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ANALYSIS, MODELING AND CONTROL OF CASCADED NPC/H-BRIDGE INVERTER FOR HIGH POWER QUALITY GRID CONNECTION

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ABSTRACT

The cascaded NPC/H- bridge inverter is first analyzed by establishing a new switching model based on a derived control law. From the developed switching model, a general model is obtained using state space technique. A new and accurate average model is developed using *abc* to *dqo* transformation technique. Finally small signal model is obtained by linearizing all the state variables around their quiescent operating points. The small signal model is used to study the effects of various control feedback variables on the dynamic performance of the Grid connected system. Feedback control scheme is designed to improve the dynamic response of the system. The system with the proposed control technique also achieves sinusoidal grid voltage and current output with low THD which is a preferred characteristic for any power injected to the grid. Simulation results are provided to validate the analytical models.

KEY WORDS

Feedback control, NPC/H-Bridge inverter, Grid connected system, small signal model, State space technique.

1. Introduction

Various power electronic converter topologies as well as control and protective schemes have been proposed for converting dc power generated by solar panels to high quality ac power at the interface to the grid. [1], [2]. Recent progress of high power electronic modules has made easier the grid interfacing of renewable energy. The multilevel inverter structure allows them to increase the voltage ratings and to reduce the harmonic distortion of the generated multilevel voltage waveforms [3], [4].

Three different major multilevel converter structures have been reported in the literature: cascaded H-bridges converter with separate dc sources, diode clamped (Neutral-Point –Clamped (NPC), and flying capacitors (capacitor clamped) [5], [6]. A cascade multilevel inverter is a special kind of multilevel inverter built to synthesize a desired AC voltage from several levels of DC voltages [7]. Past research has put more emphasize on single phase H- Bridge inverter where each inverter level generate three different voltage outputs, +Vdc, 0, and –Vdc by connecting the dc source to the ac output using different combinations of the four switches of the Bridge [8]. Past research has also concentrated on realizing a five level NPC/H-Bridge inverter without cascading the bridge [9]; this fails to address the principle of realizing a general cascaded n- level NPC/H-Bridge.

If a higher output voltage is required, one of the viable methods is to increase the number of inverter voltage levels. For NPC inverter voltage can only be increased up to five level beyond which DC voltage balancing becomes impossible. For single Phase H Bridge inverter an increase in the number levels leads to increase in the number of separate DC sources, thus by combining the NPC and H- bridge topologies, a five Level NPC/H-Bridge with reduced number of separate DC sources and a controlled DC voltage for NPC inverter is achieved

In this paper, a multivariable state space model [10] for an n- level NPC/H-bridge inverter with an LCL filter is established. Next from the switching function an average model is developed. Based on the simplified average model the steady state solutions and the small signal model are derived which incorporates all the state variables, ac currents in *dq* mode and dc link voltages with their respective switching functions. The emphasis here is to obtain a detailed analysis of the model so that a feedback controller that ensures reduced harmonic current injection into the grid and maximum active power injection into the grid at unity power factor is achieved.

2. Three phase n- level cascaded NPC/H-bridge inverter based grid application

2.1 System description

Fig. 1 shows an n-level NPC/H-bridge inverter connected to the grid, since the flow of power is always from the PV cells to the grid. The system consists of n-level DC capacitors, NPC/H-bridge inverter cells, LCL filters and the grid. The output voltage gives three level voltage output, thus each NPC/H-bridge cell gives five different voltage levels; +2Vdc, +Vdc, 0, -Vdc and –2Vdc. For an n- level cascaded model shown in fig. 1 the output voltage levels is given by:

$$m = 4n + 1 \qquad (1)$$

The topology is made up of four three level legs and each leg has four active switches and four freewheeling diodes.

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2.1 Principle of operation

For an n- level cascaded NPC/H-bridge inverter power switches are controlled to supply sinusoidal output voltage with low current harmonics and low Total Harmonic Distortion (THD). Because of the modularity of the topology, one cell is used for analysis. To prevent the top and bottom power switches in each inverter leg from conducting at the same time, the constraints of power switches can be expressed as

$$\left.\begin{aligned} &S_{i1}+S_{i3}=1\\ &and\\ &S_{i2}+S_{i4}=1 \end{aligned}\right\} \tag{2}$$

Where $i = 1, 2$.

Let $T_1 = S_{11} \,\&\, S_{12}$

$T_2 = S_{13} \,\&\, S_{13}$

$T_3 = S_{21} \,\&\, S_{22}$

$T_4 = S_{23} \,\&\, S_{24}$

Four valid expressions are given by;

$$T_1 = \begin{cases} 1 \text{ if both } S_{11} \,\&\, S_{12} \text{ are ON} \\ 0 \text{ otherwise} \end{cases} \tag{3}$$

$$T_2 = \begin{cases} 1 \text{ if both} S_{13} \,\&\, S_{14} \text{ are ON} \\ 0 \text{ otherwise} \end{cases} \tag{4}$$

$$T_3 = \begin{cases} 1 \text{ if both} S_{21} \,\&\, S_{22} \text{ are ON} \\ 0 \text{ otherwise} \end{cases} \tag{5}$$

$$T_4 = \begin{cases} 1 \text{ if both } S_{23} \,\&\, S_{24} \text{ are ON} \\ 0 \text{ otherwise} \end{cases} \tag{6}$$

$$K_a = \begin{cases} 1 \text{ if } T_1 = 1 \\ 0 \text{ if } S_{12} = 1 \\ -1 \text{ if } T_2 = 1 \end{cases} \tag{7}$$

$$K_b = \begin{cases} 1 \quad \text{if } T_3 = 1 \\ 0 \quad \text{if } S_{22} = 1 \\ -1 \quad \text{if } T_4 = 1 \end{cases} \tag{8}$$

For the control technique stated above, the voltage levels for the two legs of one of the leg is given by equations (9) and (10) [11]. Equation (9) is for one leg of the cell

$$V_a = K_a\left(\frac{K_a+1}{2}\right)V_{dc1} - K_a\left(\frac{K_a-1}{2}\right)V_{dc2} \tag{9}$$

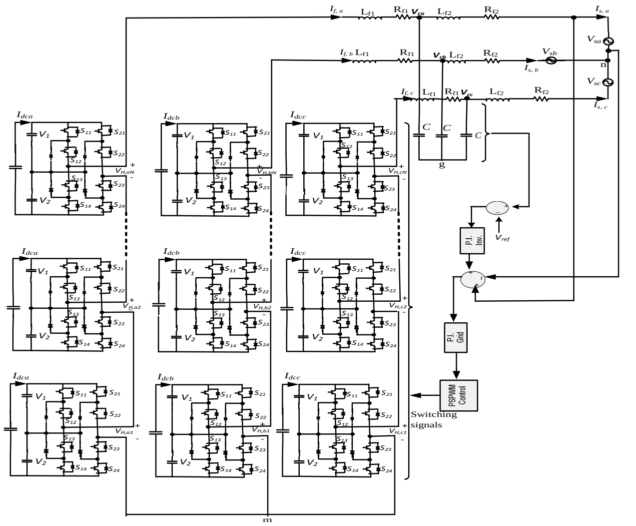


Fig. 1. The proposed control scheme of the model

$$V_{01} = V_a + V_b \tag{10}$$

Similarly for the second leg the expression is given by;

$$V_b = K_b\left(\frac{K_b+1}{2}\right)V_1 - K_b\left(\frac{K_b-1}{2}\right)V_2 \tag{11}$$

TABLE I

SWITCHING STATES AND CORRESPONDING VOLTAGE (V_{12}) FOR ONE CELL OF NPC/H- BRIDGE INVERTER

K_a	K_b	T_1	T_2	S_{12}	T_3	T_4	S_{21}	V_a	V_b	V_{01}	Mode
1	-1	1	0	1	0	1	0	V_1	$-V_2$	V_1+V_2	1
0	-1	0	0	1	0	1	0	0	$-V_2$	V_2	2
-1	0	0	1	0	0	0	1	0	V_2	$-V_2$	3
1	0	1	0	1	0	0	1	V_1	0	V_1	4
0	1	0	0	1	1	0	1	$-V_1$	0	$-V_1$	5
1	1	1	0	1	1	0	1	V_1	V_1	0	6
-1	-1	0	1	1	0	1	1	V_2	V_2	0	7
-1	1	0	1	0	1	0	1	V_2	V_1	$-V_1-V_2$	8

And finally the voltage output for a nine level cascaded NPC/H-Bridge inverter is given as;

$$V_{01} = \frac{K_a - K_b}{2}\left(V_{dc1} + V_{dc2}\right) + \frac{K^2_a - K^2_b}{2}\left(V_{dc1} - V_{dc2}\right) \tag{12}$$

3. System modeling

A general model for the conventional H- bridge cascaded multilevel converter is presented in [11]. This model describes the general dynamics in *abc* and *dqo* co-ordinate and the derived small signal model for control analysis. This paper uses the same approach to come up with a different model for this important hybrid cascaded converter whose models has never been developed and researched on.

3.1 Development of the switching model

Based on the control law derived in section II (B) above, fig. 2 (a) and (b) represents a simplified switching model of the a five level NPC/H-bridge inverter. Let *K* be the switching function, then applying the control law developed, the relationship of the dc parameters (V_1 and V_2) and the ac parameters (V_{01} and I_f) is given by;

$$\begin{cases} V_{01}=\frac{K_a-K_b}{2}(V_1+V_2) \\ I_{dc}=\frac{K_a-K_b}{2}I_f \end{cases} \tag{13}$$

For simplicity of the switching model $V_1 = V_2$, similarly the neutral point current I_0 is taken to be zero, Equation (13) is achieved. Defining K as follows:

$$K=\frac{K_a-K_b}{2} \tag{14}$$

The average model of the multilevel inverter is obtained by averaging the switching function in one switching period. The switching operator is given by [11];

$$d=\overline{K}(t)\frac{1}{T}\int_{t-T}^{t}K(\tau)d\tau \tag{15}$$

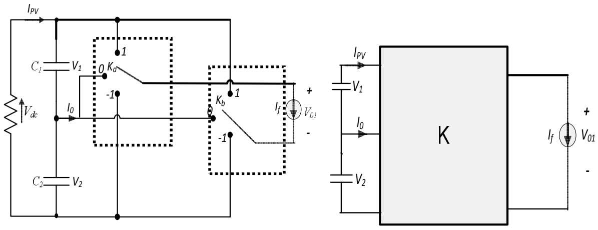


Fig. 2 Simplified representation the converter

$$\begin{cases} \overline{V}_{01}=\frac{1}{T}\int_{t-T}^{t}K(t)d\tau.(V_1+V_2)=d_1V_1+d_2V_2 \\ I_{PV}=\frac{1}{T}\int_{t-T}^{t}K(t)d\tau.(I_f)=d_3I_f \\ I_{PV}=\frac{1}{T}\int_{t-T}^{t}K(t)d\tau.(I_f)=-d_4I_f \\ I_0=\frac{1}{T}\int_{t-T}^{t}K(t)d\tau.(I_f)=d_5I_f \end{cases} \tag{16}$$

The two dc voltage and out put current are assumed to be constant in one switching period. Thus the average switching equations are as shown in (16)

Where duty cycles; d_1, d_2, d_3, d_4 and d_5 for different values of V_1, V_2, I_{pv} (I_p), $-I_{pv}$ (I_n) and I_0, where $d_h = K m \sin(\omega t - \delta)$, h = 1, 2…4,and K depends on the type of switching pattern used, from equation (14) and is given by [12]

4. State space technique

The differential equations describing the dynamics of the coupling inductor between the NPC/H-bridge inverter and the grid of the model shown in fig. 3 can be derived as:

$$\begin{cases} L_{f1}\frac{di_{f-x}}{dt}=-V_{c-x}-i_{f-x}R_{f1-x}+d_{1-x}V_1+d_{2-x}V_2 \\ L_{f2}\frac{di_{s-x}}{dt}=V_{c-x}-i_{s-x}R_{f2-x}-V_{s-x} \end{cases} \tag{17}$$

According to kirchoff’s law, the currents flowing into the dc link capacitors C_1 and C_2 can be expressed as:

$$\begin{cases} i_{c1}=C_1\frac{dV_{1-x}}{dt}=d_3i_{f-x}-\frac{V_{1-x}}{R}+\frac{V_{2-x}}{R} \\ i_{c2}=C_2\frac{dV_{2-x}}{dt}=-d_4i_{f-x}-\frac{V_{1-x}}{R}+\frac{V_{2-x}}{R} \\ i_{c-x}=C\frac{dV_{c-x}}{dt}=i_{f-x}-i_{s-x} \\ C_1\frac{dV_{1-x}}{dt}-C_2\frac{dV_{2-x}}{dt}-d_5i_{f-x} \end{cases} \tag{18}$$

The equations (17) and (18) can be rearranged as in (19); from equation (19) state matrix A is obtained as in (20). Equations (16) – (21), is used to realize the simplified average model of the NPC/H-bridge inverter for grid interface in *abc* co-ordinate is given by fig. 3.

$$\left.\begin{aligned} \frac{di_{f-x}}{dt}&=\frac{R_{f1-x}}{L_{f1}}-\frac{V_{c-x}}{L_{f1}}+\frac{d_{1-x}V_1}{L_{f1}}+\frac{d_{2-x}V_2}{L_{f1}} \\ \frac{di_{s-x}}{dt}&=\frac{V_{c-x}}{L_{f2}}-\frac{R_{f2-x}}{L_{f2}}-\frac{V_{s-x}}{L_{f2}} \\ \frac{dV_{1-x}}{dt}&=d_3i_{f-x}-\frac{V_{1-x}}{RC_1}+\frac{V_{2-x}}{RC_2} \\ \frac{dV_{2-x}}{dt}&=-d_4i_{f-x}-\left(\frac{V_{1-x}}{RC_1}+\frac{V_{2-x}}{RC_2}\right) \\ \frac{dV_{c-x}}{dt}&=\frac{i_{f-x}}{C}-\frac{i_{s-x}}{C} \\ d_5i_{f-x}&=\frac{C_1dV_1}{dt}-\frac{C_2dV_2}{dt} \end{aligned}\right\} \tag{19}$$

$$A=\begin{bmatrix} -\frac{R_{f1}}{L_{f1}} & 0 & -1 & d_1 & d_2 \\ 0 & -\frac{R_{f2}}{L_{f2}} & 1 & 0 & 0 \\ \frac{1}{C} & -\frac{1}{C} & 0 & 0 & 0 \\ d_3 & 0 & 0 & -\frac{V_1}{RC_1} & -\frac{V_2}{RC_2} \\ -d_4 & 0 & 0 & -\frac{V_1}{RC_1} & -\frac{V_2}{RC_2} \end{bmatrix} \qquad (20)$$

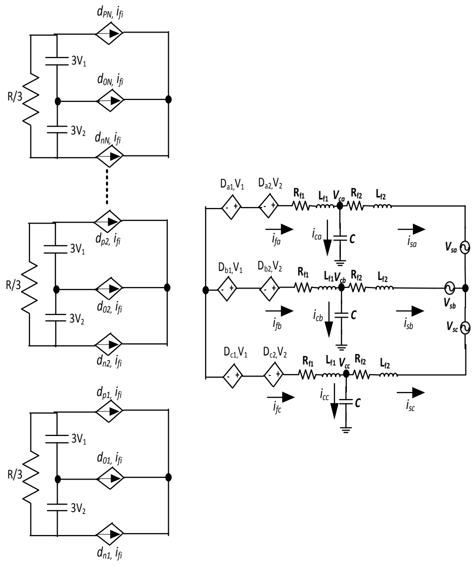


Fig. 3 Simplified average model of the NPC/H-Bridge inverter based Grid connected system in *abc*- stationary reference frame.

5. Control scheme

Feedback control technique is applied to a nine level cascaded NPC/H-bridge inverter as shown in block diagram in fig. 6. The small signal model shown in fig. 5 is applied in fig. 6 in the model controller block and the robustness of the controller model is tested based on accurate tracking of reference signals. The inverter model has to draw maximum active power from the DC link source to maintain the DC link voltage at desired level. This is achieved by a double closed loop that integrates the DC voltage of the DC capacitor voltage, the grid voltage and the inverter current, the inner loop controls the grid current i_{sd} and the quadrature axis- current i_{sq} is set zero inside the current controller in order to generate maximum active power at unity power factor. The outer loop stabilizes the DC voltage and hence ensuring sinusoidal inverter output voltage and reduced current harmonic injection into the grid, The reference for V_{s_x} and i_{s_x} comes from the three phase source voltage V_{abc} and current i_{abc} are applied to a three phase Locked Loop to synchronized the three phase voltages for the model with zero crossings of the fundamental components.PLL provides synchronous reference angle Ø (ωst) required by the *abc – dqo* and *dqo- abc* transformation. The three phase parameters are converted into equivalent direct and quadrature axis components using the transformation matrix T defined in equation (21). For a balanced three phase system zero sequence components is zero and thus the [G] and [M] matrices are given based on *dq* component. Thus the transformed matrix in *dq* is given by (22) and (23). Using equation (19), (22) and (23), the dq transformed equation is given by (24)

The inner current loop tracks the grid current reference generated by the grid voltage as shown in section V. The LCL filter are used to reduce harmonic voltages produced at the grid

$$T=\frac{2}{3}\begin{bmatrix} \cos\omega_s t & 0 & \cos(\omega_s t-\frac{2\pi}{3}) & 0 & \cos(\omega_s t+\frac{2\pi}{3}) & 0 \\ 0 & \cos\omega_s t & 0 & \cos(\omega_s t-\frac{2\pi}{3}) & 0 & \cos(\omega_s t+\frac{2\pi}{3}) \\ \sin\omega_s t & 0 & \sin(\omega_s t-\frac{2\pi}{3}) & 0 & \sin(\omega_s t+\frac{2\pi}{3}) & 0 \\ 0 & \sin\omega_s t & 0 & \sin(\omega_s t-\frac{2\pi}{3}) & 0 & \sin(\omega_s t+\frac{2\pi}{3}) \\ \frac{1}{2} & 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 & \frac{1}{2} \end{bmatrix} \qquad (21)$$

$$G=\begin{bmatrix} -\frac{R_{f1}}{L_{f1}} & \omega & 0 & 0 & -\frac{1}{L_{f1}} & 0 \\ -\omega & -\frac{R_{f1}}{L_{f1}} & 0 & 0 & 0 & -\frac{1}{L_{f1}} \\ 0 & 0 & -\frac{R_{f2}}{L_{f2}} & \omega & \frac{1}{L_{f2}} & 0 \\ 0 & 0 & -\omega & -\frac{R_{f2}}{L_{f2}} & 0 & \frac{1}{L_{f2}} \\ \frac{1}{C} & 0 & -\frac{1}{C} & 0 & 0 & \omega \\ 0 & \frac{1}{C} & 0 & -\frac{1}{C} & -\omega & 0 \end{bmatrix} \qquad (22)$$

$$M=\begin{bmatrix} \frac{D_1}{L_{f1}} & \frac{D_2}{L_{f1}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{D_1}{L_{f1}} & \frac{D_2}{L_{f1}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_{f2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{f2}} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (23)$$

$$\left.\begin{aligned}
&\frac{d}{dt}\begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{sd} \\ i_{sq} \\ V_{cd} \\ V_{cq} \end{bmatrix} = [G]\begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{sd} \\ i_{sq} \\ V_{cd} \\ V_{cq} \end{bmatrix} + [M]\begin{bmatrix} V_{1d} \\ V_{2d} \\ V_{1q} \\ V_{2q} \\ V_{sd} \\ V_{sq} \end{bmatrix} \\
&\frac{dV_1}{dt} = \frac{3V_1}{RC_1} + \frac{3V_2}{RC_2} + \frac{1}{3C_1}\left[d_{3dj}\,,\quad d_{3qj}\right]\bullet\begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} \\
&\frac{dV_2}{dt} = \frac{3V_1}{RC_1} + \frac{3V_2}{RC_2} - \frac{1}{3C_1}\left[d_{4dj}\,,\quad d_{4qj}\right]\bullet\begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix}
\end{aligned}\right\} \qquad (24)$$

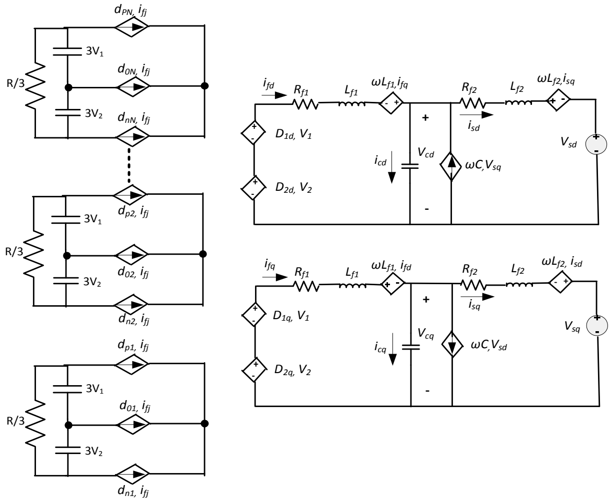


Fig. 4 Equivalent circuit of the NPC/H-Bridge inverter based Grid connected system in *dq*- rotating reference frame

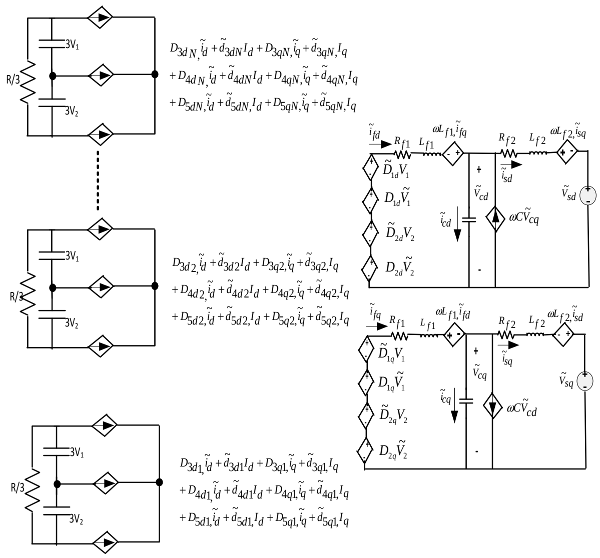


Fig. 5 Small signal model of the NPC/H-bridge inverter based Grid connected system in *dq* co-ordinate

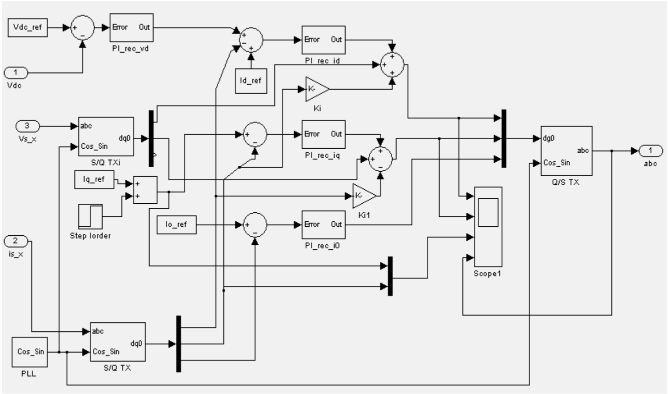


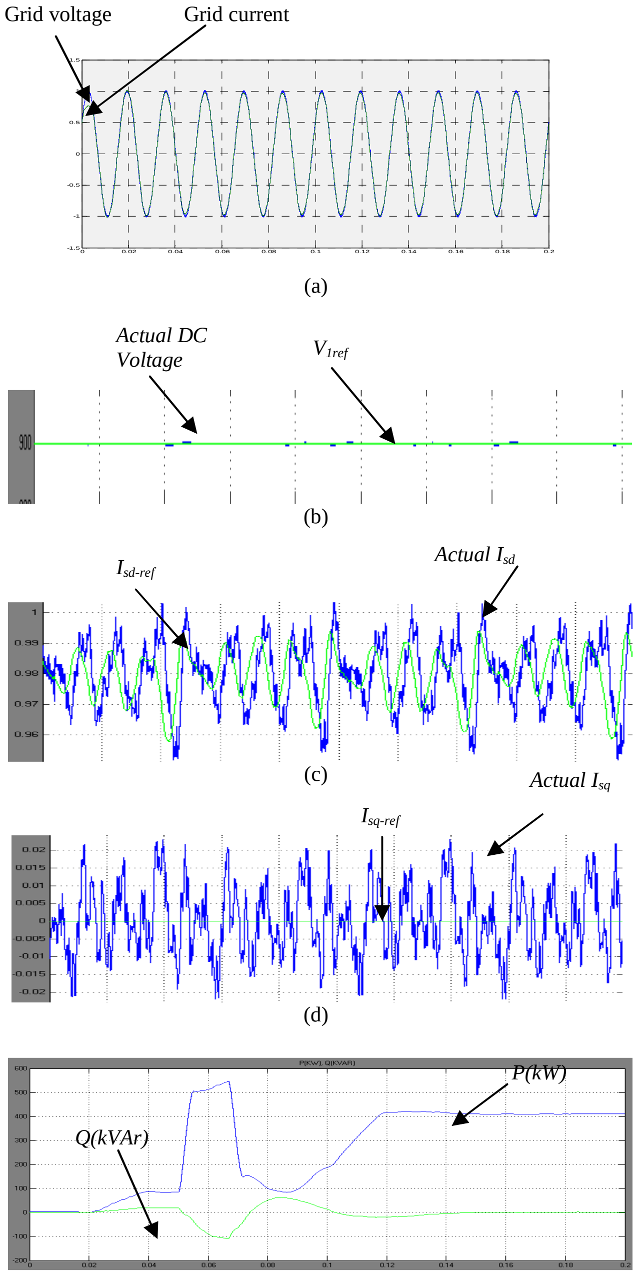
Fig. 6. Grid connected system with a nine level cascaded NPC/H-bridge inverter

6. Simulation results and discussions

In order to validate the mathematical modeling and verify the robustness of the proposed control technique, the inverter model was designed as shown in fig. 6 and simulation was done in MATLAB. Modified and improved Phase shifted PWM technique was used to realize a nine level output voltage with suppressed harmonic content [12]. The design of LCL filter and its general effect on the model and further analysis under transient condition is well explained in [13].The parameters for simulations are shown in table 1. The results shown in fig. 7 shows that the grid voltage is sinusoidal and is in phase with current. it is clearly shown in fig. 7 that all the signal track the reference signals and this verifies the accuracy of the small signal control model adopted. The robustness of the controller is shown in fig. 7(e), the DC bus voltage in increased at t= 0.05s, this increases the inverter output voltage making it larger than the grid voltage and thus reactive power is supplied to the network, at t= 0.08s DC bus voltage is reduced as shown. This reduces inverter output voltage making it lower than grid voltage, thus the inverter absorbs reactive power from the network. But after a while the two power outputs stabilizes.

TABLE 1
SYTESTEM COMPONENT PARAMETER

Symbol	Parameter	Value
$V_{s\text{-}x}$	AC source voltage (grid voltage)	480V, 50 HZ
$L_{f1\text{-}x}$	Inverter filter inductance	0.27 mH
$C_{\text{-}x}$	Input filter capacitance	300 μF
Rf1_x	Inverter Filter leakage resistance	10mΩ
C_1, C_2	DC link capacitance	C_1=C_2= 0.042F
Vdc	DC bus voltage	900V
$L_{f2\text{-}x}$	Grid filter inductance	0.27mH
$R_{f2\text{-}x}$	Grid Filter leakage resistance	1mΩ



(a)

(b)

(c)

(d)

(e)

Fig. 7 Simulation results from the model with Blue is the actual value and green is the reference value (a) Grid voltage and current (b) Actual and reference DC bus voltage (c) Actual and reference magnified direct-axis grid(i_{sd}) current (d) Actual and reference magnified quadrature -axis grid current (i_{sq}) (e) Active power to the grid under grid disturbance

7. Conclusion

This paper critically reviews and gives a complete analysis and modeling of a cascaded NPC/H-bridge inverter. Modeling of the system right from switching model to small signal model is developed. Feedback control scheme where the PI controller gains and LCL filter parameters are designed. Validation of the control technique is done using simulation where the accuracy and robustness of the controller is verified. A sinusoidal grid voltage that is in phase with grid current preferred characteristic for any power injected to the grid is achieved.

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