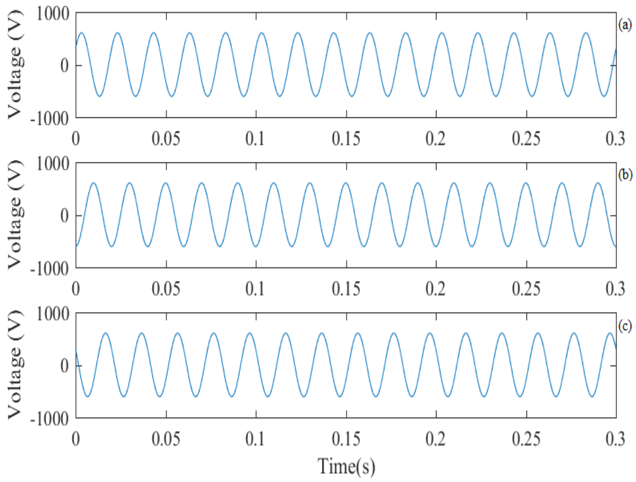

Figure 14. Grid output voltage: A phase(a), B phase(b), C phase(c)

Figure 14 presents three level NPC inverter with a T filter in the grid side voltage. The inverter output voltage is 600V, which is practically sinusoidal voltage. The filtering effect is successful in minimizing harmonics, according to simulation results.

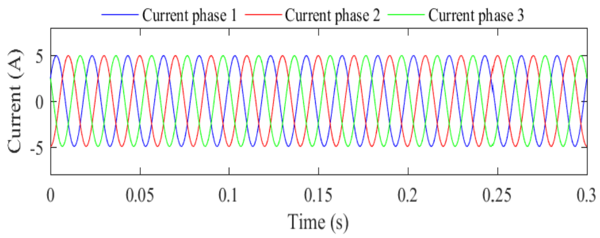

Figure 15. Output grid current

Three phase grid side current waveform is shown in figure 15. Grid connected current is sinusoidal in Figure 15, and there are no resonance phenomena. It is shown that the proportion of grid side current is almost the same as the inverter side current, while the grid side current has fewer harmonics due to the LCL filter.

The quality analysis of the system is carried out by the simulation results were shown in Figures 14 and 15, respectively. Conduction loss, as well as turn on/off losses, contribute to converter power loss. Conduction losses are generated by semiconductors, load currents and conduction resistance for instance, whiles non zero switching time and load currents are the principal causes of turn on/off losses. As a result, if the switching frequency is steady under the same load situation, the turn on/off losses are nearly constant as well. The conduction losses of these strategies are nearly equal to other strategies, but the turn on/off losses are decreased because the switching times of SVPWM are diminished by 1/3, which helps to improve output efficiency. In addition, the inverter output is combined with a T filter to reduce low pass harmonics.

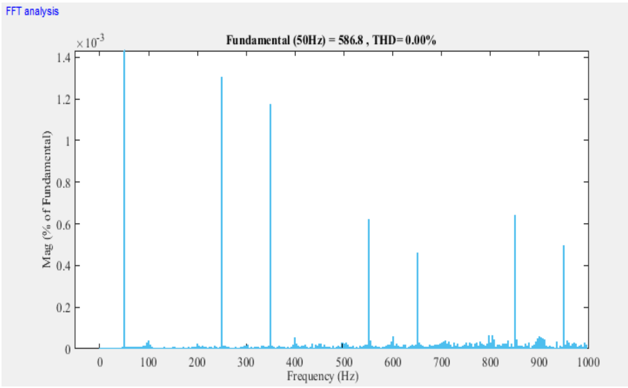

Figure 16. THD in voltage output

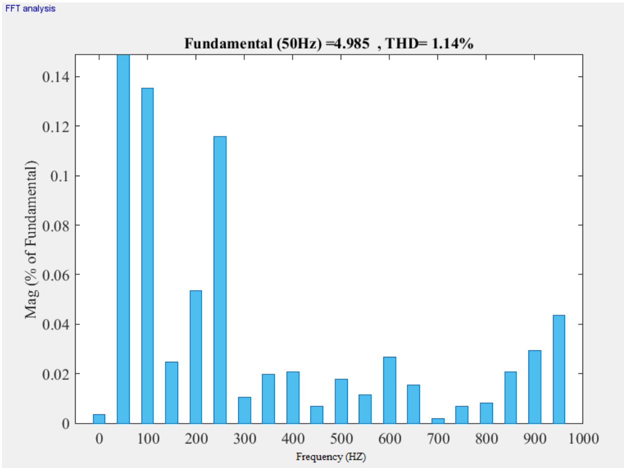

Figure 17. THD in current output

The stepped voltage is entirely transformed to a sinusoidal waveform, and the grid current waveform is also exhibited without resonance phenomena. The THD in the voltage of output grid is 0.00% as shown in figure 16, and THD in the current of output grid is 1.14% as shown in figure 17.

V. CONCLUSION AND FUTURE SCOPE

This system was created by a sort of NPC three-level inverter that is suited for grid side connected in small wind turbine systems without a transformer. The findings showed that the method aids in the regulation of leakage load currents, capacitor, and common mode voltage balancing issues. The method provides NPCTLI with better current management and improved voltage performance, lowering the amount of overall harmonic distortion in the system. It improves output efficiency and can help to create sinusoidal waveforms in the grid, which is very effective for the grid.

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