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Hysteresis Current Controller based Transformerless Split Inductor-NPC - MLI for Grid Connected PV- System

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Abstract

Non-conventional energy sources are breeding more and more widespread, mainly due to the fact of that they generate energy by keeping the spotless environment. The Multilevel inverters are highly being used in high-power medium voltage applications due to their better performance compared to two-level inverters. Among various types of multilevel inverters, neutral point clamped multi-level inverter (NPC-MLI) is suitable for a transformerless photovoltaic (PV) grid-connected system. Eliminating the leakage current is one of the most key issues for transformerless inverters Split Inductor MLI (SI-MLI) in grid-connected PV system applications, where the technical challenge is how to keep the system common-mode voltage constant to eradicate the leakage current & shoot-through possibility. The proposed elite Hysteresis Current Control (HCC) offers an admirable current control performance to SI-NPC-MLI. It is performed based on the error current value (Δi) and hysteresis Band value (h) produced between SI-MLI and grid. The proposed SI-NPC-MLI-HCC topology is guarantees for no shoot-through possibility and also maintains lower Voltage and current total harmonics distortion (THD). Test results verify the theoretical analysis and the validity of the system is verified through MATLAB/Simulink and the results are compared with conventional topologies

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Keywords: Photovoltaic (PV) system, Grid connected system, Neutral point clamped three-level inverter (NPCTLI), Transformerless Split Inductor, Hysteresis current control (HCC).

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Nomenclature

| | | | |
|----------------|---|------------|--|
| V_{dc} -link | Applied dc voltage | f_s | Switching Frequency |
| PWM | Pulse Width Modulation | CBPWM | Carrier Based Pulse Width Modulation |
| NPC-MLI | Neutral point Clamped Multilevel Inverter | SI-NPC-MLI | Split Inductor Neutral Point Clamped Multilevel Inverter |
| n | Number of Levels | Δi | Error Current |
| SVPWM | Space Vector Pulse Width Modulation | SVM | Space Vector Modulation |
| HCC | Hysteresis Current Controller | THD | Total harmonic distortion |
| V_{c1} | Voltage across Capacitor C1 | V_{c2} | Voltage across Capacitor C2 |
| V_{pv} | PV Voltage | PV | Photovoltaic Array |
| I_{pv} | PV Current | MPPT | Maximum Power Point Tracking |
| h | Hysteresis Band | i_{act} | Actual Current |
| I_{ref} | Reference Current | P&O | Perturb & Observe |
| Δ_p | Change in Power | Δ_i | Change in Current |

1. Introduction

Photovoltaic (PV) power generation is a reliable and economical source of electricity in rural areas and plays an significant role in the development of distributed electric power systems. Photovoltaic (PV) systems are solar energy supply systems, which either supply power directly to electrical equipment or feed energy into the public electricity grid. Usually, photo voltaic are considered as an expensive method of producing electricity [1]. Solar energy can be exploited in two major ways. Firstly, the captured heat can be used as solar thermal energy, with applications in space heating. Another alternative is the conversion of incident solar radiation to electrical energy, which is the most usable form of energy. This can be achieved with the help of solar photovoltaic cells [2] or with concentrating solar power plants. The grid-connected PV system does not require a battery because the grid can store the power generated by the PV array. However, it's a pity that the PV array loses the output capability when the insolation is scrawny or it is night, which forces the whole system to be removed from the grid [3]. Transformerless split inductor neutral point clamped multilevel inverter avoids the usage of transformer for connecting the inverter with grid system [4]-[5]. Topologies without a transformer generally have lower cost, size, and weight than topologies with transformers.

The main disadvantage is the connection of the PV array to the grid without galvanic isolation, which raises the leakage current through the parasitic capacitance of the PV array. Due to this capacitance and depending on the inverter topology and the switching strategy, fluctuations of the potential between the PV array and the ground can appear. These fluctuations inject a capacitive leakage current, and this current can cause grid current distortion, losses in the system, and safety problems and furthermore, the in-grid current harmonics and losses are increased [6]. In transformerless PV systems that use the connection between the neutral of the grid and the central point of the dc link, the leakage currents have low values because the potential between the PV array and the ground is constant.

Neutral point clamped three-level inverter (NPCTLI) [7] is widely adopted in a transformerless PV system [8], [9]. The NPCTLI's topology can overcome the problems of leakage current and restrict the dc component injected to the grid. The NPCTLI's topology can overcome the problems of leakage current and restrict the dc component injected to the grid. However, like other bridge-type inverters, shoot-through problem exists also in bridge leg of NPCTLI, which is a major killer of the reliability. So enhancing its reliability is worth considering [10]-[11].

Transformerless split inductor neutral point clamped multilevel inverter (SI-NPC-MLI) evades the usage of transformer for connecting the inverter with grid system [5]-[6]. O. Lopez et al [7] while using transformer, leakage current should be increasing in the system, which causes grid current distortion and safety problems. Topologies without a transformer generally have lower cost, size, and weight than topologies with transformers. In transformerless PV systems that use the connection between the neutral of the grid and the central point of the dc link, the leakage currents have low values because the potential between the PV array and the ground is constant.

I.Takahashi et al [8] neutral point clamped three-level inverter (NPCTLI) is widely adopted in a transformerless PV system [9], [10]. The NPCTLI's topology can stuned the problems of leakage current and restrict the dc component injected to the grid. The NPCTLI's topology can overcome the problems of leakage current and restrict the dc component injected to the grid. However, like other bridge-type inverters, shoot-through problem exists also in bridge leg of NPCTLI, which is a major killer of the reliability. So augmenting its reliability is worth considering [11] & [12].

In [13] the grid integration of the PV system is carried out via a three phase three level neutral point clamped inverter. To control the inverter a modified version of voltage oriented control process and the space vector pulse width modulation technique have been applied. With the proposed modification the PV system operates as a shunt active power filter, a reactive power compensator, and a load's current balancer simultaneously.

J.L.Munda [14] at el algorithm is used to optimize a 9-rule fuzzy logic controller (FLC) for maximum power point tracking (MPPT) in a grid-connected photovoltaic (PV) inverter. The FLC generates DC bus voltage reference for MPPT. A digital PI current control scheme in rotating dq-reference frame is used to regulate the DC bus voltage and reactive power. Skretas et al [15] presents a hybrid wind-PV power system with application of artificial neural networks for MPPT and inverter output voltage regulation. A variable structure controller tuned using PSO for inverter voltage regulation in distributed generation system.

Transformerless SI-NPC-MLI for grid connected PV system for single phase was proposed [16]-[18]. There is large voltage stress on the power devices. In order to solve the aforesaid problems, the multilevel leg structure was introduced. For controlling the inverter, hysteresis current control applied.

In [19] & [20] Hysteresis current control (HCC) strategy for three-phase neutral-point (NP)-clamped inverters. The main mission of this control technique is to force the actual current vector to reach the reference current vector. Then, according to the location of this error vector, a selection process of the next applied vector is used to minimize the error vector. Parameters for choosing the fixed bandwidth values are grid voltage, PV voltage, switching frequency and inductances. Based on the single phase SI-NPC-MLI structure, approached for three phase SI-NPCTLI system using PI controller for tuning the reference currents. Achieved the leakage current, low voltage stress on the power device using Transformerless grid-connected inverter with high reliability and avoid shoot through problems as well. Simulation results of this proposed system analysed using MATLAB SIMULINK.

2. PV Array and MPPT Algorithm

2.1 PV modelling

A photovoltaic cell is a semiconductor device that converts light to electrical energy by photovoltaic effect [6] & [7]. A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array. Typically a solar cell can be validated by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current. Equivalent circuit of PV modelling shown in fig.1(a).

Output current from the Photovoltaic array is,

$$I = I_{sc} - I_d \tag{1}$$

$$I_d = I_0 \left(e^{\frac{qV_d}{kT}} - 1 \right) \tag{2}$$

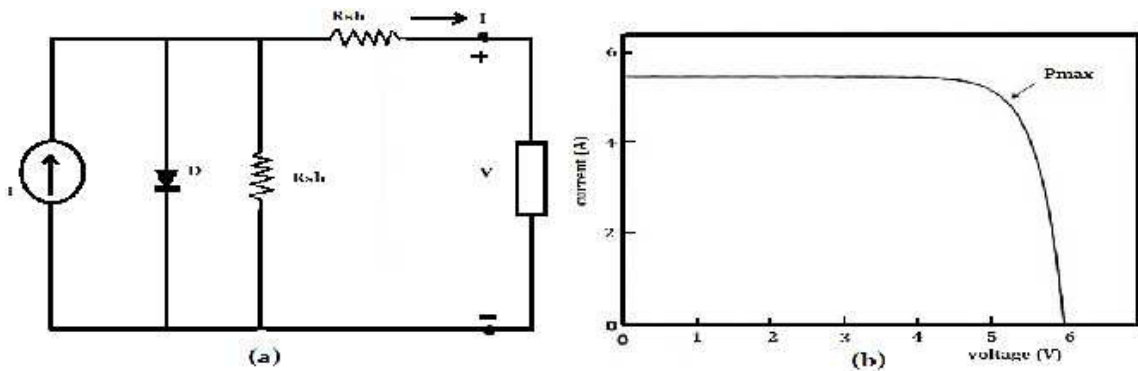


Fig.1. PV modelling a) equivalent circuit of PV system b) I-V characteristics of PV panel

Where \$I_0\$ is the reverse saturation current of the diode, \$q\$ is the electron charge, \$V_d\$ is the voltage across the diode, \$k\$ is Boltzmann constant and \$T\$ is the junction temperature, from equations (1) and (2),

$$I = I_{sc} - I_0 \left(e^{\frac{qV_d}{kT}} - 1 \right) \tag{3}$$

In order to model the solar panel, it requires two diode models but in the proposed technique it is limited to the single diode model. Also, the shunt resistance is very high and can be neglected during the course of the study. The I-V characteristics of a typical solar cell are as shown in the Fig.1b.

2.2 Perturb & Observe

Perturb & Observe (P&O) is the simplest method. In [7], [21] uses only one voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing on both the directions. When this happens the algorithm has reached very close to the MPP and it can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm. However the method does not take account of the rapid change of irradiation level (due to which MPPT changes) and considers it as a change in MPP due to perturbation and ends up calculating the wrong MPP.

The Perturb & Observe algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resultant change in power \$\Delta P\$ is positive (\$\Delta P > 0\$), then it change to shift in the direction of MPP and it keep on perturbing in the same direction. If \$\Delta P\$ is negative (\$\Delta P < 0\$), it leaves away from the direction of MPP and the sign Of perturbation supplied has to be changed. The flowchart for P&O algorithm is shown in fig.2.

In [22] & [23] a situation where the irradiance changes rapidly, the MPP also moves on the right hand side of the curve. The algorithm takes it as a change due to perturbation and in the next iteration it changes the direction of perturbation and hence goes away from the MPP.

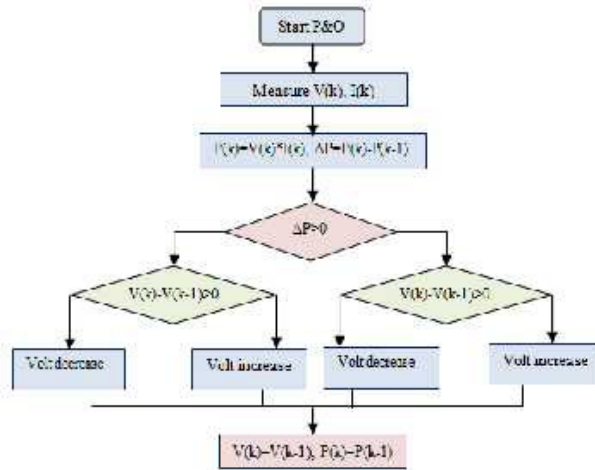


Fig.2. Flow chart of Perturb & Observe algorithm

3. Structure of SI-NPC-MLI and its operations

3.1 Structure of SI-NPC-MLI

As shown in fig.3, three phase three level transformerless split inductor neutral point clamped multilevel inverter having 3 legs; each leg has four switches and two clamping diodes. This SI-NPC-MLI avoids the usage of transformer and used to inter connect PV system with grid connected system.

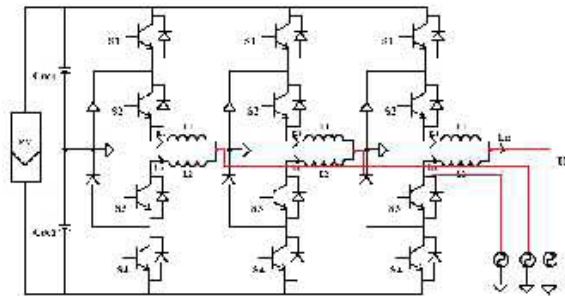


Fig.3. Structure of SI-NPC-MLI

The earth connection point is the important detail in this topology, if the midpoint of PV cluster does not connected to the earth then the output end of the SI-NPCTLI can be connected to the grid freely; otherwise if the midpoint of PV cluster earths, both the midpoint of capacitor’s bridge leg and the midpoint of PV cluster must be connected to the neutral line of the grid.

3.2 Operations of SI-NPC-MLI

By using SI-NPC-MLI, switching and conduction losses are reduced and the efficiency can be improved. The proposed SI-NPCTLI is modulating at half of the line cycle current during charging or discharging time. Before analysis, the following assumptions are given: a) all power switches and diodes are the ideal devices with ignored switching time and zero conduction voltage drop; b) all inductors and capacitors are ideal, and $C_{dc1} = C_{dc2} = C$, $L_1 = L_2 = L$; and c) the inverter operates at the unity power factor, i.e., the inductor current $i_{L1,2}$ is in phase with the grid voltage u_g . Taking the operation during the half-cycle of the positive grid voltage, the detailed analysis of the operation modes is described; it has following four modes of operation for a single leg as shown in fig.4.

Mode 1:

During this mode switches S_1 and S_2 are made to turned ON and S_3 and S_4 are OFF, then the output voltage of the bridge is the voltage across the capacitor C_{dc1} , i.e., getting half of the voltage from the input source (positive voltage), and current $i_{L1,2}$ from the

circuit is depends on the L_1 inductor, shown in fig.4.a

$$L_1 \frac{di_{L1}}{dt} = \frac{1}{2} U_{pv} - u_g \tag{4}$$

Mode 2:

Switches S_2 ON, and S_1, S_3 and S_4 are OFF, the voltage on S_1 is clamped to the half of the input voltage by the diode D_5 , and the output voltage of the bridge leg is zero, current i_{L12} from the circuit is depends on the L_1 inductor, shown in fig.4.b

$$L_1 \frac{di_{L1}}{dt} = U - u_g \tag{5}$$

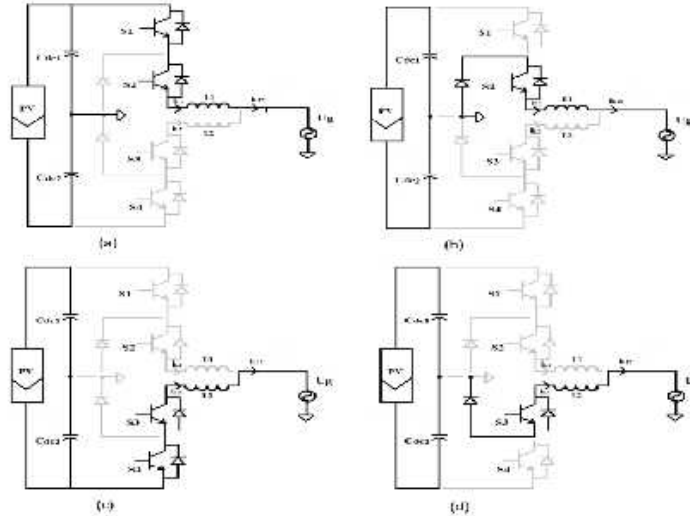


Fig.4. Modes of operation of SI-NPC-MLI (a) mode 1 (b) mode 2 (c) mode 3 (d) mode 4

Table 1. Modes of Operation of SI-NPC-MLI

| Modes | Switches | V1N | V2N | V3N |
|--------|----------------------|--------------------|--------------------|----------------|
| Mode 1 | S1,S2-ON & S3,S4-OFF | U_{pv} | $U_g+(1/2) U_{pv}$ | $(1/2) U_{pv}$ |
| Mode 2 | S2-ON & S1,S3,S4-OFF | $(1/2) U_{pv}$ | $U_g+(1/2) U_{pv}$ | $(1/2) U_{pv}$ |
| Mode 3 | S1,S2-OFF & S3,S4-ON | $U_g+(1/2)U_{pv}$ | 0 | $(1/2) U_{pv}$ |
| Mode 4 | S1,S2,S4-OFF & S3-ON | $U_g+(1/2) U_{pv}$ | $(1/2) U_{pv}$ | $(1/2) U_{pv}$ |

So, during the positive half-cycle of the grid voltage, the output-voltage levels of the bridge leg include zero and $(1/2) U_{pv}$. Similarly, during the negative half-cycle, the output voltage gets the two levels of zero and $-(1/2) U_{pv}$

4. Hysteresis Current Control

In order to ensure the correct multilevel operation, the control system has to fulfil two tasks. It must generate the correct voltage vector and hence, the correct multilevel waveform. At the same time, it must maintain the same voltage across the two capacitors for reducing the capacitor balancing problem and evade of shoot through problems.

4.1 Analysis of the Hysteresis Band (h)

The hysteresis current control can achieve accurate tracking to the inductor current. In order to ensure the zero inductor current before the zero crossing of the grid voltage, the high frequency switching signals must be stopped at the time $x\pi$, and the inductor current may be forced to zero by the grid voltage. Hysteresis current control, which is a nonlinear control method, possesses high

performance, simple realization circuit, high stability, inherent current-limiting capability, and fast dynamic response hysteresis band real-time regulation and the hysteresis band is given in Eq.(8).

$$\text{Hysteresis band (h)} = \frac{U_g(U_{pv} - 2U_g)}{U_{pv} \cdot L_s} \tag{6}$$

The goal of the proposed SVCC is to keep the actual load current close to the reference load current within the hysteresis boundaries. The reference load current $i_{L \text{ ref}}$ and the actual load current i_L can be expressed by using vector components in a complex form,

$$i_{L \text{ ref}} = i_{L \text{ ref}\alpha} + j i_{L \text{ ref}\beta} \tag{7}$$

$$i_L = i_{L\alpha} + j i_{L\beta} \tag{8}$$

Similarly, the error vector is defined by,

$$\Delta_i = i_L - i_{L \text{ ref}} \tag{9}$$

It is expressed in the $\alpha\beta$ reference frame as,

$$\Delta_i = \Delta_{i\alpha} + j \Delta_{i\beta} \tag{10}$$

5. Control process of SI-NPC-MLI

In control process of SI-NPC-MLI, the inverter works with the unity power factor, i.e., the inductor current i_{L12} is in phase with the grid voltage U_g . This assumption is reasonable under the requirement of the unity power factor between the grid current and the grid voltage, when applied to a PV grid-connected inverter.

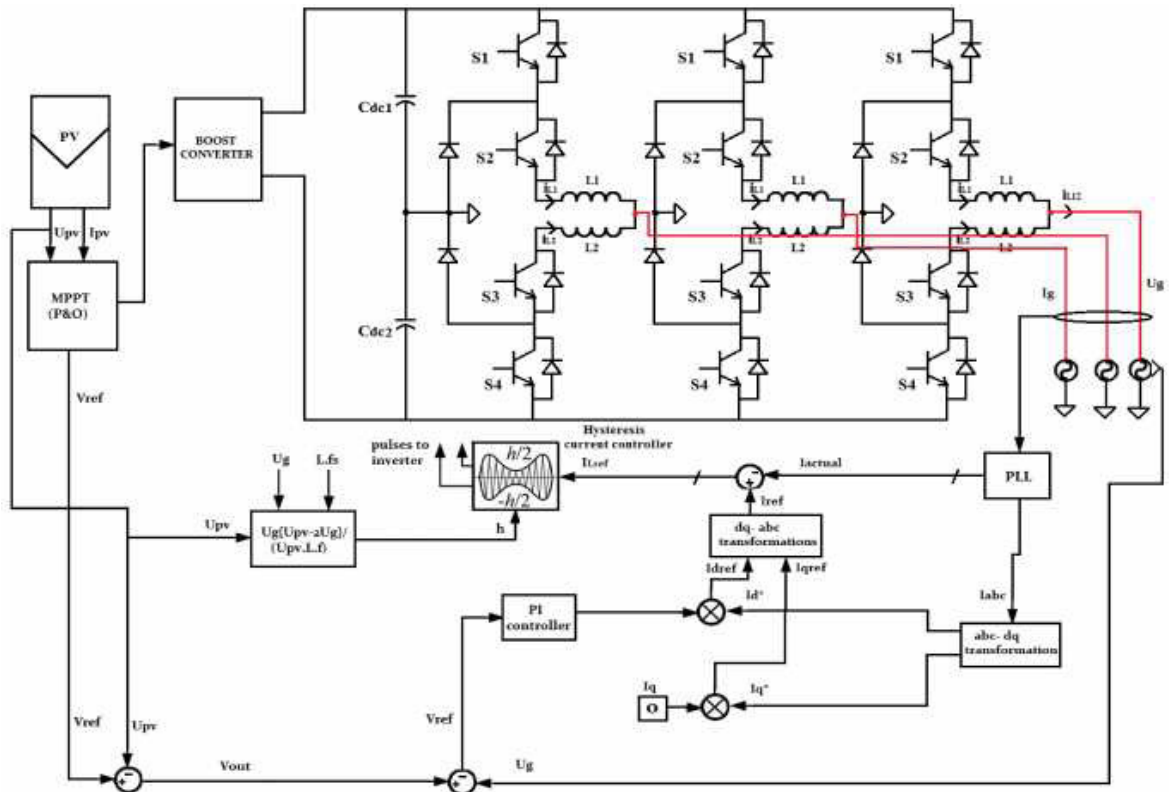


Fig.5. Control process in SI-NPC-MLI system

In order to ensure safe operation, the inductor current needs to be reliably dropped to zero before the zero crossing of the grid voltage. The hysteresis current control can achieve accurate tracking to the inductor current.

In this proposed scheme, dc voltage (V_{pv}) and current (I_{pv}) getting from the PV array. Output from the PV array given to the input of MPPT algorithm, here P&O method is used to tracking the maximum power from the PV array. Pulses (D) construct from output of MPPT algorithm and voltage is boosted by using boost converter. It given to the input of inverter and it is synchronized with the grid system by using parameters frequency, voltage and phase angle.

Reference voltage produces from comparing the actual voltage getting from the PV array and boost converter voltage. Error voltage given to the PI controller, it gives current gain value, that multiply with the output current from PLL system. This I_{ref} value is compare with the I_{act} and error current and hysteresis band value are the two inputs given to the HCC. Hysteresis current control, which is a nonlinear control method, possesses high performance, simple realization circuit, high stability, inherent current-limiting capability, and fast dynamic response. However, due to the unfixed switching frequency, the energy of spread-spectrum of output current is widely distributed. Considering the proposed SI-NPCTLI for PV grid-connected applications, the schematic control block is shown in Fig.5. The reference current $i_{L12(ref)}$ of the inductor current i_{L12} can be obtained by calculating the product of the reference amplitude I_{ref} and the phase of the grid voltage. As the result of HCC, the inductor current i_{L12} can achieve the error-free tracking to the reference current. Then, the MPPT algorithm can be fulfilled by calculating U_g and reading I_{ref} . Lastly, the driving signals of the inverter can be generated by comparing the real-time hysteresis band h with the error of inductor current i_{L12} and reference current $i_{L12(ref)}$.

6. Simulation results

The performance of the SI-NPC-MLI system authenticated by using MATLAB simulation under different PV array operating situations. In Fig.6 & Fig.7 shows output power from the PV array and pulses from MPPT algorithm. The performance of the system is tested with various solar radiations from $400W/m^2$ to $500W/m^2$ and various temperatures (0- 40) C. The Parameters considered for the simulation are, split inductor $L=4mH$, resistance $R=2\Omega$, capacitance $C=100\mu F$, and bandwidth value for HCC (h) is 0.3. Simulation parameters shown in the table 2.

Table 2. Simulation parameters

| Simulation parameters | Values |
|--|--------------------------|
| Grid voltage (V_g) | 200V |
| Grid and PLL frequency (f) | 50 HZ |
| Split inductor NPC (L) | 4mH |
| DC bus capacitance (C) | 100 micro farad |
| Inverter switching frequency (f_s) | 10kHz |
| Solar radiations (S) | $400W/m^2$ to $500W/m^2$ |
| Temperature (T) | 40 degree |

At that time of the three phase grid-connected SI-NPCTLI operates under the HCC with a fixed band, the waveforms of the grid current and voltage shown in fig.9. Here the Hysteresis control preventing the high frequency switching ahead make the current i_{L12} is zero before the zero crossing of u_g , which is certifies the current path shifting safety. Hence the grid-current reference is always less than the hysteresis band, which ensures high precision tracking of the grid-current reference

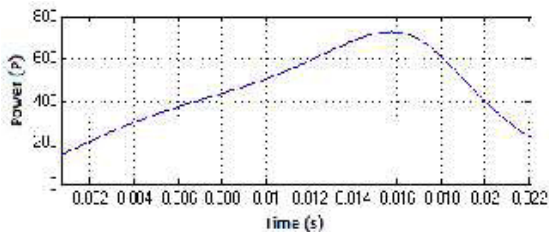


Fig.6. Output power getting from PV array

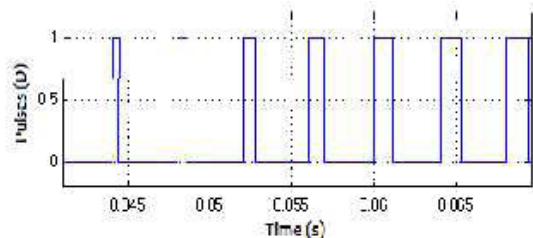


Fig.7. Pulses of MPPT algorithm

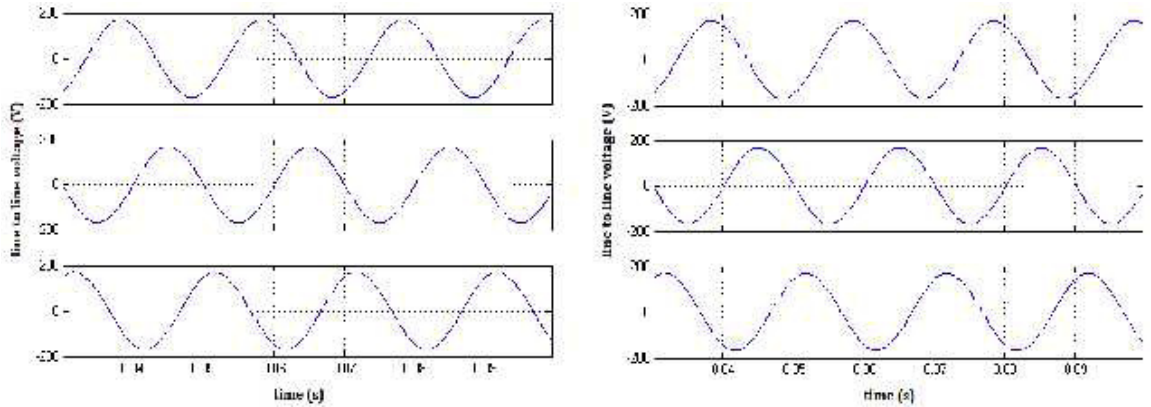


Fig.8. Line to line voltage of closed loop SI-NPC-MLI system. a) Inverter voltage b) grid voltage

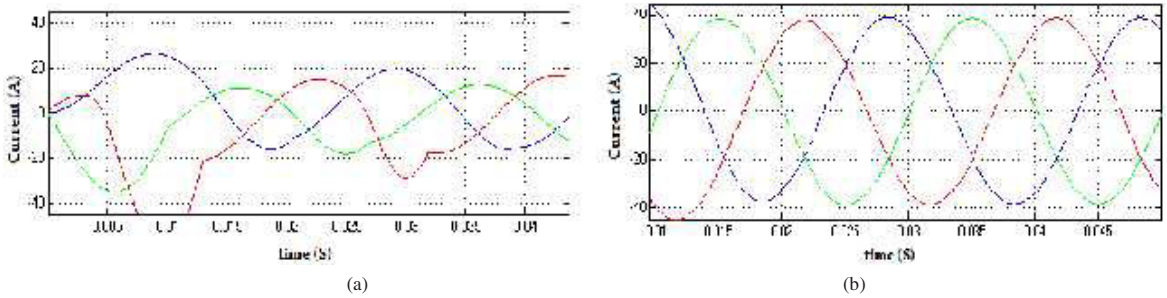


Fig.9. Current control a) Conventional current control method b) Hysteresis current control

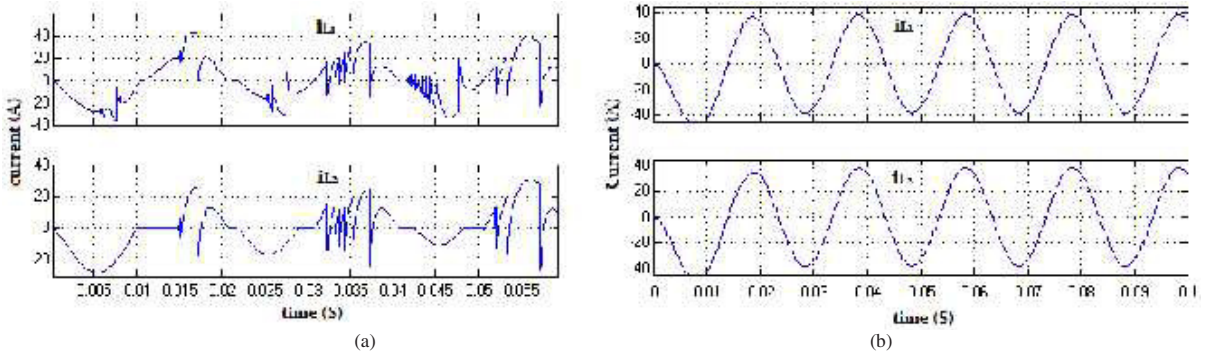


Fig.10. Inductor current control a) Uncontrolled current b) controlled current

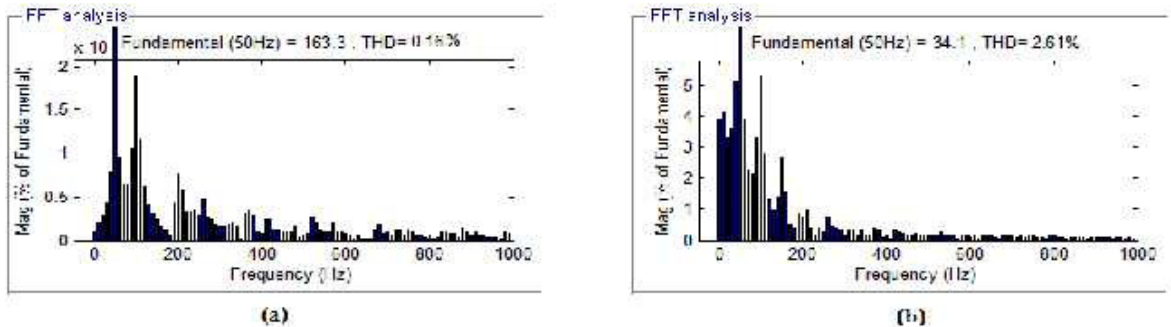


Fig.11. Harmonic spectrum analysis of inverter (a) Line to Line voltage (b) current control

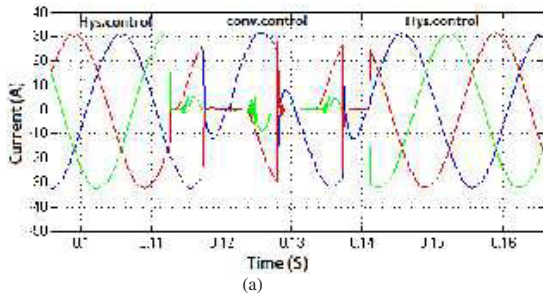


Fig.12. Hysteresis control VS Conventional control

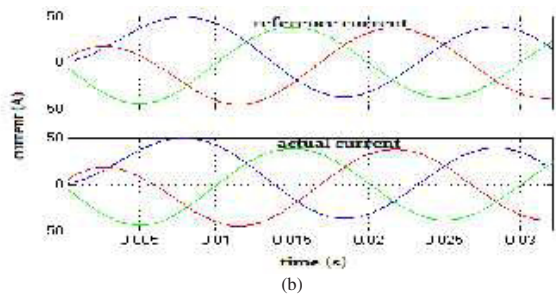


Fig.13. Reference current and actual current

fig.8 shows, line to line voltage of SI-NPC-MLI and grid system at about 164 V for an input of 170V - PV array voltage and current control value is 34.5A. THD for line to line voltage 0.16% and controlled current THD is 2.61%, which is less than that of IEEE standard 519-1922. In fig.9a & 9b illustrations, SI-NPC-MLI inverter uncontrolled current by using conventional method and controlled current in HCC method. Similarly split inductor uncontrolled and controlled current are shown in fig.10.

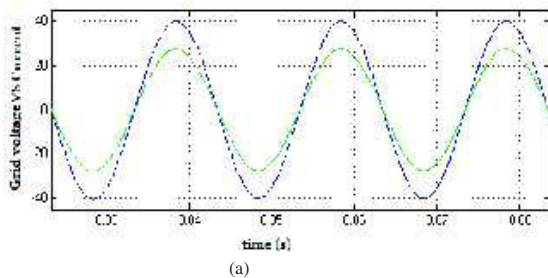


Fig.14. Grid voltage VS grid current (shoot through problem avoided) a).for 3 full cycles b).at zero point

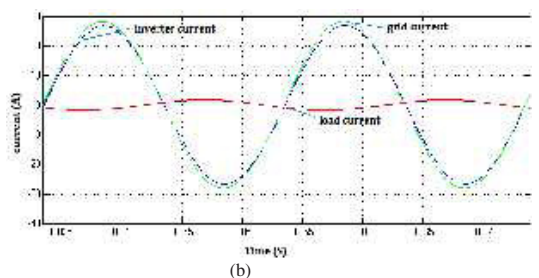
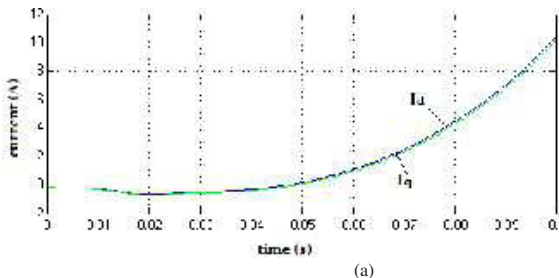
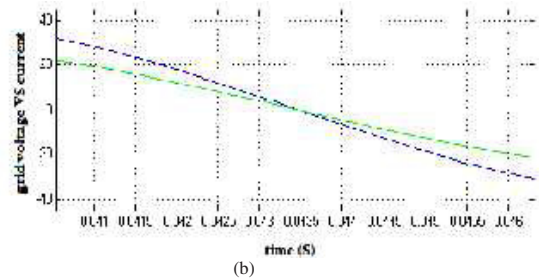


Fig.15. a) Id current b) Comparison of inverter current, grid current and zero load current

fig.12 shows comparison of HCC and conventional control, In this the system is employed up to $t=0.112$ sec under HCC and $t=0.112$ to 0.14 sec in conventional method. Here the proposed controller HCC shows his performance is better than the CC method. The fig.13 springs the variations of both references current and actual current. The controlled current I_g meeting with U_g at zero scale in x- axis, which shows (fig.14a & fig.14b) the evade of shoot through problems.

Table 3. Results Discussions

| Parameters | Values | THD |
|------------------|---------------|-------|
| Inverter voltage | 164 V | 0.16% |
| Grid voltage | 164 V | 0.16% |
| Inverter current | 34.5 A | 2.61% |
| Grid current | 34.5 A | 2.61% |
| PV array voltage | 88 V | - |
| Boost converter | (88 V- 175 V) | - |

In this proposed system, SI-NPC-MLI seeds 92% of output voltage $V_{inv}=164V$ from the input of 175V, with THD of 0.16%. and $i_{inv} = 34.1A$ with THD of 2.61%.

The significant features of the proposed scheme are,

- ✓ Attained current control of SI-NPC-MLI system with THD of 2.61%.
- ✓ Avoid the shoot through problems in this proposed system.
- ✓ Proposed system avoids the usage of Transformer.

7. CONCLUSION

A transformer less split-inductor three-level grid-connected inverter (SI-NPC-MLI) with high consistency and low-leakage current characteristics has been offered in this paper. The proposed inverter features low device voltage stress and constant common-mode voltage, which exists in the traditional neutral-point clamping three-level circuit structure. At the same time, it can escape the shoot-through problem and current control of inverter attained by using Hysteresis current control. The proposed inverter can achieve high efficiency, low cost, low leakage current and high reliability to satisfy the requirements of the transformerless PV grid-connected inverter.

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