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A grid interconnected nested neutral point clamped inverter with voltage synchronization using synchronous reference frame controller

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ABSTRACT

Nested neutral point clamped multi level inverter with inter connection to grid through the synchronous reference frame (SRF) controller for synchronization of voltage to the grid is demonstrated. The system's main feature is that voltage stress in each inverter switching device is kept to a minimum, and redundant inverter switching states are utilised for neutral point and flying capacitor voltage balancing with sinusoidal pulse-width modulation (PWM) technique, synchronisation to grid voltages, and power injection with low harmonic generation. The inverter receives its input from a photovoltaic (PV) source that is coupled to DC-DC booster converters that are regulated by the maximum power point tracking (MPPT) incremental conductance algorithm to maintain a constant dc voltage. The system is examined under various load conditions with MATLAB Simulink model.

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1. INTRODUCTION

Increased consumption of power by diverse loads throughout the world is causing demand for electrical power generation to increase day by day. Traditional methods (diesel generators, thermal plants, and nuclear plants) of larger production of electric power is causing the devastating effects of the environment. As a result of these methods of production, hazardous waste and gases are produced. Which inturn these power plants play a vital role for increase in global warming making earth a bad place for survival of living things on the planet. Better energy generation from renewable sources is the only way to safeguard the earth and make it a better place in the future [1]. Hydropower plants, solar power plants, wind farms, biogas facilities, and tidal wave units are examples of these types of generators. Wind farms, which generate large amounts of electricity yet may be constructed in remote places distant from civilization, are an instant alternative for hydro power plants. Solar power plants are the best alternative for generating large or little amounts of electricity. Sun plants are made up of a series of photovoltaic planes that use solar irradiation to create DC electricity. Photovoltaic arrays are different parallel and series configurations of these panels (PVA) [2]-[6]. Because the loads run on AC voltage, the DC power from the photovoltaic array must be converted to either single phase AC or three phases AC. Multi level inverter involves a key role in the process of conversion [7]. Extensive research on process of conversion using wide converters for higher efficiency and lower harmonic generation [8]-[10]. In this paper a nested neutral point clamped five level voltage source inverter [11] is inter connected to grid by using synchronous reference frame (SRF) controller.

The renewable energy input is obtained by means of photovoltaic array through a DC-DC booster converter controlled by incremental conductance maximum power point tracking (MPPT) technique, so that, dc output obtained is stabilized by injecting power with low harmonic distortion [12]. The prototype model and analysis of the system is carried out under various conditions of load. Section 1 presents the nested neutral point clamped converter, section 2 describes the SRF control structure, section 3 gives PVA module with MPPT algorithm, and section 4 presents the results of the proposed system at different load conditions. The final section 5 has conclusions.

2. NESTED NEUTRAL POINT CLAMPED INVERTER

Nested neutral point clamped (NNPC) inverter is shown in Figure 1. The topology has eight switches in each leg. Output voltage levels for the switching are created by the voltage dividing capacitors C1, C2, and C3 [6]. The main feature is that, that the number of diodes andcapacitors for clamping are minimised. The converter also does not need any isolated DC source at the input for regenerative applications. Also, the interconnected capacitors create stabilized output voltages with reduced overshoots in the output [13]-[16]. The capacitors Cn1 and Cn2 (n=a, b, c) are charged to a voltage of ¼ Vdc and the capacitor Cn3 is charge to voltage of ¾ Vdc.

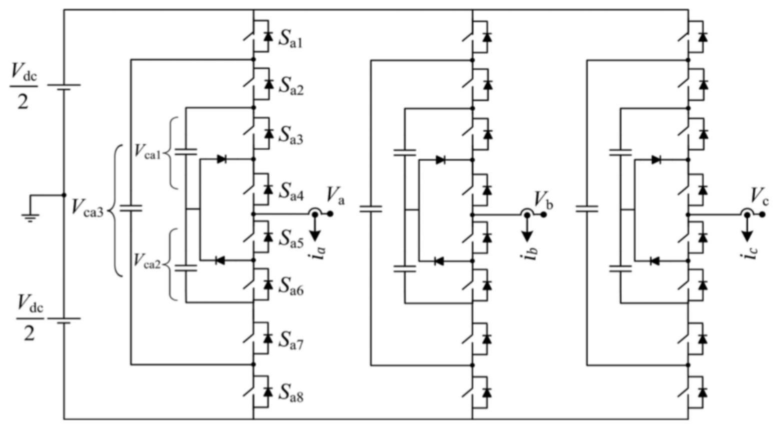

Figure 1. Five level NNPC inverter topology

The five level voltages including zero voltage are generated as per the switching of the eight switches of one leg. The zero voltage level includes charging and discharging of capacitors for achieving capacitor voltage balancing making the converter redundancy to voltage variations. The relation between V_k and L_k can be given as (1).

$$Vk = (4Lk - 8) * Vin/16 \quad (1)$$

In-phase disposition (PD) carrier modulation technique [17], [18] is employed for the generation of pulses. In this method all the carrier waveforms are in phase with no phase shift. The reference sin waveform for the above PD modulation technique is generated by SRF controller which generates reference signal in synchronization to the grid.

2.1. Capacitor voltages

Redundant switching states at levels 1, 2, and 3 to charge and discharge flying capacitors. But, there are not any redundancy switching states at 0, 4 levels. Again, level 1 is nice to control voltages of capacitor C_{x3} and C_{x2}, and further level 3 is good to control the voltage of capacitors C_{x3} and C_{x1}. Further, there are redundancy states for levels 1, 2, and 3. Each redundancy state based on direction of output current can charge or discharge 3 flying capacitors. Thus, minimize the difference between nominal voltage values and measured voltage values. The flowchart of Figure 2 illustrates the process to control voltage of flying capacitors in each phase.

The synchronous reference frame (SRF) controller [19] is major module in the proposed test system which controls the output voltage of the multilevel inverter. For the output voltage match to the grid voltage amplitude, phase and frequency the SRF controller takes feedback [20] from the grid three phase voltages, currents and DC link voltage at the input. The structure of the SRF controller is given in Figure 3.

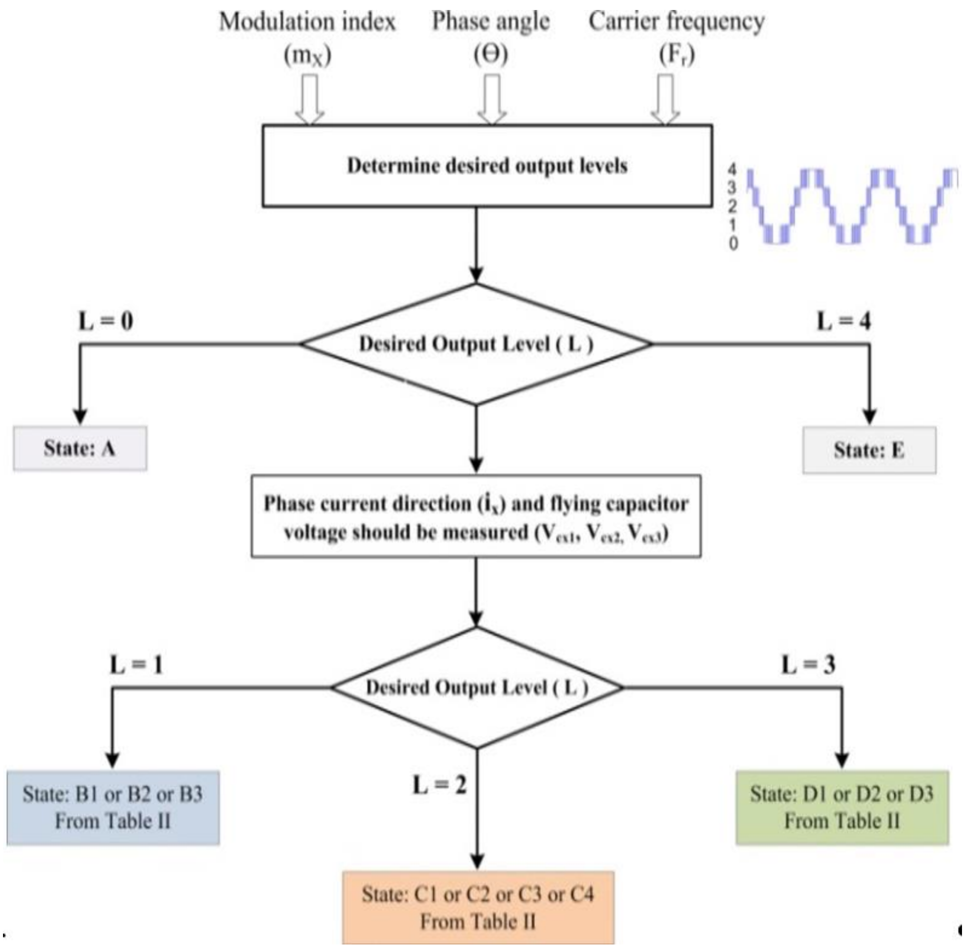

Figure 2. Flowchart to control the voltage of flying capacitor

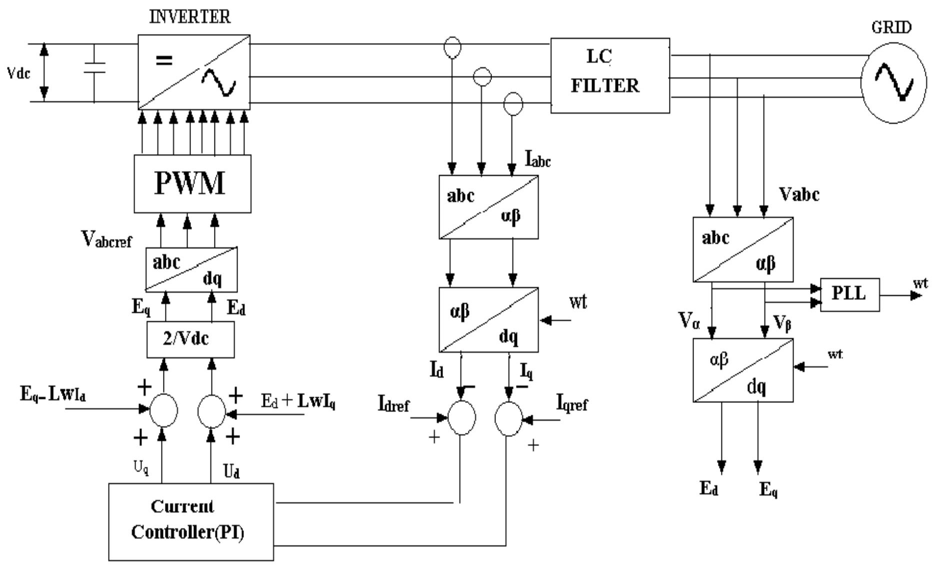

Figure 3. Block diagram of SRF control structure for PVA grid interconnection

The SRF controller uses Parks transformation for controlling the current of the inverter. The dq components of the currents are calculated with respect to PLL module [19]-[25] working in synchronization to the grid voltage. The dq axis calculation for the given controller is given as per the equations given below. Let r vector in abc coordinate system, angle between ab,ab, and ca are 120 degrees.

$$\vec{r}=r_a.\hat{a}+r_b.\hat{b}+r_c.\hat{c} \tag{2}$$

Where, r_a, r_b, and r_c be projections of r vector in direction of a, b, and c.

$$\vec{r}=r_\alpha.\hat{\alpha}+r_\beta.\hat{\beta} \tag{3}$$

Where, r_α projection of r vector in direction of α, r_β projection of r vector in direction of β. To get relation between αβ and abc:

$$\begin{aligned} r\alpha &= \vec{r}.\hat{\alpha} \\ r\alpha &= \{ra.\hat{a}+rb.\hat{b}+rc.\hat{c}\}.\hat{\alpha} \\ &= ra\ \hat{a}.\hat{\alpha}+rb\ \hat{b}.\hat{\alpha}+rc\ \hat{c}.\hat{\alpha} \\ &= ra+rb\cos(1200)+rc\cos(2400) \end{aligned} \tag{4}$$

$$r\alpha = ra-\frac{1}{2}rb-\frac{1}{2}rc \tag{5}$$

r_β projection of r vector in the direction of β is

$$\begin{aligned} r\beta &= \vec{r}.\hat{\beta} \\ r\beta &= \{ra.\hat{a}+rb.\hat{b}+rc.\hat{c}\}.\hat{\beta} \\ &= ra\ \hat{a}.\hat{\beta}+rb\ \hat{b}.\hat{\beta}+rc\ \hat{c}.\hat{\beta} \\ &= ra+rb\cos(300)+rc\cos(1500) \\ r\beta &= 0+\frac{\sqrt{3}}{2}rb-\frac{\sqrt{3}}{2}rc \end{aligned} \tag{6}$$

$$\begin{bmatrix} r\alpha \\ r\beta \\ r0 \end{bmatrix}=\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} ra \\ rb \\ rc \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} \vec{r}d \\ \vec{r}q \\ 0 \end{bmatrix}=\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \vec{r}\alpha \\ \vec{r}\beta \\ 0 \end{bmatrix} \tag{8}$$

By using Clarks transformation and from αβ-coordinates to dq-coordinates (Parks transformation) we get

$$\begin{bmatrix} \vec{r}d \\ \vec{r}q \\ 0 \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \frac{-1}{2}\cos\theta+\frac{\sqrt{3}}{2}\mathrm{Sin}\theta & \frac{-1}{2}\cos\theta-\frac{\sqrt{3}}{2}\sin\theta \\ -\sin\theta & \frac{1}{2}\sin\theta+\frac{\sqrt{3}}{2}\cos\theta & \frac{1}{2}\sin\theta-\frac{\sqrt{3}}{2}\cos\theta \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{9}$$

The voltage controller is a PI controller with input taken by comparison of DC voltage at the DC link capacitor and reference value given by the user. The output of the voltage controller is direct axis component reference and quadrature axis reference component is considered to be 0. The current controller generates the required reference dq voltage reference component with PI controller in it. The reference dq voltage components (Vd* and Vq*) [19] are converted to sinusoidal by inverse parks transformation. The final three phase sinusoidal reference waveforms are compared to phase disposition multi carrier modulation technique for generation of pulses for the novel five level inverter. As the SRF controller uses PLL to generate the reference signals and the PLL is operated with grid voltage as feedback, the inverter operates in synchronization with the grid.

3. PVA-MODULE

The PVA is a DC source which generates power by converting solar irradiation. The DC voltage from the PVA is not always constant as the solar irradiation is variable with change in climaticconditions. For constant DC voltage generation, the PVA is connected to a stabilizing DC-DC booster converter controlled by MPPT technique [22] for maintaining the output voltage at a specified value. A DC-DC booster converter is utilized for this purpose so as to increase the input voltage to the inverter as the AC loads operate at high voltages. The duty ratio for the IGBT switch is generated by incremental conductance MPPT algorithm [20]-[25]. This algorithm is considered to be robust and operates with faster response rate as compared to traditional P&O MPPT algorithm which is used in most of the MPPT techniques.

4. RESULTS AND DISCUSSION

The prototype of PVA renewable source connected to nested neutral point clamped five level inverter controlled by SRF controller interconnected to three phase grid is modelled is simulated MATLAB Simulink. The parameters of simulation are given in Table 1.

Table 1. Parameters of Simulink block diagram

Parameter	Value
Input dc link voltage	Vin=600 V
Switching frequency	F_{sh}=2000 Hz
Diode	Rin=0.001 ohms, Forward voltage =0.8V
Flying capacitor	C=1000 µ F
IGBT switch	Rin=0.001 ohms
Modulation index	MI=0.95
Fundamental frequency	F=50 Hz
Switching frequency	Fs=2000 Hz
R-load	R=100 ohms
RL-load with 0.7 power factor lagging	P=700W, Q_L=714.14 VAR
LC-filter	L=10 mH, C=810 µf
3-phase breaker	Breaking resistance (R_{ON})=0.01 ohms Switching time=0.1sec for all 3 phases
Frequency	=50 Hz
Poles	=4
(Rs)	=0.55 ohms
(Ls)	=0.00288 H
(Rr)	=0.78 ohms
(Lr)	=0.00286 H
(Lm)	=0.0905 H
Inertia (J)	=0.019 kg-m^2
Friction factor (B)	=0.002985 Nm-sec
Rating of grid connected	
Ph-Ph voltage RMS	=132KV
3-phase short circuit level at base voltage (VA)	=2500 MVA
Frequency	=50 Hz
X/R ratio	=7
Rating of transformers	
Stepdown transformer 1	100 KVA, 11 KV/260 V
Stepdown transformer 2	47 MVA, 132 KV/11 KV
Stepdown transformer 3	100 KVA, 11 KV/400 V
Ratings of LC-fitter	
Resistance (R_L), Inductance (L)	=3.14 mOhms, 0.5 mH
Active power (P), Reactive power (Q_C)	=100 W, 10 KVAR

Figure 4 shows the Simulink diagram of prototype model with SRF controller with induction motor load. Figure 5 shows the output voltages of Nested neutral point clamped inverter with 0.95 modulation index. Figure 6 shows the three phase line voltages Vabc of NNPC inverter which is sinusoidal, but Iabc is “M-W type” sinusoidal current because system is connected to non-linear load across the 3-phase power supply.

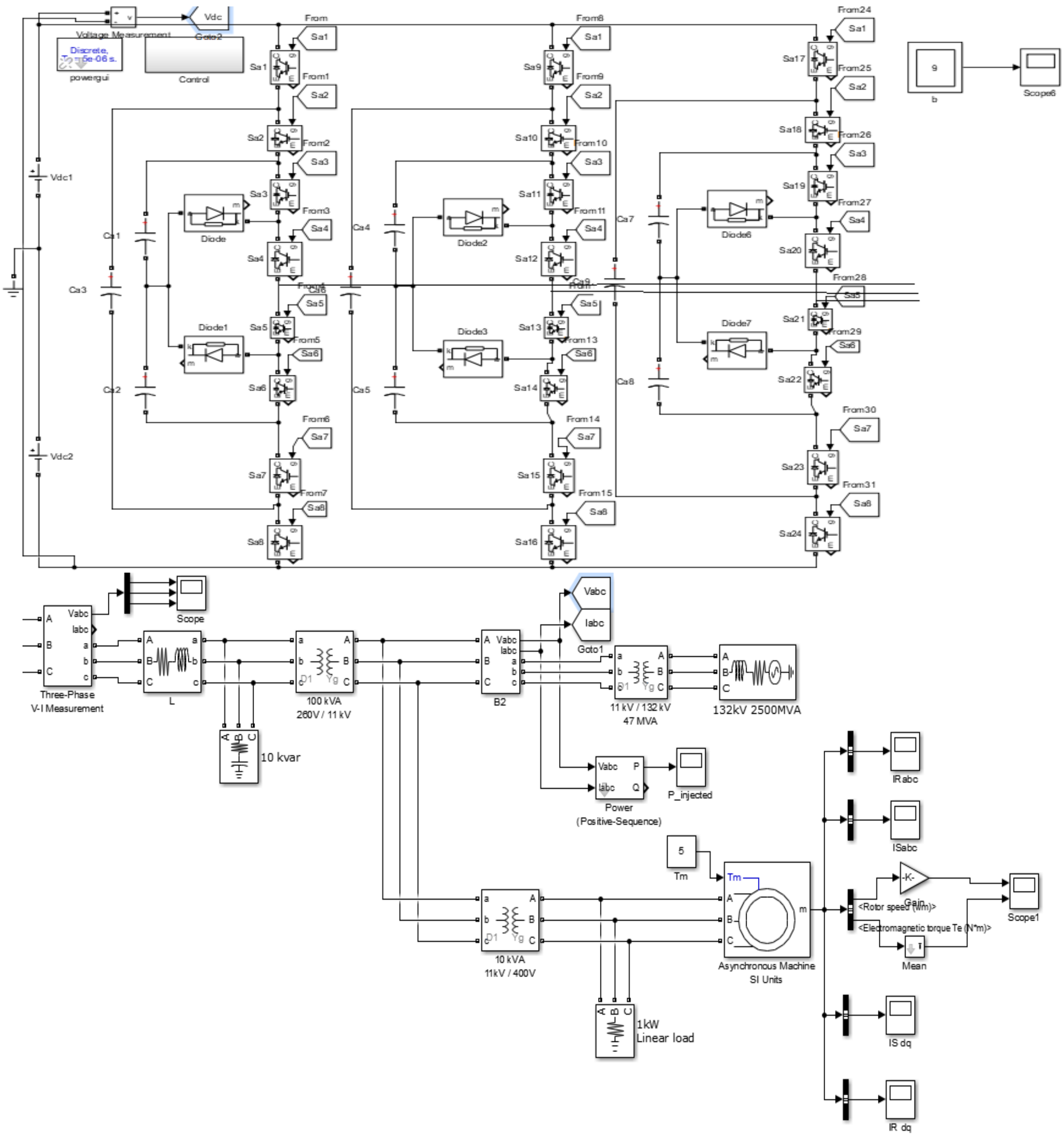

Figure 4. Simulink diagram with SRF controller with induction motor load

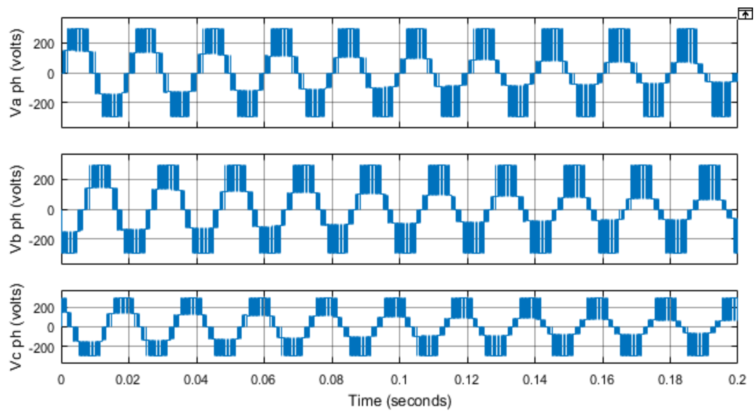

Figure 5. Five level output voltage for modulation index=0.95 with R-Load (R=100 Ω)

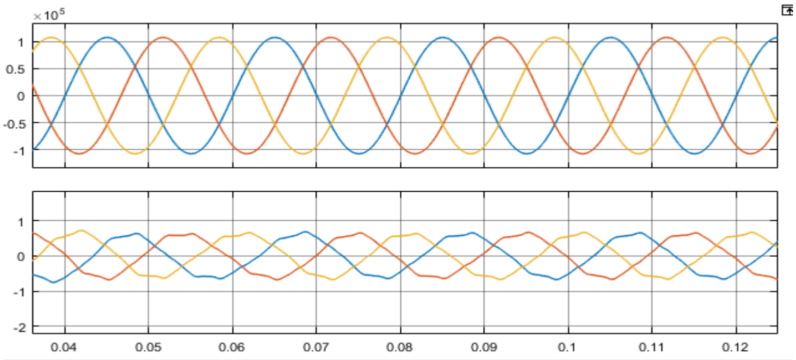

Figure 6. Grid voltage and grid current

Induction motor–load:
T_a = Gross mechanical torque (or) motor torque
T_{sh} (or) T_L=Load torque
T_{loss}=Loss due to friction, windage, and iron losses.

$$Ta = Tloss + Tsh\ Power\ (Pout) = Tsh * W$$

$Tsh = \frac{Pout}{W} = \frac{10*746}{\frac{2\pi*1440}{60}} = 49.47\ N-m$. Consider 49.47 N-m as full load.

So, consider 24.73 N-m as half-load, 12.36 N-m as half–load, and 0 N-m as no-load.

Figure 7 shows the variation of load torque applied. Figure 8 and Figure 9 shows as the load is decreased from full-load to half-load to quarter-load to no-load, the rotating magnetic field produced will also decrease. So, the current required to produce RMF is also decrease as shown Is_abc & Ir_abc. (full-load started at 0.6 sec).

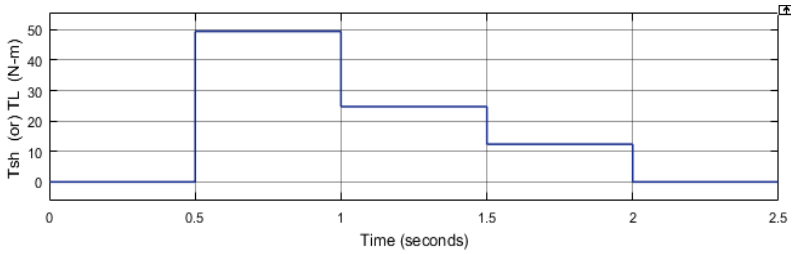

Figure 7. Load torque applied to induction motor

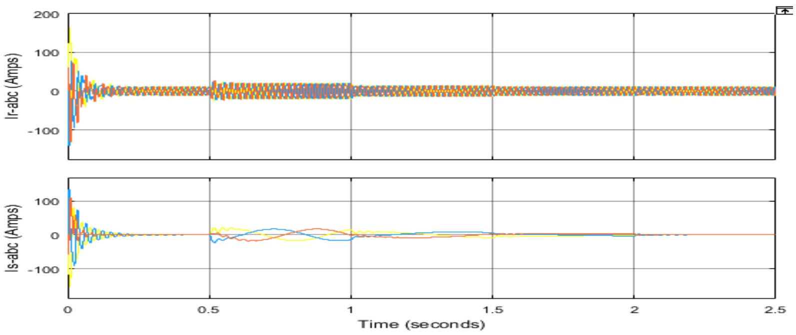

Figure 8. Stator and rotor currents I_{abc}

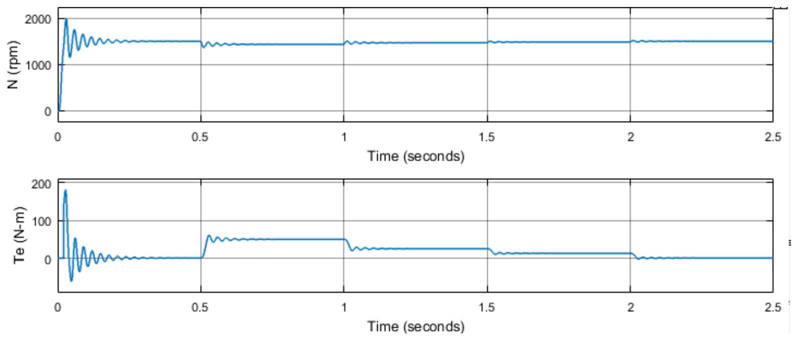

Figure 9. Speed, T_e vs time

Table 2 shows %THD of phase voltages at output for various types of loads without SRF controller THD obtained is higher, further THD is minimized by SRF controller there by eliminating the harmonics.

Table 2. Output phase voltage THD of inverterside for R, RL, and induction motor–load

Case studies	%THD of Ph-Ph output voltage	
	Without SRF controller	With SRF controller
R-Load	25.35%	0.06%
RL-Load	48.75%	0.07%
Induction motor-load	308.19%	0.05%

5. CONCLUSION

Nested neutral point clamped five level inverter interconnected to grid controlled by SRF structure with PD multi carrier modulation technique is analysed. The connection to grid by means of inverter is synchronized and the power from the PVA is injected to the system compensating the loads connected at PCC. The system is well tested for both static and dynamic load conditions. The results show the reduction of output phase voltage THDs within the permissible limit (<1%). The system can be further extended with multiple renewable sources that can be connected at the input to the inverter and optimal controller can be incorporated for better voltage.

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