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Transformerless inverter for grid-connected photovoltaic systems using fuzzy logic controller

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Abstract *- With worldwide increasing demand for electric energy, there has been a great interest in exploring photovoltaic (PV) sources. In the latest period, there have been quite a few new transformerless topologies, which remove the conventional frequency transformers to accomplish lesser cost and better efficiency and maintain decreased leakage current as well. However, one of the difficulties of the transformerless inverter is the protection issue of leakage current. The leakage current allows through the stray capacitors between the PV module and the grounded grid is harmful because of unstable common mode voltage and absence of galvanic isolation. This leakage current that flows between the grid and the parasitic capacitance of PV array has to be removed, may otherwise leads to major protection issues. Besides, according to the global standards, transformerless inverter should be able of managing a proper amount of reactive power. Here, a proposed transformerless inverter for grid connected PV system can remove the risk of leakage current. This topology also has the capability to give reactive power to the grid. Fuzzy logic controller and PR controller is used to ensure high quality injected current to the grid. Detailed analysis of operation modes of common mode of this proposed transformerless inverter, analysis of leakage current and results in MATLAB simulation model is presented.*

Keywords - Common mode voltage, Fuzzy Logic controller, Grid connected photovoltaic systems, leakage current, parasitic capacitance, transformerless inverter.

I. INTRODUCTION

The increasing demand for electrical power, along with the decreasing stock of traditional energy sources, has caused a growing interest towards micro production from renewable power sources. In particular, photovoltaic energy (PV) has witnessed an increasing attention and the scientific community has concentrated its efforts in view to develop innovative solutions for the integration of PV systems into the existing distribution grid. PV systems can be majorly categorized into two categories: stand-alone or grid connected. The first topology is befit for remote locations where the PV panels power a local load, while grid-connected systems work in conjunction with the existing electrical grid. Obviously, considering the highly discontinuous output of a PV field during a day, in a stand-alone system suitable electric energy storage must be provided. Moreover, when the accumulators are fully charged, no more power can be taken from the panels. A grid linked system does not suffer from these drawbacks, as the maximum power available from the field can be continuously transferred to the grid. Considering that the majority of the systems are of the grid-tied kind, a lot of study was done in this field.

The primitive schemes of PV grid-tied inverters presented a full-bridge topology linked to the main services with a low frequency transformer. The transformer guarantees the isolation of galvanic between the grounded grid and the PV field, simplifies the output filter design and the compliance with the electromagnetic interference (EMI) international regulations. However, converters embedding frequency transformer (50 Hz) are bulky and the transformer accounts for 1-2% of the power losses.

For these reasons, researchers have been active in studying solutions for the removal of the line frequency transformer, in view to pursue the maximum efficiency without increasing the converter cost. The main issue that arises when the low frequency transformer is eliminated is owing to the sight of a parasitic capacitance between the photovoltaic cells and the metal frame of the panel. This implies that a ground leakage current (i.e., common mode current) can flow into the resonant circuit comprises of the line conductors, the earth connection of the MV/LV distribution transformer and the parasitic capacitance of the PV field .If a simple full-bridge is employed without any transformer coupling or specific modulation strategy, the high-frequency common mode voltage variations at the converter output cause abnormal levels of ground leakage current, that generate EMI, reduce the safety of this system and cause the disconnection of the device owing to the Residual Current Device (RCD).

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The simplest PV transformerless topology is the H-bridge inverter, as shown in Fig.1, which utilizes the insulated-gate-bipolar-transistors (IGBTs) as the power device. The advantages of this topology are not complex in structure and capability of producing reactive power. The main overcome for this inverter scheme is it requires the use of bipolar PWM modulation to prevent the common mode (CM) voltage. As a result, the efficiency suffers owing to more switching loss on IGBTs, high current ripple induced core and copper losses on the filter inductor of output. The MOSFET voltage drop is a resistive and is preferred for maintaining high efficiency under light-load conditions and also for fast switching speed. However, high-voltage MOSFETs suffers from the issues of reverse recovery diodes and snappy body diode, which not only produces high dv/dt, di/dt, and high power loss, but also creates phase-leg shoot through risk due to reverse conducting current.

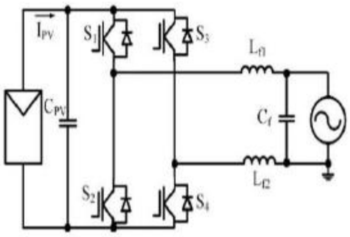

Fig.1: The single phase H-bridge inverter

The HERIC topology of inverter, shown in the Fig. 2 may adopt IGBT or MOSFET as the main switch. This novel inverter circuit utilizes a pair of ac switches (S_5/D_5 and S_6/D_6) to decouple the solar panel from the grid during current freewheeling period to minimize the common mode voltage. Its associated unipolar modulation method allows the reduction the switching loss and the core loss of the output filer. Compared with the bipolar modulation, the power device switching loss, core loss and inductor voltage stress can be all minimized. When the HERIC inverter is working under unity power factor condition, antiparallel diodes of S_1 to S_4 will not conduct the current, so power MOSFETs can be used. In the MOSFET based inverter that is similar to HERIC inverter, 99% efficiency is reported by using high-voltage MOSFETs. However, when the HERIC inverter is working under reactive power generation, the antiparallel diodes of main switches will conduct the current, and it is difficult to use MOSFET for reactive power generation due to the body diode reverse recovery problem. As compare with 4-IGBTs based H-bridge inverter with bipolar modulation, the HERIC inverter needs two more active switches and two more diodes, but the system efficiency is enhanced, and the filter inductor and heat sink sizes are minimized.

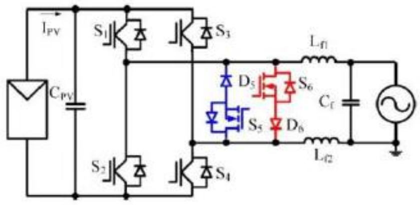

Fig. 2: The HERIC inverter with paralleled auxiliary freewheeling switches

The principle of the unipolar modulation is that: in the positive half grid cycle, the S_1 and S_4 will be turned on instantly in high frequency, and the S_5 is turned on in entire positive grid cycle; In the negative half cycle, the S_2 and S_3 will be operated at a time in high frequency, and the S_6 is turned on in entire positive grid cycle. One patent-free transformerless inverter is the H6 inverter, which is shown in Fig.2. Compared with the HERIC inverter, the H6 inverter also uses a pair of auxiliary freewheeling switches (S_5/D_5, S_6/D_6) to separate the grid from PV dc source. Categorized with the H5 inverter, the auxiliary freewheeling switches of the H6 inverter is also plugged into the H-bridge. The advantage of the H6 inverter over the H5 inverter is that it can adopt Cool MOS to replace the IGBTs for auxiliary freewheeling switches (S_5 and S_6), which can minimize the low load conduction loss with MOSFET.

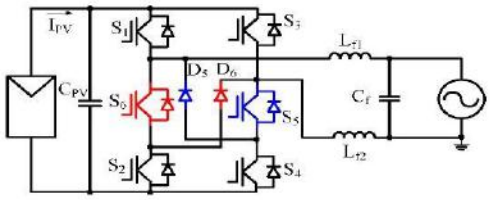

Fig .3: The H6 inverter topology

As shown in Fig.3, splits S_5 of H6 topology into S_6 and S_5 in cascade and operates them in high frequency switching, S_1~S_4 in line grid line frequency switching. With this structure, this system configuration is more symmetrical, so this inverter can be named as symmetrical H6 inverter topology in this dissertation. Two pair of auxiliary freewheeling switches (S_1/S_2, S_4/S_3) is used to separate the grid from PV dc source during the current freewheeling. By switching S_1~S_4 in high frequency, paper introduces a double frequency modulation method, which can decreases the output filter at the cost of increasing switching loss. Drawbacks of this inverter are more switching loss and more conduction loss (4 devices in conduction loop).

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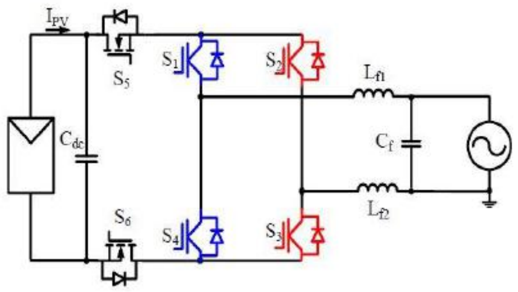

Fig .4: The symmetrical H6 inverter topology

An important task related to the photovoltaic system tied to the grid is that it can operate the dual functions of generation of real power and compensation of reactive power. The appropriate power factor is preferred according to reactive power and real power that the grid demands. Two current controllers are implemented for this single phase grid tied transformerless inverter: the Fuzzy logic controller and PR current controller. The current controller takes concern of the quality of current gives to the grid and the exchange of power takes place between the grid and system. The second current controller which manages the current enforces into grid in phase with the voltage of grid by the inverter so that unity power factor can be obtained. A harmonic compensator (HC) is connected with second controller to reduce low order odd harmonic components in the output current of inverter and reduce the THD loop. In stationary or α-β frame control structure the control parameters are time changing. The second controller comes under the classification of stationary frame controllers are easy to prepare and has superior reference tracking signal potentialities. The PR controllers can obtain every high gain at resonant frequency thus decreasing the steady state error to zero. More over HC's can be used to reduce low order harmonic without affecting action of the current controller. Hence these have excellent performance compared with PI controllers in terms of eliminating steady state errors and harmonic current rejection.

In this paper, a proposed transformerless inverter topology for grid tied PV system is developed. In Section II, proposed PV transformerless inverter topology is presented. In Section III, Common-mode voltage and leakage current analysis in transformerless PV Inverter is shown. In Section IV, the control methods of this proposed topology are described. Section V presents the simulation results of proposed topologies with real and reactive power control using Fuzzy Controller and PR Current controller .After that, the theoretical analysis is initially verified in the MATLAB/Simulink software environment and the results are presented in section V.

II. PROPOSED TOPOLOGY AND OPERATING PRINCIPLE

A. Structure of the Proposed Topology

Fig.5 presents the proposed transformerless inverter topologies comprises of 6 diodes (D_1-D_6) and MOSFET switches (S_1-S_6). L_{2A}, L_{2B}, L_{1A}, and L_{1B}, are the inductors and capacitor which constitute the LCL type filter tied to the distribution grid. V_{PV} and C_{dc} represent the dc input voltage and link capacitor DC. This is to nullify the low reverse-recovery problems of MOSFETs diode when provides reactive power to the grid. Therefore, this can be developed with MOSFET switches without efficiency penalty and reliability.

B. Principle operation of the Proposed Topology

Figure.6 shows the sequence of switches are operating for this proposed topology, where switches(S_1-S_6) represent the switches and their corresponding gate pulse signals are (G_1-G_6) respectively. The main principle of operation of this proposed topology has been classified into four regions as shown in Fig.5 within a grid period. Here positive half cycle explanation was given only, owing to the symmetry of the operation of these two half cycles of grid current. However, the operation for negative half cycle is delineated in Fig.7.

Region I: In this region, both the grid voltage and current are positive. During the period within this region, S_2 is always on, while S_3 & S_1 synchronously and S_5 complementary commutate with switching frequency. There are always two states that generate the output voltage of + V_{PV} and 0.

State 1(t_0:t_1): At $t = t_0$, the switches S_3 & S_1 are switched on and the current through inductor rises through grid as shown in Fig.7 (a). In this state, the voltages V_{1N} and V_{2N} can be defined as: $V_{1N} = + V_{PN}$ and $V_{2N} = 0$, thus the output voltage of inverter $V_{12} = (V_{1N} - V_{2N}) = + V_{PV}$.

State 2(t_1:t_2): When the switches S_3 and S_1 are turned-off, the current through inductor freewheels through D_5 and S_2 .In this state,V_{1N} falls and V_{2N} rises until their values are equal. Therefore, the voltages V_{1N} and V_{2N} becomes: $V_{1N} = V_{PV}/2$ and $V_{2N} = V_{PV}/2$ and the inverter output voltage $V_{12} = 0$.

Region II: In this region, the inverter output voltage is negative, but the current remains positive. During the period of this region, S_5 is always on, while S_6 & S_4 synchronously and S_2 complementary commutate with switching frequency. There are also two states that give the output voltage of – V_{PV} and 0.

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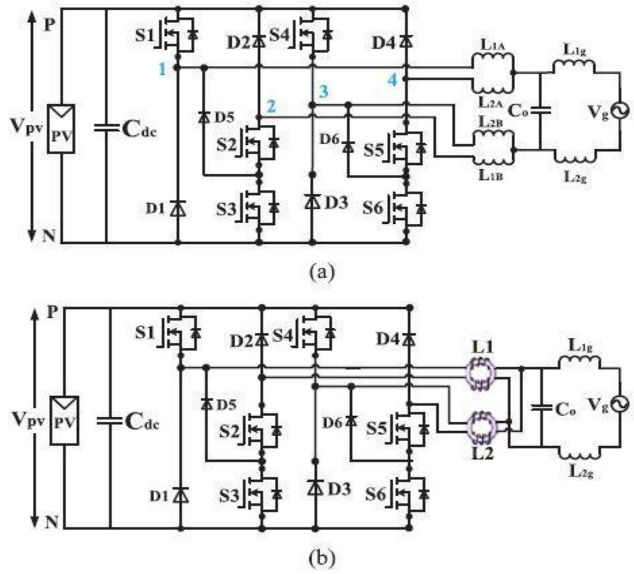

Fig.5 :(a) Circuit of the proposed transformerless topology for grid tied PV system
(b) Circuit with coupled inductor.

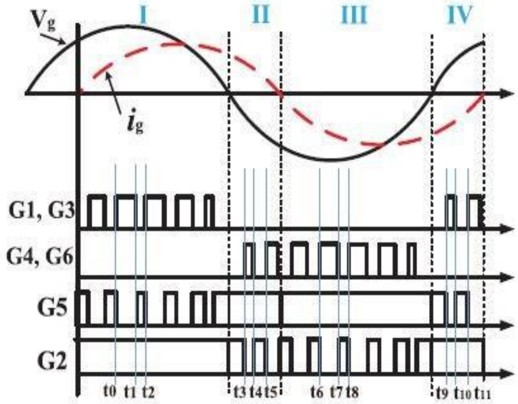

Fig.6: Switching sequence of this proposed topology.

There are also two states that produce the output voltage of – V_{PV} and 0.

State 3(t_3:t_4): In this state, the switches S_6 and S_4 are turned-on and the filter inductors are demagnetized. Since the inverter output voltage is negative and the current remains positive; therefore, the inductor current is forced to freewheel through the D_1 and D_2 diodes and decreases rapidly for enduring the reverse voltage as shown in Fig. 7(c). The voltages V_{1N} and V_{2N} can be defined as: $V_{1N} = 0$ and $V_{2N} = + V_{PV}$, thus the inverter output voltage $V_{12} = (V_{1N} – V_{2N}) = − V_{PV}$.

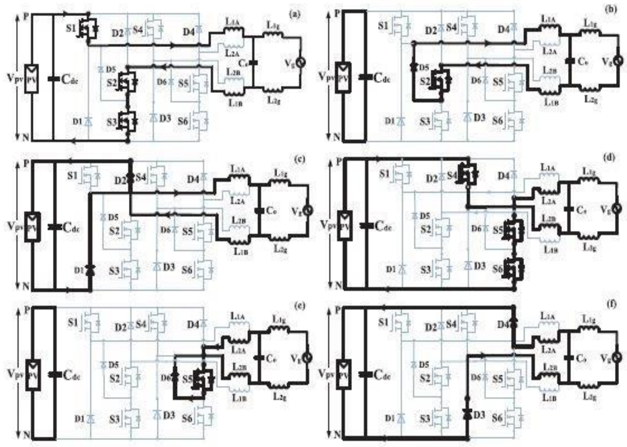

Fig.7: The operating principle of the proposed topology: (a) state 1 (b) state 2 (c) state 3 (d) state 4

State 4(t_4:t_5): At t = t_4, the switches S_6 and S_4 are switched off and S_2 is turned-on. Therefore, the current allows through D_5 and S_2 like as state 2 (Fig. 7(b) can be referred as equivalent circuit) in inductor. This state is called as energy storage mode.

The voltages V_{1N} and V_{2N} could be: $V_{1N} = V_{PV}/2$ and $V_{2N} = V_{PV}/2$, and thus the inverter output voltage, $V_{12} = 0$.

III. HIGH FREQUENCY CM MODEL OF THE PROPOSED TOPOLOGY FOR LEAKAGE CURRENT ANALYSIS

The PV panel produces a chargeable electrical surface area which looks a grounded frame. A capacitance is formed between the grounded grid and PV Module in this kind of configuration. Since this capacitance arises as an undesirable side effect, it is referred as parasitic capacitance. Due to the lack of galvanic separation between the grounded grid and the PV Panel, a CM resonant circuit can be formed. An alternating CM voltage that relies on this topology structure and control design, can excite the resonant circuit and may lead to higher ground leakage current. In order to analyze the CM characteristics, an equivalent circuit of the proposed topology as shown in Fig. 8 can be drawn, where V_{1N}, V_{2N}, V_{3N} and V_{4N} are the controlled voltage source connected to the negative terminal N, L_{CM} and C_{CM} are the CM inductor and capacitor, C_{PVg} is the parasitic capacitance, and Zg is the grid impedance. During the positive half-cycle, the switches S_4 and S_6 are always off. As a result, the controlled voltage sources V_{3N} and V_{4N} are zero and can be removed. According to the definition of common-mode and differential-mode voltage:

$$V_{CM} = \frac{1}{2}(V_{1N} + V_{2N}) \quad (1)$$

$$V_{DM} = V_{1N} – V_{2N} \quad (2)$$

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Solving (1) and (2), V_{1N} and V_{2N} can be expressed as follows:

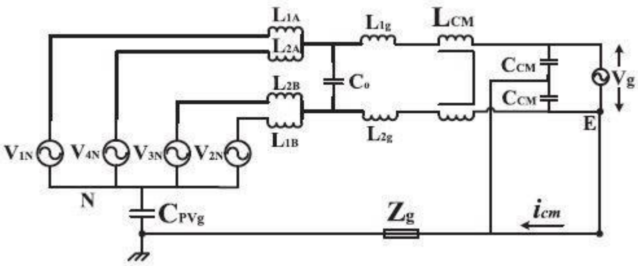

Fig.8: Equivalent CM model of the proposed topology.

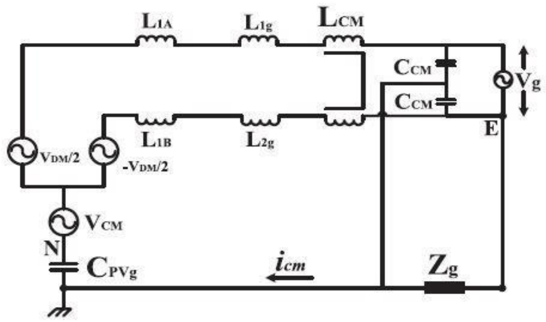

Fig.9: Simplified CM model at switching frequency for positive half cycle.

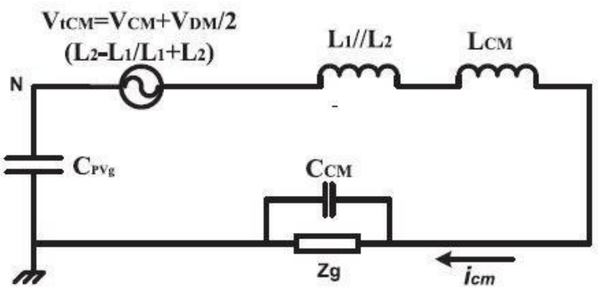

Fig.10: Simplified single loop CM model.

$$V_{1N} = V_{CM} + \frac{1}{2} V_{DM} \qquad (3)$$

$$V_{2N} = V_{CM} - \frac{1}{2} V_{DM} \qquad (4)$$

In view to illustrate the CM model at switching frequency, equation (3) and (4) could be replaced for the bridge-leg in Fig.7. The grid is a frequency (50–60 Hz) voltage source; thus the impact of grid on the leakage current can be neglected. The DM capacitor Co can also be removed since it shows no effect on the leakage current. Consequently, modified model of this topology for positive half-cycle could be drawn as Fig.9. At last, this model of this topology for positive half cycle is derived in Fig.10. From Fig.10, the following equation of the total CM voltage can easily be derived as:

$$V_{tCM} = V_{CM} + \frac{V_{DM}}{2} \left(\frac{L_2 - L_1}{L_2 + L_1}\right) \qquad (5)$$

where V_{tCM} represent total CM voltage, and $L_1 = L_{1A} + L_{1g}$ and $L_2 = L_{1BA} + L_{2g}$. In this inverter if $L_{1A} = L_{1B}$ and $L_{1g} = L_{2g}$ for a well-designed circuit with symmetrically structured magnetics, equation (5) can be rewritten as follows:

$$V_{tCM} = V_{CM} = \frac{1}{2} (V_{1N} - V_{2N}) \qquad (6)$$

According to the principle of operation of this topology presented, the total CM voltages can be calculated for each state of positive half cycle operation as follows:

State 1 : $V_{tCM} = \frac{1}{2}(V_{1N} + V_{2N}) = \frac{1}{2}(V_{PV} + 0)$

$$= \frac{1}{2} V_{PV} \qquad (7)$$

State 2 : $V_{tCM} = \frac{1}{2}(V_{1N} + V_{2N}) = \frac{1}{2}(\frac{1}{2} V_{PV} + \frac{1}{2} V_{PV})$

$$= \frac{1}{2} V_{PV} \qquad (8)$$

State 3 : $V_{tCM} = \frac{1}{2}(V_{1N} + V_{2N}) = \frac{1}{2}(0 + V_{PV})$

$$= \frac{1}{2} V_{PV} \qquad (9)$$

State 4 : $V_{tCM} = \frac{1}{2}(V_{1N} + V_{2N}) = \frac{1}{2}(\frac{1}{2} V_{PV} + \frac{1}{2} V_{PV})$

$$= \frac{1}{2} V_{PV} \qquad (10)$$

It is clear from equations (7)-(10) that the total CM voltage for this topology is kept same at $V_{PV}/2$ during positive half cycle operation. Likewise, the total CM voltage for the negative half cycle operation can be calculated and found to be constant at $V_{PV}/2$ due to the symmetry of operation for the negative and positive half cycle of grid current. The only variation is the activation of different power devices. Hence, it can be summarized that the total CM voltage during the entire grid cycle is kept same, decreasing ground leakage current.

IV.CONTROLLER DESIGN FOR SINGLE PHASE GRID TIED TRANSFORMERLESS INVERTER

For the single phase grid tied inverter, two controllers are developed. They are Fuzzy Logic controller and PR Current controller. The current controller takes care of the quality of current injected into the grid and the power exchange between the system and grid. $I g\alpha\ ref$ which is in phase with the grid voltage controls the real power of the system and the orthogonal component $I g\beta\ ref$ controls the reactive power exchange of the system with the grid. Hence a decoupled control of reactive and real power can be achieved.

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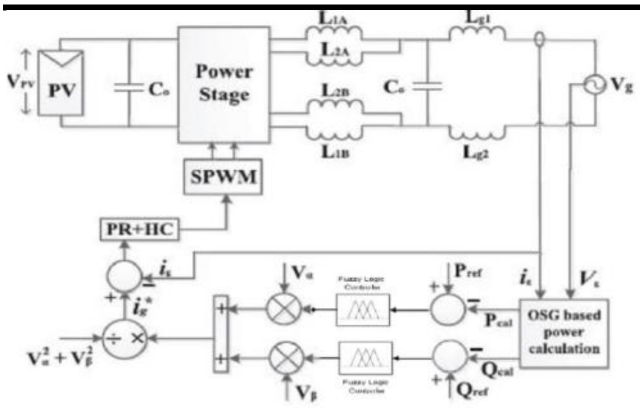

Fig.11: Block diagram of control of proposed system with Fuzzy Logic controller

A. Fuzzy Logic controller

The traditional PI controller requires rigorous linear mathematical models, which are not easy to acquire and cannot give satisfactory results under parameter variations, load disturbances, etc. In these latest years, the number and variety of uses of fuzzy logic have increased significantly. Fuzzy logic is a superset of Boolean logic which has been prolonged to manage the idea of partial truth- truth values between "totally false" and "totally true". This is a path to prepare machines more brilliant capacitating them to reason in a fuzzy manner like humans. This developed by Lotfy Zadeh in 1965, emanated as a tool to plan with improper, imprecise or qualitative decision making problems. These control strategies come from trails and practices rather than form mathematical models and linguistic implementations are much faster accomplished. These control schemes entail more number of inputs, most of which are common only for some special conditions.

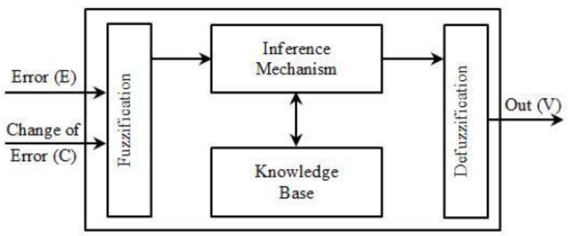

Fig .12: Structure of the Fuzzy Logic Controller.

These systems generally consist of four components: Fuzzification, Rule base, Inference engine and Defuzzification interface as shown in Fig.12. The first process is altering the crisp values of input variables into membership values according to proper fuzzy sets and there are three methods which are utilized in inference process. When the changes occur in the second process, then the results of all rules are integrated into a single precise value for output. Fuzzy inference is the process of mapping the given input variables to an output space via fuzzy logic based deducing mechanism which is comprised by If-Then rules, membership functions and fuzzy logical operations. Out of three, Mamdani inference is used, the consequent of If-Then rule is defined by fuzzy set. The output set of each rule will be reshaped by a matching number, and Defuzzification is needed after aggregating all of these reshaped sets.

B. Proportional Resonant Current Controller

The PR current controller is utilized in the stationary frame which is different from the traditional PI controller. Due to no transformation from stationary frame to synchronous frame, the computation pattern of this controller is simple. For these cases, processor which is less in cost can be used. Besides, when grid imbalances or a sensing error occurs, this controller is more robust than the PI controller. Especially, the PR controller is suitable for constant frequency operation in the grid-connected system. Generally, the PI controller has disadvantages such as issue in eliminating the steady-state error in a stationary reference frame. This controller structure has obtained familiarity due to its ability of removing steady-state error when regulating sinusoidal signals. Moreover, the simple execution of a harmonic compensator without any counter cause on the controller results prepares this controller well befit for grid-linked systems.

The block diagram of the PR controller with harmonic current compensator is shown in Fig.13 where $G_c(s)$, $G_h(s)$, and $G_d(s)$ are the transfer function of fundamental current controller, harmonic compensator, and inverter respectively.

The transfer function of the PR controller is defined below:

$$G_c(s) = K_{pi} + K_{ii} * \frac{n}{s^2 + w^2}$$

$$G_h(s) = \sum_{h=3,5,\ldots} \frac{K_{ih} s}{s^2 + (h w_f)^2}$$

$$G_d(s) = \frac{1}{1 + 1.5 T_s s}$$

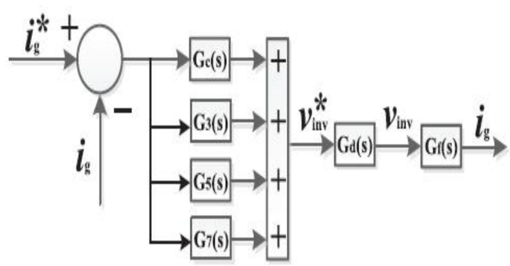

Fig.13: Block diagram of PR controller with harmonic compensator

Where K_{pi} and K_{ii} are the proportional and resonant gain, w_f is the fundamental frequency, K_{ih} is the resonant gain at the nth order harmonic, *h* is the harmonic order, and T_s is the sampling period

PARAMETERS OF SYSTEM

Table I-System parameters

V. SIMULATION RESULTS

The performance of simulation of this topology was performed using the MATLAB SOFTWARE. The parameters are used in simulation are given in Table I. In this section, comparison of different parameters such as inverter voltage, common mode voltage (CMV), leakage current and the performance of proposed topology under changes of reactive and real power are discussed.

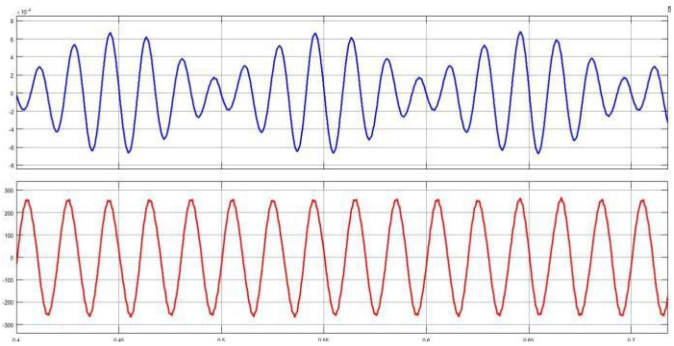

Fig.14 Simulation performance using PR and fuzzy logic controller with control of reactive and real power : (a) Leakage current (A) (b) Grid Voltage (V) .

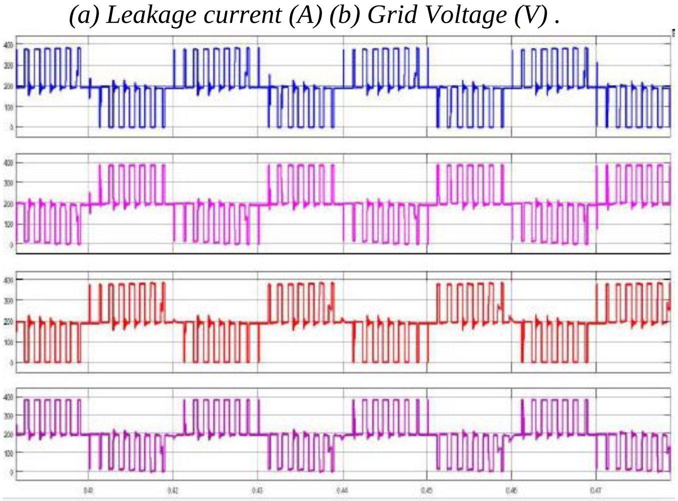

Fig.15. Simulation results for characteristics of CM voltage

VI. CONCLUSIONS

This Project Proposed a system for governing the flow of current from PV system when with the grid depended on FLC (fuzzy logic controller). PV system with inverter topology and its regulation action was developed using MATLAB / Simulink environment. With the Proper design of FLC and PR controller, the proposed PV

Inverter Parameter	Value
Input Voltage	400 V DC
Grid Voltage /Frequency	230V/50 Hz
Switching Frequency	20kHz
DC bus capacitor	470 μF
Filter Capacitor	2.2 μF
Filter Inductor L_{1A},L_{2A} ,L_{1B} ,L_{2B}	1 mH
Filter Inductor L_{g1}, L_{g2}	0.5 mH
PV Parasitic Capacitor C_{PV1},C_{PV2}	75 nF

inverter had succeeded in producing an excellent response, where the output current of inverter was sinusoidal and the harmonic values met with international standards. The Simulated Results have been analyzed.

Furthermore, the topology has the following advantage

1. This proposed topology had the capability to inject reactive power into the grid with less harmonic distortion.
2. The CM mode voltage is kept same during the entire grid period. Thus, the leakage current is well suppressed.
3. Higher performance can be obtained by introducing super junction MOSFETs for all devices which have frequency 20 KHz operation is allowed to decrease the ripple current of output and the passive elements dimensions.

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