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Performance Analysis of Three Level NPC Inverter for Integration of Renewable Energy Resources in to AC Grid

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***Abstract*— This paper deals with the three level converters control strategy for renewable energy resources integration in to distribution grids. The proposed control scheme ensures the injection of the generated power in the distribution grid with fast dynamic response, while providing an additional active power filtering capability, providing the required harmonic and reactive currents to the considered non-linear loads. The proposed control scheme is applicable to a general multilevel converter and to any types of the renewable energy resources. The proposed model has been derived from the abc / αβ and αβ / dq transformation of the AC system variables. The control scheme is validated by means of simulations with a three level diode clamped converter which interfaces a wind power generation system to a distribution grid supplying non-linear loads. In order to evaluate the performance of the proposed approach, a model of the AC grid, non-linear load, multilevel inverter and renewable energy resources (e.g., wind power generation) had developed in MATLAB / SMULINK environment.**

***Index Terms*— Distributed generation (DG) resources, harmonic elimination, multilevel inverters, reactive power compensation, renewable energy, space vector pulse width modulation (SVPWM).**

1. INTRODUCTION

Now a days DG (distributed generation) resources are playing a prominent role in electrical networks. By applying these DG resources (e.g. wind power generation, solar energy, fuel cells, micro turbines and etc) in to power system many changes occurs such as change in operation and design of distribution network. The main advantages of DG technology are environmental aspects and the short period of construction leads in the development of DG technology. The important aspects to be considered while synchronizing the DG system to the distribution grid are practical, cost effective and flexible control strategies [1]. Power electronic devices are increasing in demand to achieve flexible distribution networks. An important issue in the control of distribution systems is reactive power compensation. Due to reactive current not only increases the distribution losses also reduces the power factor, causes heat losses in machines, also reduces the capability of active power which causes the variations in voltage amplitudes which may cause the changes in the electrical demand [2]. The main intention of the DG technology is to provide active power by using power electronic devices and the reactive power can be can be compensated by using the active power filters. This compensation of active and reactive power can be obtained by using the proper control techniques for interfacing circuits. The DG systems can connect to distribution grid in series or shunt type, but the main issue of control is reactive power, this can be achieved by shunt compensation. By shunt connected compensation the reactive current can be compensated. In this paper we propose a VSI (voltage source inverter) as an interfacing power electronic circuit. For better compensation of reactive power and to reduce the total harmonic distortion a three level NPC inverter is used for shunt connected DG system in to distribution grid. By using the multilevel inverters the harmonic distortion can be reduced enormously. Several control techniques have been proposed for NPC VSI. The simple and predictive current control SVPWM (space vector pulse width modulation) for shunt connected NPC VSI to three phase three wire distribution grid. The current control technique uses the proportional integral current control technique in stationary and synchronous reference frame. For the proposed SVPWM technique the currents voltages to be represented in stationary and synchronous reference form. The instantaneous angle θ can be obtained from PLL which is connected to PCC at load side of the distribution grid. This control technique provides fast dynamic response and reduces the overshoots [3]. The distribution grid, NPC inverter, renewable energy resources are simulated in MATLAB/SIMULINK to verify the mathematical analysis of the distribution grid.

2. THREE LEVEL NPC INVERTER TOPOLOGY

Multilevel inverters plays an important role in many ways, these can used as SAPF (shunt active power filters) to compensate the reactive currents and also reduces the total harmonic distortion, in present days it was very popular as shunt connected inverter to connect DG system in to distribution grid, and static VAR to compensate load reactive power. Multilevel inverters are categorized in to three types they are Diode clamped or Neutral point clamped (NPC) inverter, cascaded H-bridge inverter and flying capacitor inverter. Neutral point clamed (NPC) inverter is widely used in three phase three-wire grid connection.

Neutral-Point-Clamped multilevel inverter or also known as Diode Clamped Multilevel inverter was first proposed by Nabae et.al in 1980 (Krug et.al., 2004; Marchasoniand mazzucchelli, 1993) [4]. Figure 1: depicts the three level NPC inverter in the figure three phases of a inverter share a common DC bus, subdivided by two capacitors in to three level which is one of the advantage of NPC inverter. The voltage across each capacitor is $\frac{V_{DC}}{2}$ and the stress caused by voltage across each device is limited by $\frac{V_{DC}}{2}$ by connecting the clamping diodes.

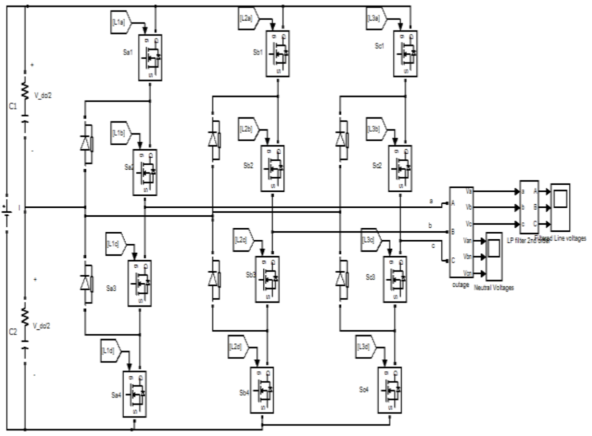

Fig. 1 Three-phase three level structure of a NPC inverter.

TABLE 1

VOLTAGE LEVELS AND SWITCHING STATES OF NPC INVERTER

Voltage level, V_{AN}	Switches ON
$-V_{DC}/2$	S_{a3}, S_{a4}
0	$S_{a2}.S_{a3}$
$+V_{DC}/2$	S_{a1}, S_{a2}

In this paper we have proposed an SVPWM technique for shunt connected NPC inverter. In SVPWM the voltage vectors are represented in space, for NPC inverter has three levels and it was three phase it results in 3^3 possible combinations. Therefore it have 27 state space vectors and in each phase it have +1,0,-1 state. Similarly for three phase n-level inverter there are n^3 states of switching and $n_{vec}=3n(n-1)+1$ voltage vectors shown in Fig. 2. There are 24 active states are present in the figure 3 in which 12 vectors are single and 6 vectors are double vector and the triple vector (111, 000, -1-1-1) is on the centre of the hexagon shown in Fig. 2.

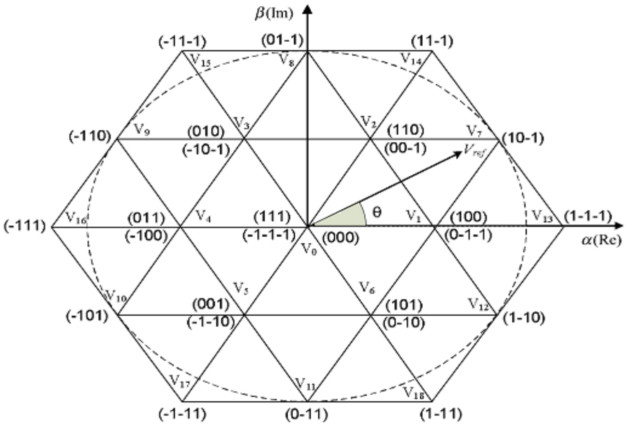

Fig. 2 Representation of voltage vectors for three level NPC inverter.

The point (+1, 0, -1) on space vector plane represents the connection of phase to the bus , phase (a) is connected to the positive bus, phase (b) is connected to the neutral point, and phase (c) is connected to the negative bus. And this also represents the switching pattern of the inverter and the number of upper switches is on each phase of NPC inverter. The switching states of Fig. 1 is represented as given below

$$\left\{\begin{array}{l} S=(S_{a,} S_{b,} S_c),\ S_{a,b,c}\ \in\{-1,\ 0,+1\} \\ \quad +1 \rightarrow S_{x1},\ S_{x2}\ are\ ON \rightarrow V_{xN}\ =+\frac{V_{DC}}{2} \\ \quad 0\ \rightarrow S_{x2},\ S_{x3}\ are\ ON \rightarrow V_{xN}\ =0 \\ \quad -1 \rightarrow S_{x3},\ S_{x4}\ are\ ON \rightarrow V_{xN}\ =-V_{DC}/2 \end{array}\right\} \qquad (1)$$

3. VOLTAGES AND CURRENTS IN STATIONARY AND SYNCHRONOUS REFERENCE FRAME

In this paper the scheme proposed for control technique is SVPWM. In SVPWM technique the voltages and currents are represented in stationary and synchronous reference frame. The synchronous reference frame is also known as Park transformation which maps the three phase currents and voltage components of abc phases in to dq0 reference frame. The stationary reference frame is also known as Clarke transformation which maps the voltage and current components in abc phases in to the instantaneous $\alpha\beta0$ reference frame. By changing the voltage and current components from abc to dq frame the grid voltage currents are represented in rotating synchronous frame. Therefore the control variables are represented in DC values, then the controlling can be achieved easily [5]. The equations (2) and (3) represents the three phase voltage and current components in αβ transformation

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}=\sqrt{2/3}.\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{l1} \\ i_{l2} \\ i_{l3} \end{bmatrix} \qquad (3)$$

Where u_i and i_{li} (i= 1,2,3) are the three phase grid voltages [or voltages at point of common coupling (PCC)] and load currents, respectively. Let assume that null value for the zero voltage component is zero. By considering the absence of a neutral wire the zero components becomes null. Figure 3 depicts the functional diagram of shunt connected renewable energy resource in to AC grid using three level NPC VSI. Conventional signs of voltages and currents also indicated. In this paper the renewable energy resource and other components assumed to be a DC current source. Next to that the αβ components are transformed in to dq reference frame.

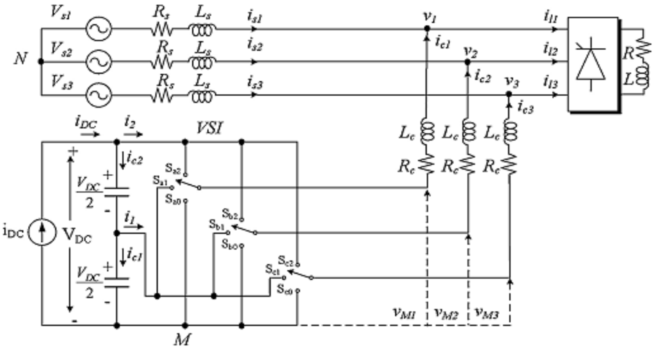

Fig. 3 Functional diagram of shunt connected NPC VSI to the AC grid.

The voltage and current transformation matrices in a stationary and rotating synchronous reference frames are given below:

The transformation matrix for current and voltage (αβ/dq) which is based on park equations is given below as

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = T_{dq}^{\alpha\beta} \cdot \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}, \text{ and } \begin{bmatrix} u_{ld} \\ u_{lq} \end{bmatrix} = T_{dq}^{\alpha\beta} \cdot \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} \qquad (4)$$

Where $T_{dq}^{\alpha\beta} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$, and the inverse matrix is $T_{\alpha\beta}^{dq} = (T_{dq}^{\alpha\beta})^\wedge - 1$. $u_{ld}, u_{lq}, i_{ld}, and i_{lq}$ are d and q component of voltages and currents in rotating synchronous reference frame, respectively, and θ is the instantaneous angle of load voltage or voltage at the PCC.

The d-component of the voltage in stationary and rotating synchronous reference frame can be calculate as follows:

$$u_d = |u_{dq}| = |u_{\alpha\beta}| = \sqrt{u_{\alpha}^2 + u_{\beta}^2} \qquad (5)$$

By substituting (3) in (4) and assuming that $i_{l1} = -(i_{l2} + i_{l3})$

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{2} . \begin{bmatrix} \sin(\theta + \pi/3) & \sin\theta \\ \cos(\theta + \pi/3) & \cos\theta \end{bmatrix} \begin{bmatrix} i_{l1} \\ i_{l2} \end{bmatrix} . \qquad (6)$$

By (6), d and q components of currents in rotating synchronous reference frame can be calculated by means of current components in 123 variable system.

4. DYNAMIC MODEL OF SHUNT DG SYSTEM

The DG system can be connected to the distribution grid in series or shunt type. In shunt connection DG system injects current at PCC, while in a series connection it injects a voltage between the utility supply and the customer load. Consideration of compensation quantities may decide the connection of DG system in to distribution grid. In this paper we proposed to compensate the reactive power and reduction of THD. Therefore a shunt type connection of renewable energy resources is used in this part [6]. To develop a proper plan to control the shunt connection of DG systems in to the distribution grid, a dynamic model of the distribution system should be developed. By applying the KVL law for load voltage (voltage at PCC) in Fig. 3 leads to the following equation (7)

$$\sum_{i=1}^{3} u_i = -L_c \frac{di_{c2}}{dt} - R_c i_{c2} + u_{Mi} \qquad (7)$$

Where i=1,2,3.

By summation of above three equations in (7) we get

$$\sum_{i=1}^{3} u_i = \sum_{i=1}^{3} \left(-L_c \frac{di_{ci}}{dt} - R_c i_{ci} \right) + \sum_{i=1}^{3} (u_{Mi} + u_{MN}) \qquad (8)$$

By assuming the sum of the currents and voltages at PCC was considered as $i_{c1} + i_{c2} + i_{c3} = 0 \ and \ (u_1 + u_2 + u_3) = 0$, by considering all the terms in (8), in (9) AC NP can be found.

$$u_{MN} = -\frac{(u_{M!} + u_{M2} + u_{M3})}{3} \qquad (9)$$

Now a first order differential equation can describe the AC side of the system is given below:

$$\frac{di_{ck}}{dt} = -\frac{R_c}{L_c} i_{ck} - \frac{1}{L_c} U_i + \frac{1}{L_c} v_{Mi} + \frac{1}{L_c} u_{MN} \qquad (10)$$

k=1,2,3.

Considering the switching function S_k of the kth leg of NPC VSI shown in figure 3 can be described as

$$S_k = \begin{cases} +1 & S_{k2} \rightarrow \ ON \\ 0 & S_{k1} \rightarrow \ ON \\ -1 & S_{k3} \rightarrow \ ON. \end{cases} \qquad (11)$$

Let us assume $v_{KM} = S_k \frac{U_{DC}}{2}$, and substituting equations (8), (9), (10), and (11), which are developed for switching model of three level NPC inverter. Now Equation (12) can be written as follows:

$$\frac{di_{ck}}{dt} = -\frac{R_c}{L_c} i_{ck} + \frac{1}{L_c} \left(s_k - \frac{1}{3} \sum_{j=1}^{3} s_j \right) \frac{U_{DC}}{2} - \frac{u_k}{L_c} . \qquad (12)$$

The equation (12) represents the dynamic equation of the shunt NPC VSI of phase k then the switching state function D_{nk} of three level NPC voltage source inverter can be given as follows:

$$D_{nk} = \left(s_k - \frac{1}{3} \sum_{j=1}^{3} s_j \right) . \qquad (13)$$

Equation (13) shows that the value of D_{nk} depends on the switching functions of the three legs of the shunt connected NPC VSI which shows the relation between the three phases. By substituting equation (13) in to equation (12), we obtain a dynamic equation of shunt connection of NPC VSI:

$$\frac{d}{dt}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} = -\frac{R_c}{L_c}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} D_{n1} \\ D_{n2} \\ D_{n3} \end{bmatrix}\frac{V_{DC}}{2} - \frac{1}{L_c}\begin{bmatrix} u_1 \\ u \\ u_3 \end{bmatrix} \qquad \ldots\ldots\ldots\ldots \quad (14)$$

By Considering that sum of currents at PCC is zero then $i_{c3} = -(i_{c1} + i_{c2})$,
The dynamic model of shunt connected NPC VSI as an interfacing circuit for integration of renewable energy resources to the AC grid in abc frame (123 frame) can be obtained as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{c1} \\ i_{c2} \end{bmatrix} = -\frac{R_c}{L_c}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i_{c1} \\ i_{c2} \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} D_{n2} \\ D_{n1} \end{bmatrix}\frac{U_{DC}}{2} - \frac{1}{L_c}\begin{bmatrix} u_2 \\ u_1 \end{bmatrix}. \quad (15)$$

It is well known that (15) is a non linear and time variant equation. For the proposed control technique we need the dynamic model of shunt NPC VSI in dq reference frame which is given below:

$$\frac{d}{dt}\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} = \begin{bmatrix} \frac{-R_c}{L_c} & \omega \\ -\omega & \frac{-R_c}{L_c} \end{bmatrix}\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} D_{nd} \\ D_{nq} \end{bmatrix}\frac{U_{DC}}{2} - \frac{1}{L_c}\begin{bmatrix} u_d \\ 0 \end{bmatrix}. \quad (16)$$

The homo polar component is omitted.

5. CURRENT CONTROL TECHNIQUE AND SVPWM FOR NPC VSI

The current control should be developed to reduce overshoot, to obtain high accuracy and fast dynamic response to provide load active and reactive powers and also to reduce the total harmonic distortion in currents compensation. From model (16) two equations to be controlled in two different and independent loops. By considering $\lambda = L_c\frac{di_c}{dt} + R_c i_c$ switching state function as the original control inputs can be calculated as follows [7]:

$$D_{nd} = 2\frac{\lambda_d - L_c\omega i_c + u_d}{U_{DC}} \quad (17)$$

$$D_{nq} = 2\frac{\lambda_d + L_c\omega i_{cd}}{U_{DC}} \quad (18)$$

The inputs D_{nd} and D_{nq} are components of two different compensation term. To obtain a fast dynamic response and zero steady state errors, a PI type regulator is needed.

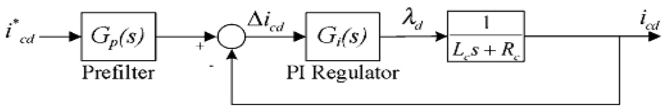

Fig. 4 Inner current control loop of i^*_{cd}

To design PI regulator in circuit of current controller, it is necessary to decouple the model of the system by adding the measured voltage of d-axis and cross coupling terms are needed. The closed loop transfer function of the PI regulator and transfer function of the pre filter was given in [8]. This current control technique can supply load active power, and supply load reactive power and reduce the total harmonic distortion by providing an appropriate control to SVPWM.

Various pulse width modulation algorithms have been studied for current control in multilevel inverters. SVPWM is the best method is for current control. The advantages of SVPWM are fast dynamic response and wide linear range of fundamental voltage compared to conventional PWM. By applying this technique to the diode clamped inverter and flying capacitor inverter it solves the neutral point balance problems.

Many modulation techniques have been studied to realize the switching state functions in rotating synchronous reference frame, i.e.,D_{nd} $andD_{nq}$. SVPWM stands out for three phase three wire distribution system for current control. SVPWM offers high flexibility to optimize switching waveforms and also reduces the switching losses. It can also increase the fundamental component of voltage up to 27.39% that of SPWM. In order to make an appropriate selection of D_{nd} $andD_{nq}$, the space phase's plane is first subdivided in to six 60^0 sectors 1, 2, 3…….., 6.[9], [10].

6. SIMULATION RESULTS

The performance of the proposed current control approach for three level NPC VSI as an interfacing circuit for integration of renewable energy resources in to AC grid is validated by simulation of the circuit in MATLAB/SIMULINK environment. The schematic diagram of the three-level NPC VSI as an interfacing circuit for integration of renewable energy resource in to AC grid is shown in Fig. (5). Fig. (6) Depicts the simulation diagram of wind power generation by using PMSG. The simulation parameters are given in appendix.

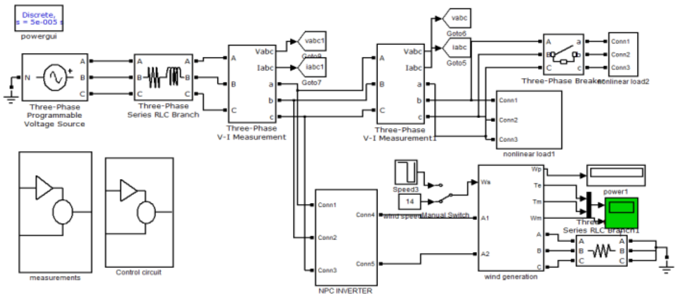

Fig. 5 Schematic diagram of shunt connected renewableenergy resource in to AC grid using NPC inverter

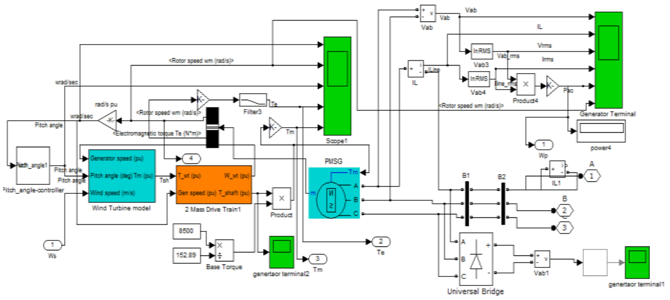

Fig. 6 Wind power generation by using PMSG

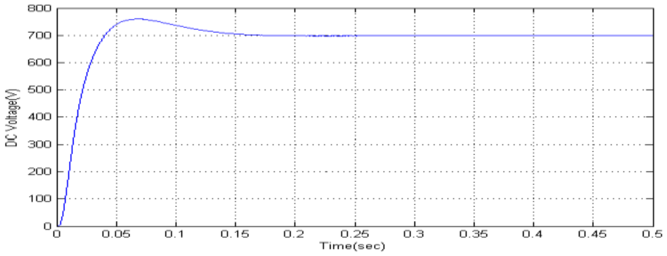

Fig.7 the DC voltage obtained by wind power generation.

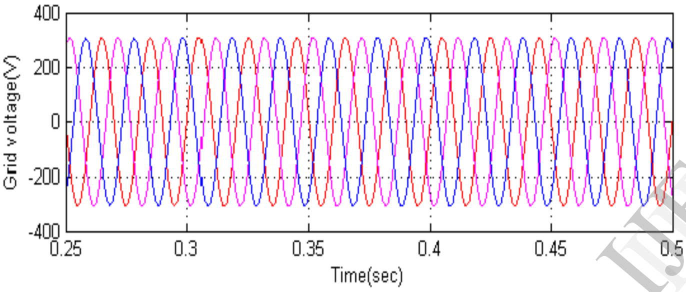

Fig. 8 Grid voltage

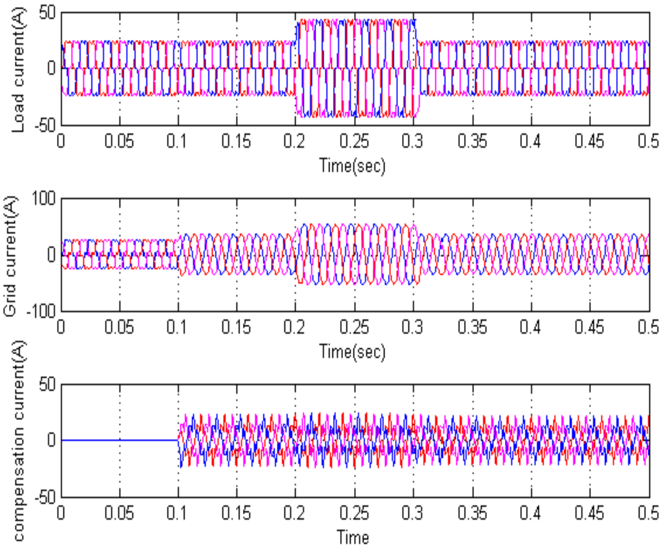

Fig. 9 Load current, grid current, compensating currents before after connecting three level NPC VSI as an interfacing circuit for integration of renewable energy resources in to AC grid.

$P_{Load} = 8KW\ and\ Q_{Load} = 6Kvar$, and maximum active power of proposed converter is set to constant ($P_{ref} = 8KW$). The renewable energy resource is connected to the distribution grid at t = 0.1 s Via NPC VSI as an interface to the AC grid. This process is continued until t = 0.2 s; at this moment an extra load prior to similar non linear load is connected to the PCC and the extra load is disconnected at t =0.3s. Fig. 9 shows the simulation results of three phase load currents, grid currents and inverter currents during a non linear load is connected to the distribution grid. Here renewable energy resource is connected via three level NPC VSI. When a non linear load is connected it produces the harmonic currents which disturb the grid currents and these currents were compensated by drawing the current from NPC VSI. Hence the non linear load current was supplied by renewable energy source Via NPC VSI. Hence NPC VSI act as an shunt active power filter.

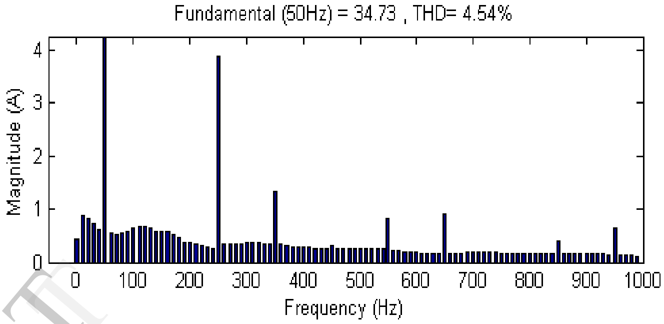

Fig. 10 THD of current spectra after connection of NPC VSI

Similarly the proposed control technique is verified by using two level inverter and unbalanced load condition. The THD‘s also listed in table 2.

TABLE 2
THD OF CURRENT SPECTRA

Current Spectra	THD for Load current (A)
Uncompensated current	THD=24.51%
Compensated current with two level VSI	THD=11.83%
Compensated current with NPC VSI	THD=4.54%
Unbalanced current with NPC VSI	THD=2.69%

6. CONCLUSION

In this paper, the performance of three level NPC VSI to integrate renewable energy resource in to AC grid was presented. The high performance of the proposed control strategy has been verified through simulation results. The dynamic model of NPC VSI during integration of renewable energy resource in to AC grid is investigated. Simulation results clarified the ability of control scheme in compensation of load active and reactive power. We can observe that for three level NPC VSI THD of current is less compared to two level inverter as interfacing circuit to integrate renewable energy in to AC grid. The proposed control scheme has the ability to be used in all types of converter topologies and can be used as a multi objective strategy for integration of renewable energy resources in to AC grids.

APPENDIX

Parameters for simulation are as follows: $V_s(line) = 380V$, f = 50 Hz, R_s = 0.1Ω, L_s = 0.1mH, $R_c = 0.1\Omega, L_c = 0.045\ H, and\ V_{DC} = 700\ V,$ where the transformer parameters are included in$R_c\ and\ L_c$.

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