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Leakage Current and Harmonic Reduction in Transformerless Grid Connected PV Systems

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***Abstract*— The technological advances in the society, demands and consumes more energy, thrusting the government to take more active attitudes on increasing its generation. Due to this renewable energy sources are gaining more importance in the energy scenario. The advances in the technologies associated with the increase of efficiency of solar panels, the photovoltaic solar energy has gained momentum in this new scenario. The absence of galvanic isolation in transformerless PV systems will give rise to capacitive leakage current between the photovoltaic system and the load. The problem of leakage current in the PV will result in current distortions and losses in the system. Also the presence of non – linear loads in a distribution system will inject harmonics in to the system. The main contribution of this paper is to reduce the current harmonics generated due to nonlinear loads in the distribution system and also to eliminate the leakage current in grounded photovoltaic panels, which is being fed to the shunt active filter. The reduction of leakage current is possible by the control of the common mode voltage by applying appropriate pulse width modulation techniques. For the suppression of harmonics NPC inverter is used as an active filter which makes use of the Instantaneous Reactive Power Theory for suppressing harmonics along with its respective modulation technique for reducing leakage current in PV side. Active Power Filter is connected in shunt with the phases to suppress the current harmonics in the system. The inverter generates a compensating harmonic voltage into the phases connected in shunt with it. The filter current and the harmonics injected in the phases will cancel each other without affecting the fundamental part. Hence the load current distortions are reduced along with reduced leakage current.**

***Index Terms*— Energy conversion, photovoltaic power systems, pulse width modulated power converters, shunt active filter.**

I. INTRODUCTION

In recent years, the increasing demand for energy has stimulated the development of alternative power sources such as photovoltaic (PV) modules, wind turbines, and fuel cells. The PV modules are attractive renewable sources due to their relative small size, noiseless operation, simple installation, and to the possibility of installing them closer to the user. The DC voltage amplitude value is low in case of PV modules. In order to be connected to the grid, the PV modules output voltage should be boosted and converted into an ac voltage [3]. This task can be performed using one or more conversion stages.

Many topologies for PV systems are multi-stage, having a dc-dc converter along with a high-frequency transformer that adjusts the inverter dc voltage and isolates the PV modules from the load [7]. However, the conversion stages decrease the efficiency and make the system more complex [5]. The transformerless centralized configuration with one-stage technology uses only one inverter and a large number of PV modules are connected in series to form strings, are used in order to generate sufficient voltage to connect to the grid [3]. In PV systems where series modules are connected to a conventional two-level inverter, the occurrence of partial shades and the mismatching of the modules lead to a reduction of the generated power. To overcome these problems, the connection of the modules can be made using a multilevel converter. The multilevel converter maximizes the power obtained from the arrays, reduces the device voltage stress, and generates output voltages with lower total harmonic distortion (THD).

Avoiding transformers is a benefit of multilevel inverters and normally neutral point clamped (NPC) inverters are not used with transformers. However, in PV applications, the transformerless systems have problems related to leakage currents, thus it is necessary to pay special attention to this issue [4]. The main disadvantage of the topologies without transformer is the connection of the PV array to the grid without galvanic isolation. Thus, the fluctuations in the potential between the PV array and ground give rise to capacitive leakage current and these currents can cause grid current distortion and losses in the system [9].

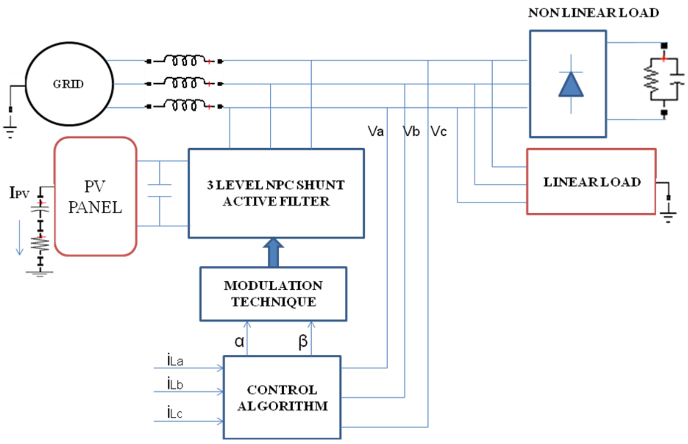

Fig.1 Block Diagram of the Project

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The paper is organized as follows: in Section 2, common-mode voltages (CMV) and leakage currents in three-level inverters are analyzed. In Section 3, modulation techniques for three-phase NPC inverters are proposed in order to eliminate the leakage current in transformerless PV systems. In Section 4, Simulation results of NPC inverters with different modulation techniques for three-phase systems are compared based on the leakage currents. In Section 5, Conclusion and Future Scope are discussed.

II. COMMON-MODE VOLTAGES IN PV FED INVERTERS

In transformerless grid connected PV systems, there is a connection between the grid and the dc source and thus, a leakage current appears through a circuit that is created if the PV array is grounded.[4]

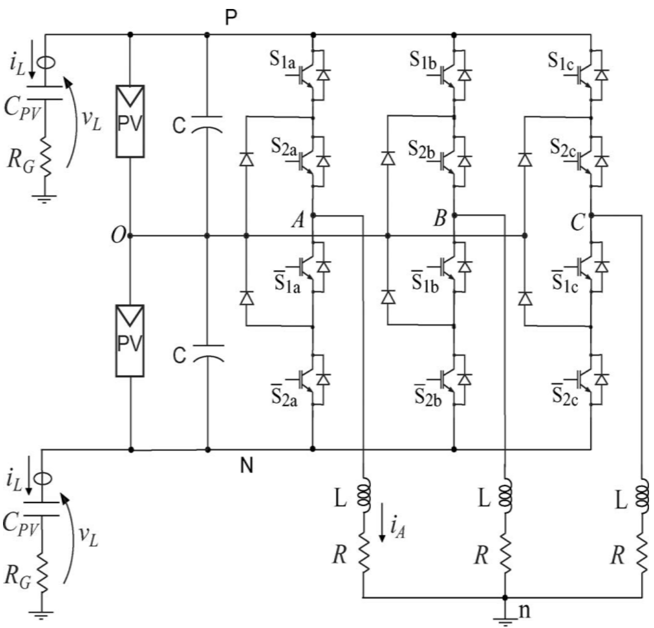

Fig.2 Three phase three level NPC inverter connected to RL load and fed by PV system

The leakage current can reach high values therefore becoming an important issue in transformerless PV systems. It is possible to express the voltages between the positive (P) or negative (N) dc bus and the neutral (n) V_{Pn} or V_{Nn} in terms of the inverter output voltages

$$V_{Nn} = V_{kn} - V_{kN} \tag{1}$$

$$V_{Pn} = V_{Nn} - V_{PN} \tag{2}$$

Where k = A, B, C

$$V_{An} + V_{Bn} + V_{Cn} = 0 \tag{3}$$

Under balanced operation, the above condition for the inverter voltages can be observed.

A. Common Mode Voltage

The common mode voltage is defined as the average of the voltages between the output and a common reference at the input. The common mode voltage for the shown Fig 2 is given by

$$V_{CM} = \frac{V_{AN} + V_{BN} + V_{CN}}{3} \tag{4}$$

Using equation (1) and (3) we can state that

$$V_{Nn} = -\frac{V_{AN} + V_{BN} + V_{CN}}{3} \tag{5}$$

Using equation (4.2) and (4.3) we can state that

$$V_{Pn} = V_{PN} - \frac{V_{AN} + V_{BN} + V_{CN}}{3} \tag{6}$$

On comparing equation (5) and (6) with (4) the voltage values of V_{Pn} & V_{Nn} are written in terms of common mode voltage as

$$V_{Nn} = -V_{CM} \tag{7}$$

$$V_{Pn} = V_{PN} - V_{CM} \tag{8}$$

It is therefore found that from equations (7) and (8), the leakage currents can be attenuated by the control of the CMV.

III. TECHNIQUES FOR LEAKAGE CURRENT REDUCTION

A. Space Vector Modulation

The space vector PWM (SVPWM) is generally used to control the three-level inverter output voltages with the sequence of steps which is shown in Fig 4. SVPWM algorithm uses a simple mapping strategy to generate gate signals for the inverter. The location of the reference vector and time are easily determined and there are 19 possible space vectors as shown in Fig 3. [6] [10]

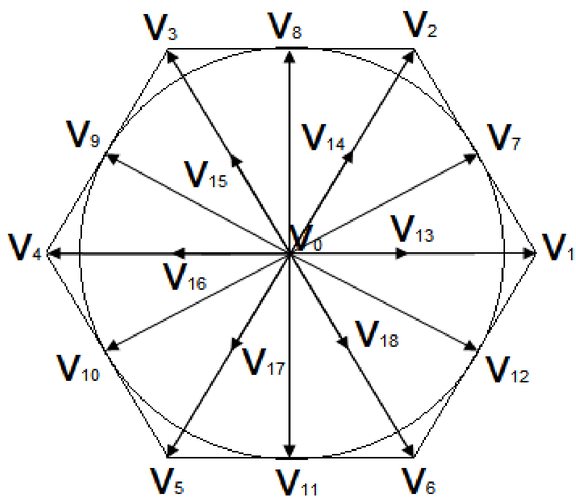

Fig.3 Space Vector Diagram for Three Level Inverter

One zero vector V_0 with three switching possibilities, six long vectors (V_1,V_2,V_3, V_4,V_5 and V_6) six medium vectors (V_7,V_8,V_9,V_{10},V_{11} and V_{12}) and six small vectors (V_{13},V_{14},V_{15},V_{16},V_{17} and V_{18}) with two switching possibilities each, which total to 27 possible switching combinations.[1]

Table 1: Space Vector for Possible Combinations of the Inverter Switches

S_{1a}	S_{2a}	S_{1b}	S_{2b}	S_{1c}	S_{2c}	VECTOR	V_{CM}
0	0	0	0	0	0	V_{01}	0
1	1	1	1	1	1	V_{02}	V_{PN}
0	1	0	1	0	1	V_{03}	$(1/2)V_{PN}$
1	1	0	0	0	0	V_1	$(1/3)V_{PN}$
1	1	1	1	0	0	V_2	$(2/3)V_{PN}$
0	0	1	1	0	0	V_3	$(1/3)V_{PN}$
0	0	1	1	1	1	V_4	$(2/3)V_{PN}$
0	0	0	0	1	1	V_5	$(1/3)V_{PN}$
1	1	0	0	1	1	V_6	$(2/3)V_{PN}$
1	1	0	1	0	0	V_7	$(1/2)V_{PN}$
0	1	1	1	0	0	V_8	$(1/2)V_{PN}$
0	0	1	1	0	1	V_9	$(1/2)V_{PN}$
0	0	0	1	1	1	V_{10}	$(1/2)V_{PN}$
0	1	0	0	1	1	V_{11}	$(1/2)V_{PN}$
1	1	0	0	0	1	V_{12}	$(1/2)V_{PN}$
0	1	0	0	0	0	V_{131}	$(1/6)V_{PN}$
1	1	0	1	0	1	V_{132}	$(2/3)V_{PN}$

The switching states for obtaining the space vectors located in the region from 0^0 to 360^0 of the α–β plane were presented in Table 1.Their corresponding CMV were also presented along with that. The space vector diagram of the three level inverter has 19 vectors and 27 states. The common mode voltage changes at every instant depending on the vector used for switching the inverter at that particular instant as shown in above table [2]

The modulation index for the space vector pulse width modulation is defined by

$$m = \frac{\sqrt{3}V_{kn}^{*}}{V_{PN}} \qquad (9)$$

where, k = A ,B , C

V_{PN} - Total dc link voltage

V_{kn}^{*} - The reference amplitude of the phase-to neutral voltages

The flowchart of operation is shown in below diagram wherein sector selection and switching vector determination plays an important role in the generation of gate pulses which are applied to the inverter

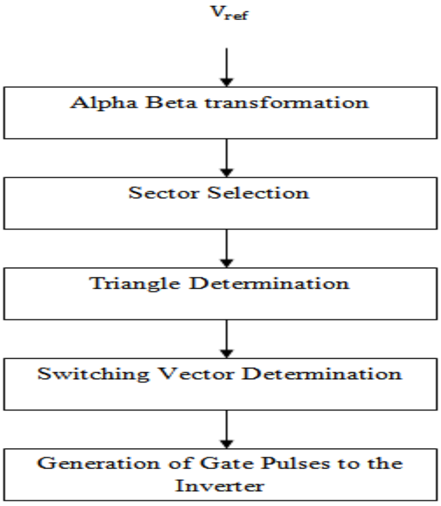

Fig.4 Flowchart Operations Involved in SVPWM

B. PWM with Three Medium Vectors

Studying the vector space for the NPC three-level inverter, it is possible to define some vector combinations that are capable of reducing the leakage currents in PV systems. The first alternative is applying of the three medium vectors (3MV) nearest to the reference to compose the vectors as shown in Figure 5.

Therefore, if the reference voltage vector is in the region between vectors say V_1 and V_2.That is V_7 is the medium vector in the chosen interval while V_8 &V_{12} are the vectors nearest to V_7. The switching pattern for 3MV is shown in Table 2. The vectors are switched as in a pattern which is shown in Table 2. In that switching is given based on the respective state of the chosen vector. Here the Vectors for an interval of 60^0 unlike the SVPWM technique where vector for each 30^0 are chosen. Here as cited from Table 2 due to the use of only medium vectors the common mode voltage is maintained constant thus reducing the leakage current. [8]

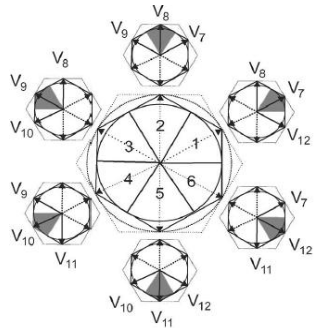

Fig.5 Vectorial Space for 3MV

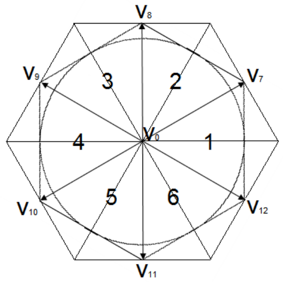

Fig.6 Vectorial Space for 2MV1Z

C. PWM with two medium and one zero vectors

The second alternative consists of using only the medium vectors and specific zero vector which has V_{CM} = $V_{PN}/2$(which is termed as 2MV1Z) to compose the reference vector as shown in Fig 6. Considering the region between vectors V_{12} and V_7 (ie., -30^0 to 30^0), the vectors V_{12} , V_7 and V_0 (with $V_{CM} = V_{PN/2}$) are used. In any option, it can be seen that the CMV always assumes the value $V_{PN}/2$. The switching pattern for the 2MV1Z is shown in Table 4.2.

In this Technique two patterns will appear for each sector and also a pattern remains for an interval of about 60^0. That is each pattern is present for an interval of about 30^0 of one sector and another 60^0 in the next sector. For example if we consider the interval (-30^0 to 30^0),(-30^0 to 0^0) belongs to the 6^{th} sector and interval (0^0 to 30^0) to the 1^{st} sector of the Fig 4

Table: 2 Switching Pattern for SVPWM, 3MV and 2MV1Z modulation Techniques from 0^0 to 180^0

Sector No	Region in Degrees	Vectors for SVPWM	Vectors for 3MV	Vectors for 2MV1Z
1	0 – 30	1 – 7 – 13– 7 – 1	12 – 7 – 8– 7 – 12	12 – 7 – 0 – 7 – 12
	30 – 60	7 – 14 – 2 – 14 – 7	12 – 7 – 8– 7 – 12	7 – 8 – 0 – 8 – 7
2	60 – 90	2 – 14 – 8– 14 – 2	7 – 8 – 9 – 8 – 7	7 – 8 – 0 – 8 – 7
	90 – 120	8 – 15 – 3– 15 – 8	7 – 8 – 9 – 8 – 7	8 – 9 – 0 – 9 – 8
3	120 – 150	3 – 15 – 9 – 15 – 3	8 – 9 – 10 – 9 – 8	8 – 9 – 0 – 9 – 8
	150 – 180	9 – 16 – 4 – 16 – 4	8 – 9 – 10 – 9 – 8	9 – 10 – 0 – 10 – 9

The above modulation techniques were applied to the three phase three level PV fed NPC inverter to produce the output voltage with minimal leakage current.

IV. INSTANTANEOUS REACTIVE POWER THEORY

The instantaneous reactive power theory is used to extract the fundamental component in the supply voltage or current.

The theory of active and reactive instantaneous power, or simply pq Theory Akagi was proposed in 1983 for control of current harmonics. This theory was initially developed for making three-phase system and a processing system stationary ABC reference coordinates, to a coordinate system $\alpha-\beta-0$. This transformation is known as the Clarke transform, which produces a system also the stationary reference where the coordinates $\alpha-\beta$ are orthogonal to each other and coordinate 0 corresponds to the zero sequence component.

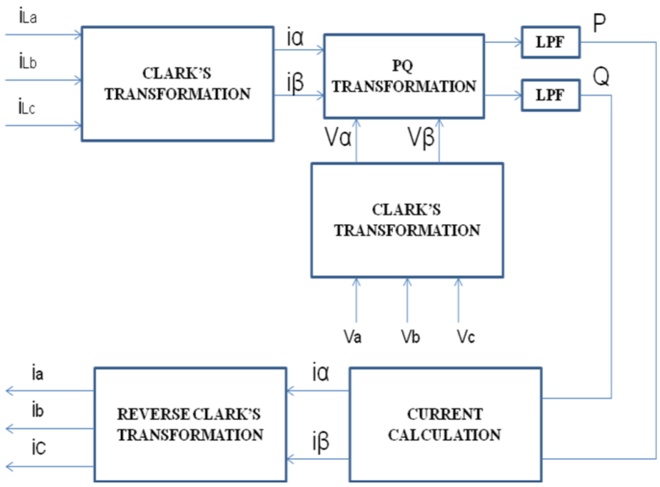

Fig: 7 Instantaneous Reactive Power Theory

A.Clarks Transformation

The Clark transform is applied in the phase voltages and currents in the load is given by

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{11}$$

This transformation has the advantage of allowing separate component sequence present at zero voltage and the current (v_0 and i_0).

B. Power Calculation (pq Theory)

The instantaneous power in three-phase abc axes is calculated as follows:

$$p_3 = p_a + p_b + p_c = v_a i_a + v_b i_b + v_c i_c \tag{12}$$

Axes a-b-c instantaneous phase power is given by

$$p_3 = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{13}$$

This power may be separated into two components:

$$p_3 = p + p_0 \tag{14}$$

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{15}$$

$$p_0 = v_0 i_0 \tag{16}$$

The p component matches the actual instantaneous power and p0 component corresponds. The instantaneous power in zero sequence. The output power q corresponds to the imaginary instant:

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \tag{17}$$

With certain voltages and currents in coordinates $\alpha-\beta-0$, we can calculate the real power (p), the instantaneous imaginary power (q) and zero-sequence power (p0) in matrix form:

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{18}$$

The three-phase instantaneous power (p3) is the sum of the instantaneous real power (p) power and zero sequence (p0). The zero sequence power only exists when is faced with a system that contains voltage and current zero sequence. Thus, if a these electrical quantities do not have zero sequence component, the instantaneous power phase (p3) is numerically equal to the instantaneous real power (p).The instantaneous imaginary power (q) can be understood as a power that flows enters phases in the electrical system, with no three-phase power flow between the source and load.

The instantaneous imaginary power abc the axes is calculated as follows:

$$q = \sqrt{\frac{2}{3}} \cdot \left(v_a - \frac{v_b}{2} + \frac{v_c}{2}\right) \cdot \frac{1}{\sqrt{2}} \cdot (i_b - i_c) - \frac{1}{\sqrt{2}} \cdot (v_b - v_c) \cdot \sqrt{\frac{2}{3}} \cdot \left(i_a - \frac{i_b}{2} + \frac{i_c}{2}\right) \tag{19}$$

Axes $\alpha-\beta-0$ instantaneous imaginary power is given by:

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \tag{20}$$

The power q differs from conventional three-phase reactive power, since it all harmonic voltage and current are also considered. It is noted that the components p and q do not depend on the zero-sequence voltage and current component but only on the components α and β. Thus the power can be written as in the following equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{21}$$

C. Reference Current Calculation

The powers of reference $\alpha-\beta-0$ can be divided in their middle and alternating values, each having the following meaning

$\bar{p}$ - It is the average value of the instantaneous real power. It is the average energy per unit time transferred evenly from the source to the load.

$\tilde{p}$ - It is the alternate value of the instantaneous real power. It is the energy exchanged between the source and the load. This portion should be compensated for not having transferred between the source and load.

q- Instantaneous imaginary power. Does not match any exchange or transfer energy between the source and the load. This portion may also give rise to non-current desired and thus, should be compensated. This power may be further divided into two components, continuous, $\bar{q}$ alternating, $\tilde{q}$. In some cases where there is distortion or imbalance in the source $\bar{q}$ correspond to q.

$\bar{p}_0$- It is the average value of the instantaneous power of zero sequence. It is the energy per unit time transferred from source to load through the zero sequence components of voltage and current at coordinates $\alpha - \beta - 0$.

$\widetilde{p_0}$ - It is the alternate value of the instantaneous power of zero sequence. It is the energy per unit time exchanged between the source and the load through the following components zero voltage and current in the coordinates $\alpha - \beta - 0$.

Thus, the powers to be compensated are:

$$p_x = \tilde{p} - \bar{p}_0 \quad (22)$$

$$p_x = q \quad (23)$$

In practice it is desirable to compensate for all the powers, allowing only $\bar{p}$ is delivered to the load by source. The control tries to maintain the DC bus voltage level (s) of capacitor (s) in levels Suitable causing SAF work properly. The pq theory calculations allow a simple method to adjust and regulate the tension.To control the voltage of the DC bus of NPC it is necessary to calculate two powers of regulation (p_{reg}). As the DC bus lies divided, it is necessary adjust the tension of the two bus capacitors. Then you must charge the capacitor higher in the positive half cycle of the line voltage, when he can absorb energy source and for charging the lower bus capacitor, one should expect the negative half cycle of voltage.

The value preg can be obtained through a proportional controllerK_p. So

$$p_{regx} = K_p.(v_{ref} - V_{dcx}) \quad (24)$$

Where,

p_{reg} - Power regulation

K_p - Proportional gain

v_{ref} -Reference voltage

X - For higher 1-and 2-bus for the lower bus.

Importantly, the p_{reg1} only exist in the positive half-cycle of the network and the p_{reg2} negative half cycle. Thus, the p_{reg} assumes a different value for each half cycle of the voltage Network.

$$p_{reg} = p_{reg1} + p_{reg2} \quad (25)$$

This power of regulation, p_{reg}, is included with a negative sign in the value of real power instant to be compensated, so p_x:

$$p_x = \tilde{p} - \bar{p}_0 - p_{reg} \quad (26)$$

Proceeding from the point that only $\bar{p}$ is delivered to the load, as said above, can calculate the compensation currents from the inverse equations

$$i_0 = \frac{1}{\sqrt{3}}.(i_a + i_b + i_c) \quad (27)$$

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2}.\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}.\begin{bmatrix} \tilde{p} - \bar{p}_0 - p_{reg} \\ q_x \end{bmatrix} \quad (28)$$

In these expressions, p_x, q_x and p_{0x} are the powers to be compensated allowing just to select the value for offset (p_0, $\bar{p}_0$ and $\widetilde{p_0}$ or even a portion of these powers). The current values in the equation 28 are again converted to three phase quantities using inverse clark's transformation. This is made use of as the reference signal which is to be given to the modulation technique to produce gate pulses for the inverter

V. RESULTS AND DISCUSSIONS

This paper addresses the problem of Leakage current in photovoltaic systems, the current harmonics due to nonlinear loads and the techniques that were employed to eliminate them. Three modulation techniques namely SVPWM, 3MV, 2MV1Z power theory applied for inverter switching have been simulated along with instantaneous reactive using Matlab simulink and their corresponding results are being discussed in this session.

A.Space Vector Pulse Width Modulation Technique (SVPWM)

In this case the leakage current oscillated between the value to about 750 mA. But according to german standards the leakage current should be maintained below 300 mA for the proper operation of the PV and to reduce losses and current distortions.Due to the presence of leakage current the load current of the inverter seems to be distorting due to which the load current THD reaches a value of 7.08%. While implementing this to the shunt active filter the harmonics due to non linear load will also gets reduced to 9.94%.

B. PWM with Three Medium Vector

In this technique only medium vectors that produce constant common mode voltage is used hence the leakage current is also minimised to nearly below the value of 10 mA here the zero level is not present because only the medium vectors were used and the zero vectors have been eliminated for generating the output voltage.Due to the reduction in leakage current the current become more sinusoidal so that the load current THD on the distribution side also gets reduced.

C.PWM with Two Medium and One Zero Vectors

In case of the three medium technique the zero voltage stage is not present in the output voltage as the technique does not uses any zero vector.Hence a zero vector having the same common mode voltage of the medium vectors is also included so that we can obtain a three level output even after the reduction of leakage current.So this technique uses two medium one zero vector for switching at every instant.The leakage current on PV side and the load current THD were reduced and while comparing to the space vector pulse width and three medium vector modulation techiques.

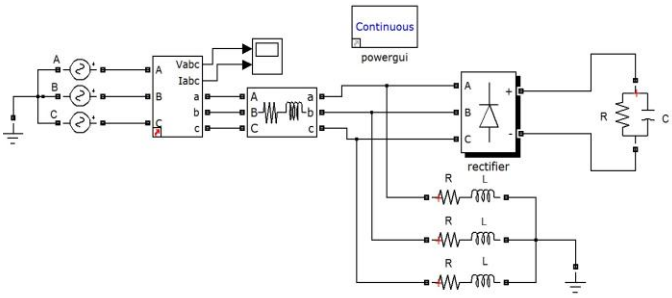

Fig.7(a) Model of System Connected to Non Linear Load Without Filter

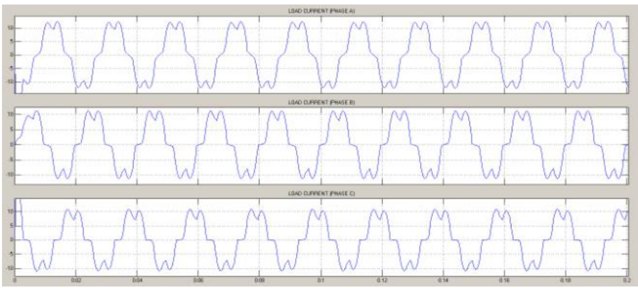
Fig.7(b) Current Waveform without Filter

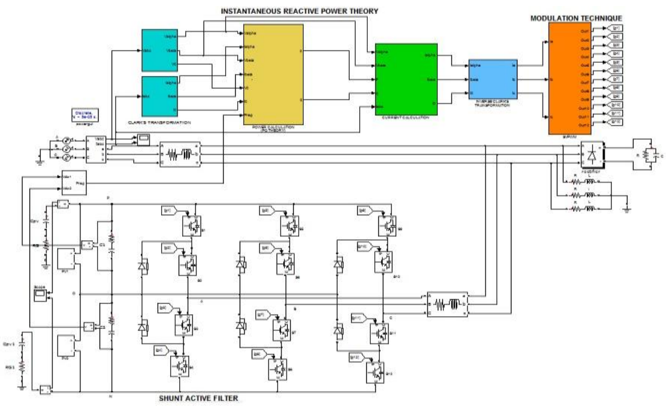

Fig.8 Model of System Connected to Non Linear Load With Filter

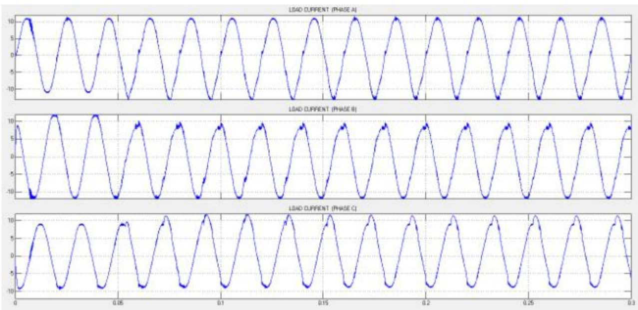
Fig.9(a) Current Waveform with Filter using SVPWM

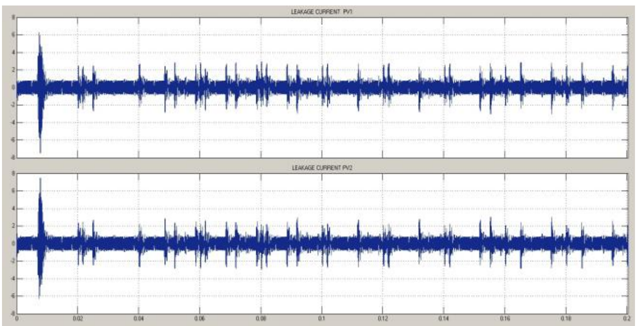
Fig.9(b) Output of leakage current in PV module using SVPWM

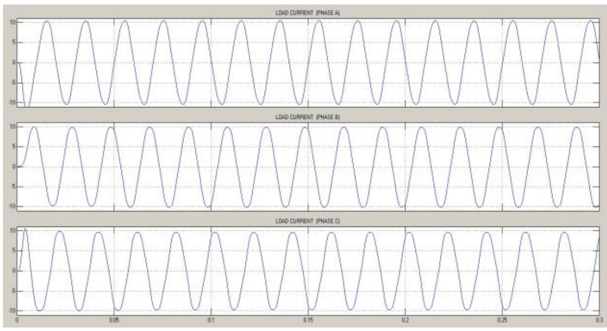
Fig.10(a) Current Waveform with Filter using 3MV Technique

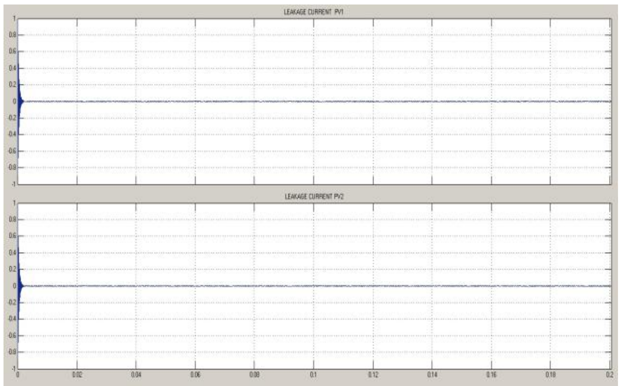
Fig.10(b) Leakage current in PV module using 3MV Technique

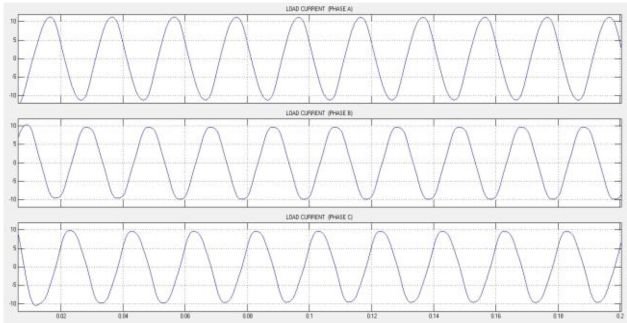
Fig.11(a) Current Waveform with Filter using 2MV1Z Technique

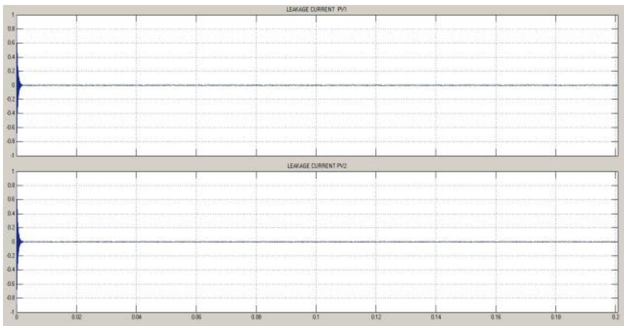
Fig.11(b) Leakage current in PV module using 2MV1Z Technique

D.Comparitive Analysis of The Modulation Techniques

The SVPWM, 3MV and 2MV1Z modulation methods are used for the analysis of leakage current. For reduction of Leakage current the common mode voltage should be maintained constant this is realized by the modulation techniques. The comparison of results using the above mentioned methods are given in the following Table 3

Table:3 Comparison of the Results

MODULATION TECHNIQUE USED	COMMON MODE VOLTAGE	LEAKAGE CURRENT	CURRENT THD %
SVPWM	Variable	>300mA	9.94
3MV	Constant	<300mA	2.93
2MV1Z	Constant	<300mA	2.7

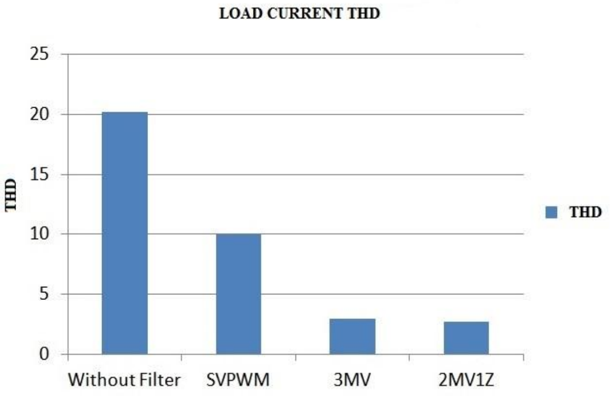

Fig.12 Comparision of THD Values with and without Filter

In accordance with the German Standard VDE 0126-1-1 300mA is used as the reference rms value for representing the Leakage current. As stated earlier the current THD reduces with the reduction in leakage current. Using SVPWM the CMV jumps between different levels with a high frequency resulting in high leakage currents. From these methods it is proved that the 3 MV and 2 MV1Z techniques were proved to be efficient methods for reducing leakage current and also the load current harmonics.

VI. CONCLUSION

The problem of leakage current in PV arrays has been the motivation for the development of this work. A multilevel inverters study was conducted to determine the best topology adjustment that has to be made in the technique. Three level Neutral point clamped inverter is chosen

In this proposed model, three possibilities of modulation techniques are described. Space vector pulse width modulation, 3MV pulse width modulation, 2MV1Z pulse width modulation techniques are designed for three phase transformerless photovoltaic systems are proposed. For achieving constant common-mode voltage, the inverter switches are controlled by using only medium vectors and one specific zero vector. Simulation results of the neutral point clamped inverter fed by photovoltaic arrays are presented to validate the theoretical models. This 2MV1Z technique better solves the problem of current dispersion in the distribution system with three level output voltage and also reduces the leakage current compared to other techniques.

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