Complete analysis of a multilevel inverter based on 3 level NPC/H- bridge topology for photovoltaic application

T.Wanjekeche, D.V.Nicolae, *Member, IEEE*, and A.A.Jimoh, *Member, IEEE*

Abstract—**The cascaded NPC/H- bridge inverter is first analyzed by establishing a new switching model based on a derived control law, then using the model a general model using state space technique is obtained. A new and accurate average model is developed using *abc* to *dqo* transformation technique. A small signal model is developed 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 PV- Grid system. Based on the transfer function developed feedback control loop is developed to improve the dynamic response of the system as well as voltage balancing of the DC link. Simulation results are provided to validate the analytical models.**

***Index Terms*— Feedback control, NPC/H-Bridge inverter, PV-Grid system, small signal model, State space technique.**

I. Nomenclature

I_{fd}, I_{sd}, V_{sd}, V_{cd}	Direct axis inverter current, grid current, grid voltage and capacitor voltage
I_{fq}, I_{sq}, V_{sq}, V_{cq}	Quadrature axis inverter current, grid current, grid voltage and capacitor voltage
$S(t)$	Switching function
N	Number of NPC/H-bridge inverter per phase
j	*1…N*
d_1,d_2,d_3,d_4,d_5	Duty cycles for different switching patterns
D	*Total duty cylces*
V_1, V_2	Capacitor voltages
C_1, C_2	DC capacitance
D_1,D_2,D_3,D_4,D_5	Quiescent operating point of D
d_1, d_2, d_3, d_4, d_5	Small signal perturbation of D
x	Phases a, b and c

II. Introduction

INTEGRATION of the photovoltaic power generation system plays in important role in securing an electric power supply in an environmentally friendly manner [1].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. [2], [3]. 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 [4], [5].

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) [6], [7]. A cascade multilevel inverter is a special kind of multilevel inverter built to synthesize a desired AC voltage from several levels of DC voltages [8. 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 [9]. Past research has also concentrated on realizing a five level NPC/H-Bridge inverter without cascading the bridge [10]; 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 [11] for an n- level NPC/H-bridge inverter, interfaced to the grid using LCL filter. 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 obtained 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.

III. Three phase n- level cascaded NPC/H-bridge inverter based PV- grid interface

A. System description

Fig. 1 shows an n- level NPC/H-bridge inverter interfacing the photovoltaic cells to the grid, since the flow of power is always from the PV cells to the grid, the inverter operates in one quadrant. The system consists of n- level PV array,

The authors are with Department of Electrical Engineering, Tshwane University of Technology- South Africa. (e-mail: wanjekeche@yahoo.com, nicolaedv@tut.ac.za, JimohAA@tut.ac.za)

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:

$$m = 4N + 1 \tag{1}$$

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

B. 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

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

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;

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

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

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

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

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

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

Where a and b are the two NPC –legs. Using equation (2 – 6), a switching state and corresponding voltage output Van can be generated as shown in table 1. The voltage V_{01} generate by the inverter can be expressed as:

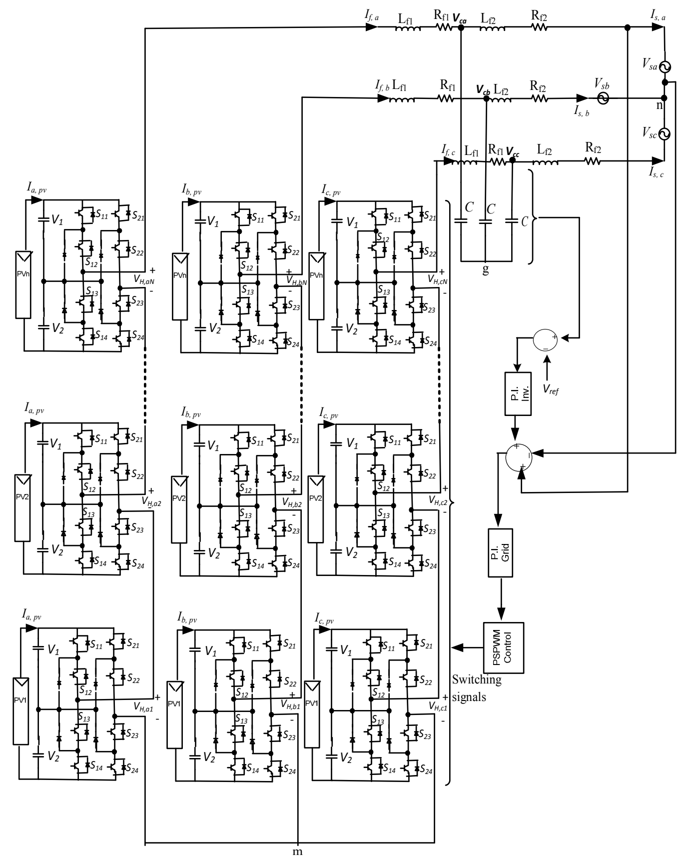


Fig. 1. The proposed control scheme of the model

The

$$V_{01} = V_a + V_b \,. \tag{9}$$

Using table 1, V_a for leg a is expressed as;

$$V_a = K_a\left(\frac{K_a+1}{2}\right)V_1 - K_a\left(\frac{K_a-1}{2}\right)V_2 \tag{10}$$

Similarly for the second leg the expression is given by;

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

Using equation (10), the voltage V_{12} is given by;

$$V_{01} = \frac{K_a - K_b}{2}\left(V_1 + V_2\right) + \frac{K^2 a - K^2 b}{2}\left(V_1 - V_2\right) \tag{12}$$

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

IV. SYSTEM MODELING

A general model for the conventional H- bridge cascaded multilevel converter is presented in [12]. 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.

The following are some of the assumptions made in the modeling and analysis process;

- The utility is a three phase balanced, sinusoidal voltage source
- The DC- link capacitors V_{dc1}, V_{dc2}, V_{dc3} and V_{dc4} have the same capacitance (PV cell modeling is not part of this paper)
- The power losses of the whole system are categorized as series loss and parallel loss.

A. 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 mole 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;

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

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 [12];

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

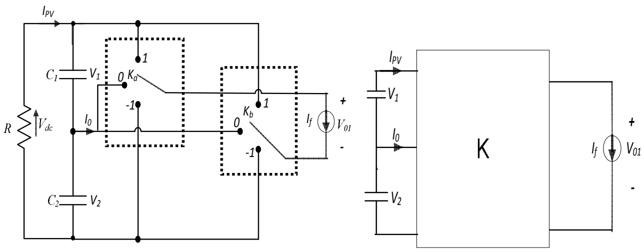


Fig. 2 Simplified representation the converter

The two dc voltage and out put current are assumed to be constant in one switching period. Thus the average switching equations are as follows:

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

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 [13] from equation (12) are given by [13]

B. 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:

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

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

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

The equations (17) and (18) can be rearranged as;

$$
\left.
\begin{aligned}
\frac{di_{f-x}}{dt} &= \frac{R_{f1-x}}{L_{f1}} - \frac{V_{c-x}}{L_{f1}} + \frac{d_{1-x}V_1}{L_{f1}} + \frac{d_{2-x}V_2}{L_{f1}} \\
\frac{di_{s-x}}{dt} &= \frac{V_{c-x}}{L_{f2}} - \frac{R_{f2-x}}{L_{f2}} - \frac{V_{s-x}}{L_{f2}} \\
\frac{dV_{1-x}}{dt} &= d_3 i_{f-x} - \frac{V_{1-x}}{RC_1} + \frac{V_{2-x}}{RC_2} \\
\frac{dV_{2-x}}{dt} &= -d_4 i_{f-x} - \left(\frac{V_{1-x}}{RC_1} + \frac{V_{2-x}}{RC_2}\right) \\
\frac{dV_{c-x}}{dt} &= \frac{i_{f-x}}{C} - \frac{i_{s-x}}{C} \\
d_5 i_{f-x} &= \frac{C_1 dV_1}{dt} - \frac{C_2 dV_2}{dt}
\end{aligned}
\right\} \qquad (19)
$$

Equation (14) can be expressed in matrix form:

$$\dot{X} = A X + B U \qquad (20)$$

Where X is the state vector. Capacitor current, inverter current and utility line current and DC- Link capacitors are taken as state variables.

From equation (18) state matrix A is obtained as:

$$
A = \begin{bmatrix}
-\frac{R_{f1}}{L_{f1}} & 0 & -1 & d_1 & d_2 \\
0 & -\frac{R_{f2}}{L_{f2}} & 1 & 0 & 0 \\
\frac{1}{C} & -\frac{1}{C} & 0 & 0 & 0 \\
d_3 & 0 & 0 & -\frac{V_1}{RC_1} & -\frac{V_2}{RC_2} \\
-d_4 & 0 & 0 & -\frac{V_1}{RC_1} & -\frac{V_2}{RC_2}
\end{bmatrix} \qquad (21)
$$

From equations (16) – (21), the average model of the NPC/H-bridge inverter based PV-grid interface in *abc* co-ordinate is given by fig. 3.

For a simplified average model the following assumption are made and the simplified model is as shown in fig. 4

- All the dc voltages in three phases are assumed constant; $V_{a1} = V_{b1} = V_{c1} = V_1$ and same to V_{a2}
- well designed converter have same losses in the cells i.e. $R_{a1}=R_{a2}= R_{an} =R_{b1} = R_{b2} =R_{bn} = R_{c1}= R_{c2} = R_{c3} = R$
- Current switching on the dc side of the mode are defined as follows; $d_{pj}i_{fj}$
- Voltage source current controlled parameters on the ac side are defined as:
  $D_{1a}V_1=d_1V_{1a1}+d_1V_{1a2}+d_1V_{1AN}$,
  $D_{2a}V_2= d_2V_{2a1}+d_2V_{2a2} =d_2V_{2AN}$

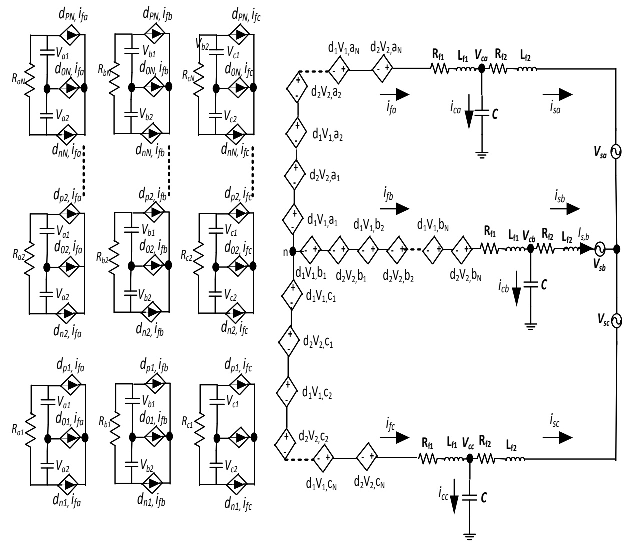


Fig. 3. Average model of the NPC/H-Bridge inverter based PV-Grid interface in *abc*- stationary reference frame

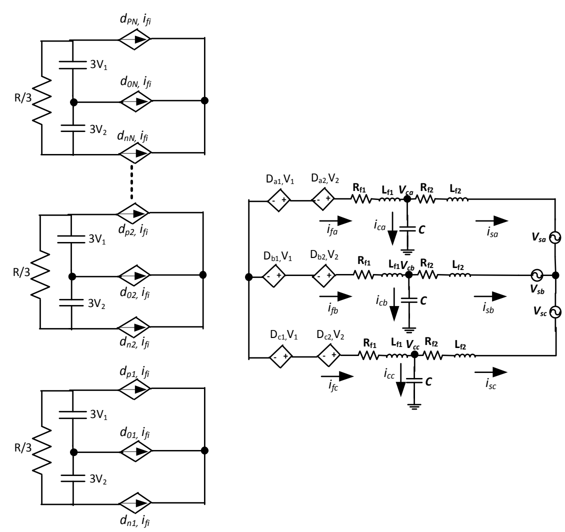


Fig. 4 Simplified average model of the NPC/H-Bridge inverter based PV-Grid interface in *abc*- stationary reference frame.

C. The circuit dq transformation of the PV-Grid interface system

In order to establish the state space mathematical model of the proposed model, the inverter output current I_{f1} through the inductance (L_{f1}), the grid current I_{sa}, the capacitor voltage and the current through DC link capacitor voltage are taken as state variables. The switching function of the model build is a function of time, thus matrix of the model is time variant, this becomes difficult to solve. Using co-ordinate transformation, three phase symmetrical sinusoidal components are transformed into constant DC components. The dynamic time invariant model in *dq0* reference frame is more suitable for analyzing and designing the control system since the conventional linear time invariant (LTI) circuit analysis and design can be easily applied. The transformation matrix T employed in the transformation of the model equations from *abc* – to – *dq0* is defined as;

$Z\dot{X}_{dq0} = A_{dq0}X_{dq0} + B_{dq0}U_{dq0}$, and T is defined as

$$T=\frac{2}{3}\begin{bmatrix} \cos\omega_s t & 0 & \cos(\omega_s t-\frac{2\pi}{3}) & 0 & \cos(\omega_s t+\frac{2\pi}{3}) & 0 \\ 0 & \cos\omega_s t & 0 & \cos(\omega_s t-\frac{2\pi}{3}) & 0 & \cos(\omega_s t+\frac{2\pi}{3}) \\ \sin\omega_s t & 0 & \sin(\omega_s t-\frac{2\pi}{3}) & 0 & \sin(\omega_s t+\frac{2\pi}{3}) & 0 \\ 0 & \sin\omega_s t & 0 & \sin(\omega_s t-\frac{2\pi}{3}) & 0 & \sin(\omega_s t+\frac{2\pi}{3}) \\ \frac{1}{2} & 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 & \frac{1}{2} \end{bmatrix} \quad (22)$$

$$G=\begin{bmatrix} -\frac{R_{f1}}{L_{f1}} & \omega & 0 & 0 & -\frac{1}{L_{f1}} & 0 \\ -\omega & -\frac{R_{f1}}{L_{f1}} & 0 & 0 & 0 & -\frac{1}{L_{f1}} \\ 0 & 0 & -\frac{R_{f2}}{L_{f2}} & \omega & \frac{1}{L_{f2}} & 0 \\ 0 & 0 & -\omega & -\frac{R_{f2}}{L_{f2}} & 0 & \frac{1}{L_{f2}} \\ \frac{1}{C} & 0 & -\frac{1}{C} & 0 & 0 & \omega \\ 0 & \frac{1}{C} & 0 & -\frac{1}{C} & -\omega & 0 \end{bmatrix} \quad (23)$$

$$M=\begin{bmatrix} \frac{D_1}{L_{f1}} & \frac{D_2}{L_{f1}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{D_1}{L_{f1}} & \frac{D_2}{L_{f1}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_{f2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{f2}} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (24)$$

For a balanced three phase system zero sequence component is zero and thus the [G] and [M] matrices are given based on *dq* component. Thus the transformed matrix in *dq* is given by (23) and (26). Using equation (19), (23) and (24), the dq transformed equation is given by;

$$\left.\begin{aligned} &\frac{d}{dt}\begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{sd} \\ i_{sq} \\ V_{cd} \\ V_{cq} \end{bmatrix} = [G]\begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{sd} \\ i_{sq} \\ V_{cd} \\ V_{cq} \end{bmatrix} + [M]\begin{bmatrix} V_{1d} \\ V_{2d} \\ V_{1q} \\ V_{2q} \\ V_{sd} \\ V_{sq} \end{bmatrix} \\ &\frac{dV_1}{dt} = \frac{3V_1}{RC_1} + \frac{3V_2}{RC_2} + \frac{1}{3C_1}\left[d_{3dj}\,,\; d_{3qj}\right]\bullet\begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} \\ &\frac{dV_2}{dt} = \frac{3V_1}{RC_1} + \frac{3V_2}{RC_2} - \frac{1}{3C_1}\left[d_{4dj}\,,\; d_{4qj}\right]\bullet\begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} \end{aligned}\right\} \quad (25)$$

From the three transformed equations contained in (25), the average model of the NPC/H-bridge inverter based PV-Grid interface system is obtained as shown in fig. 5.

D. *Small signal model and analysis of the system*

The small signal model is obtained by linearising the large scale average model around its quiescent operating point. The small signal model of the NPC/H-bridge inverter based PV-Grid interface is shown in fig. 6 where the symbol ~ denotes the perturbed variable and the upper case variables denotes the operating point variables.

V. CONTROL SCHEME

Feedback control technique is applied to a nine level cascaded NPC/H-bridge inverter as shown in block diagram in fig. 7. The small signal model shown in fig. 6 is applied in fig. 7 in the model controller block and the robustness of the controller model is tested based on accurate tracking of reference signals. The system adopts the double closed loop that integrates the DC voltage of the photovoltaic cells, 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 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 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.

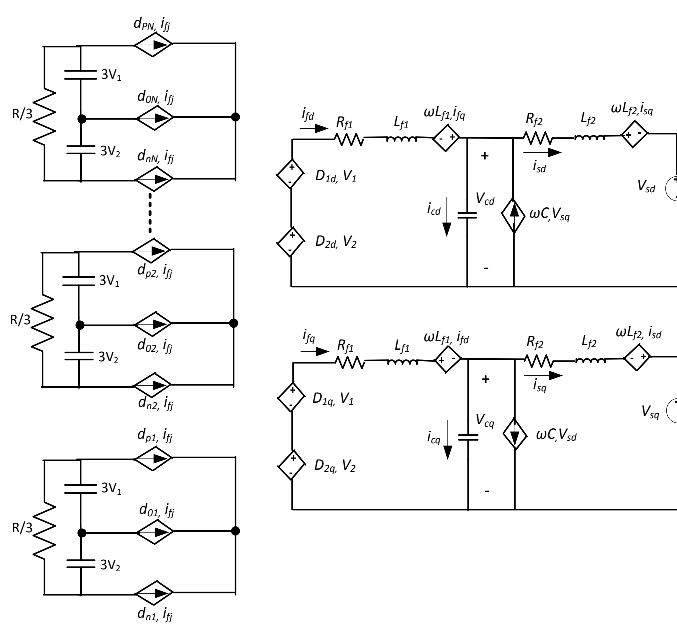


Fig. 5 Equivalent circuit of the NPC/H-Bridge inverter based PV-Grid interface in *dq*- rotating reference frame

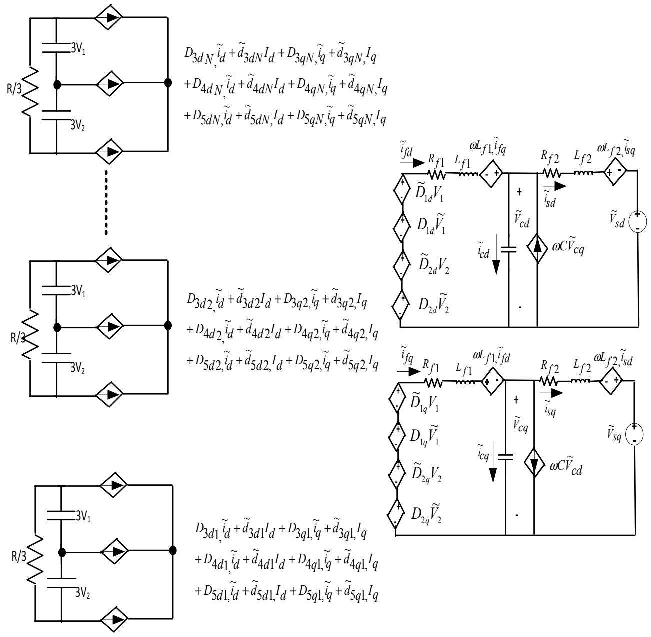


Fig. 6 Small signal model of the NPC/H-bridge inverter based PV-Grid interface in *dq* co-ordinate

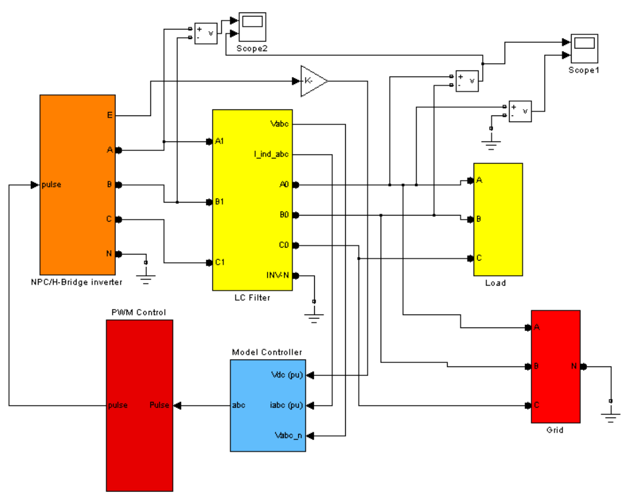


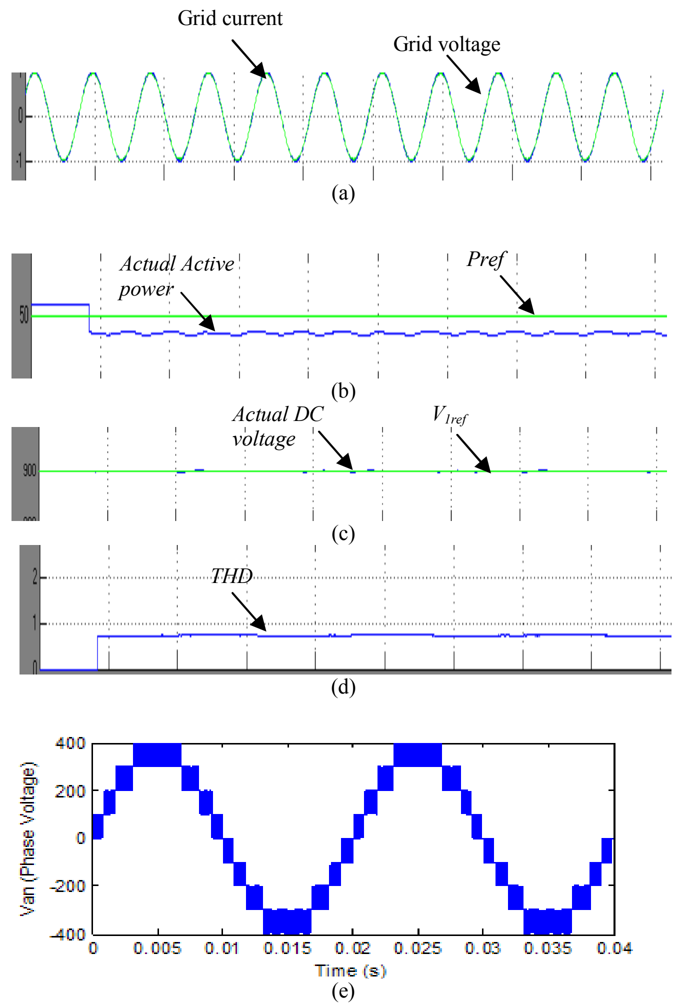
Fig. 7. Grid connected photovoltaic system with a nine level cascaded NPC/H-bridge inverter

VI. SIMULATION RESULTS

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. 7 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 [14], [15]. The parameters for simulation are shown in table 2 and 3. The results shown in fig. 8 are the small signal results with the control and fig. 9 without control. it is clearly shown in fig. 8 that all the signal track the reference signals and thus the grid voltage is sinusoidal with reduced THD, same applies the grid current with a THD OF 1.22, and is in phase with the voltage. From fig. 9 it is shown that the actual DC bus voltage does not track the reference, this result in harmonic production in the grid current and reduced active power injected to the grid. The robustness of the controller is shown in fig. 9(f), where disturbance in the active power reduces it to zero at 0.18 sec. (not shown in the figure). From the fig., the actual value tracks the reference after the disturbance

TABLE 3
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



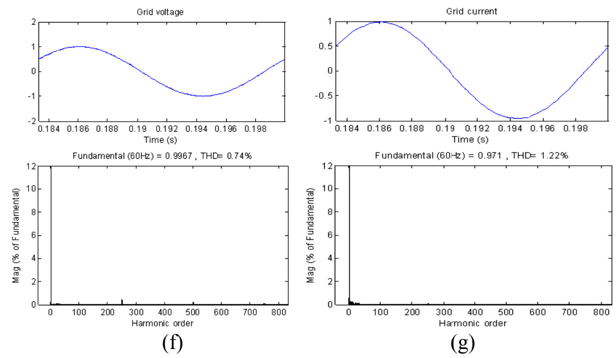
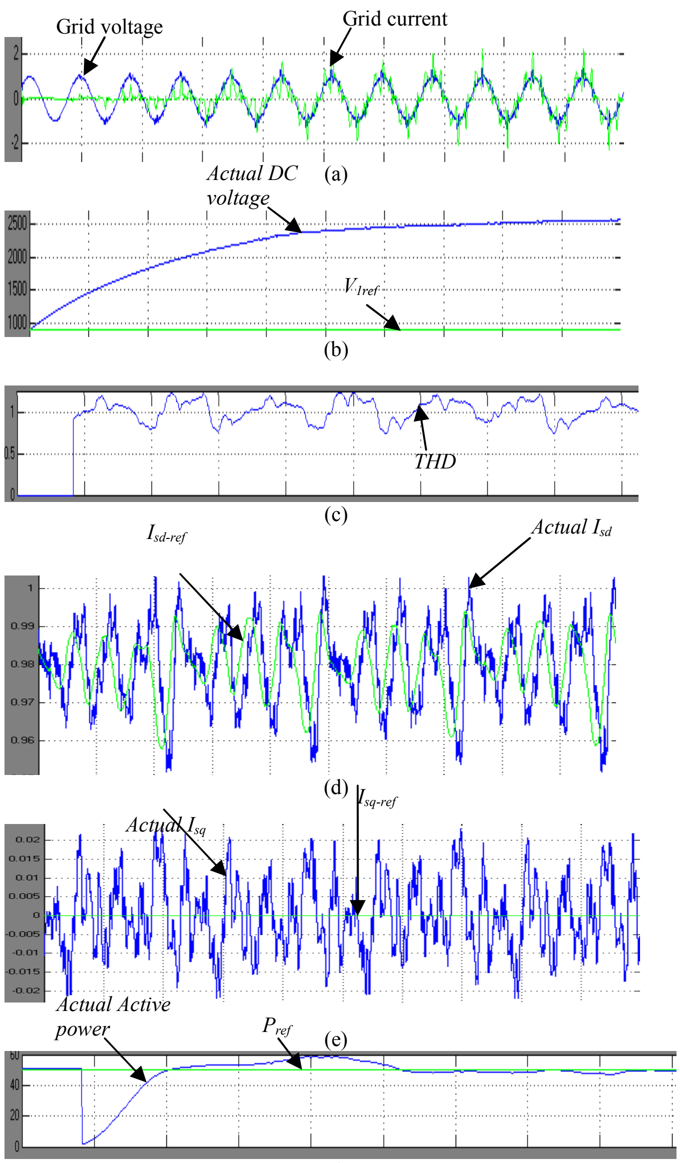


Fig. 8 Simulation results from the model with control; Blue is the actual value and green is the reference value (a) Grid voltage and current (b) Active power to the grid (c) DC bus voltage (d) THD (e) Inverter output voltage (f) Grid voltage and its spectrum (g) Grid current and its spectrum



(f)

Fig. 9 Simulation results from the model without control; Blue is the actual value and green is the reference value (a) Grid voltage and current (b) DC bus voltage (c) THD (d) Magnified direct- axis grid current (i_{sd})

(e) Magnified quadrature - axis grid current (i_{sq}) (f) Actual and reference active power after disturbance

V. Conclusion

This paper critically reviews and gives a complete analysis 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 and low THD gird current preferred characteristic for any power injected to the grid is achieved.

VI. References

[1] J.P.Benna, L.Kasmerski, “Photovoltaics gaining greater visibility,” *IEEE spectr,* September 1999.

[2] R.L.Steigerwald, A. Ferraro, R.E.Tompkins, “Final report - investigation of a family of power conditioners integrated into the utility grid-residential power level,” DOE Contract DEAC02-80ET29310, Sandia National Lab., Rep. SAND81 – 7031, 1981

[3] A. Cocconi, S. Cuk, R.D.Middlebrook, “High frequency isolated 4-kW photovoltaic inverter for utility interface,” *Powercon. Int.,* May 1984.

[4] M. Mario Marchesoni, P. Tenca, “Diode clamped multilevel converters: A Practical way to balance DC- link voltages,” *IEEE Trans. on Industrial Electronics,* vol. 49, No. 4, August 2002, pp. 752 -765.

[5] K.A. Corzine, J.R. Baker, Multilevel voltage source duty cycle modulation: Analysis and implementation,” *IEEE Trans. on Industrial Electronics,* vol. 49, No. 5, October 2002, pp. 1009 -1016.

[6] G. Carrara, S. Gardella, M. Marchesoni, R. Salutari and G. Sciutto, “A new multilevel PWM method a theoretical analysis,” *IEEE Trans. on power electronics,* vol. 7, pp. 497 -505, July, 1992.

[7] J. S. Lai, F. Z. Peng, “Multilevel Converters - A New Breed of Power Converters,” *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 509-517, May 1996.

[8] L. M. Tolbert, F. Z. Peng, and T. Habetler, “Multilevel Converters for Large Electric drives,” *IEEE Trans. Ind. Applicat.*,vol.35,pp. 36-44, Jan./Feb. 1999.

[9] F. Z. Peng, J. S. Lai, J. W. McKeever, J. VanCoevering, “A Multilevel Voltage-Source Inverter with Separate DC Sources for Static Var Generation,” *IEEE Transactions on Industry Applications*, vol. 32, no. 5, pp. 1130-1138, Sept. 1996.

[10] C.M.Wu, W.H. Lau and H.Chung, “A five-level neutral-point-clamped H-bridge PWM inverter with superior harmonics suppression: A theoretical analysis,” *ISACS '99, proceedings of the 1999 IEEE international symposium,* vol. 5, pp.198-201, 1999.

[11] L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bindner, P. Sørensen, and B. Bak-Jensen, *Conceptual Survey of Generators and Power Electronics for Wind Turbines*, Dec. 2001, Roskilde, Denmark: Risø National Laboratory. [Online]. Available: www.risoe.dk/ rispubl/VEA/ris-r-1205.htm

[12] S. Sirisukprasert, A. Q. Huang, and J. S. Lai, “Modeling, analysis and control of cascaded- multilevel converter- based STATCOM,” *In Proc. IEEE – PES general meeting*, vol. 4 , pp. 13- 17, July 2003

[13] Bor-Ren lin, “A single phase three level pulse width modulation AC/DC converter with the function of power factor corrector and active power filter,” *Electrical power system research,* No. 58, pp. 157-167, 2001

[14] T. Wanjekeche, A.A. Jimoh and D.V. Nicolae, “A Novel Multilevel 9-level inverter based on 3 – level NPC/H-Bridge topology for Photovoltaic application” *INTERNATIONAL REVIEW OF ELECTRICAL ENGINEERING-IREE* Vol. 4, No.5, pp.769-777 Sept., 2009

[15] T. wanjekeche, D.V. Nicolae and A.A. Jimoh, “A Cascaded NPC/H-bridge inverter with simplified control strategy and minimum component count” *IEEE – Africon,* Sept., 2009