High Reliability And Efficiency Single-Phase Transformerless Inverter For Grid-Connected Photovoltaic Systems

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Abstract: When no transformer is used in a grid-connected photovoltaic (PV) system, a galvanic connection between the grid and the PV array exists. In these conditions, dangerous leakage currents (common-mode currents) can appear through the stray capacitance between the PV array and the ground. In order to avoid these leakage currents, different inverter topologies that generate no varying common-mode voltages, such as the half-bridge and the bipolar pulse width modulation (PWM) full-bridge topologies, have been proposed. There is a new high-efficiency topology that generates no varying common-mode voltage and requires the same low-input voltage as the bipolar PWM full bridge. The proposed topology has been verified in a 5-kW prototype with satisfactory results.

This paper deals with a high-reliability single-phase transformerless grid-connected inverter that utilizes superjunction MOSFETs to achieve high efficiency for photovoltaic applications. Effectiveness of proposed technique is investigated through computer simulation by using MATLAB/SIMULINK software.

Keywords: Photovoltaic systems, Power Electronic Converters, Transformerless power inverters, grid connected PV systems, Proposed transformerless inverters.

I. INTRODUCTION

Grid-Connected photovoltaic (PV) systems, particularly low-power single-phase systems (up to 5 kW), are becoming more important worldwide. They are usually private systems where the owner tries to get the maximum system profitability. Issues such as reliability, high efficiency, small size and weight, and low price are of great importance to the conversion stage of the PV system. Quite often, these grid-connected PV systems include a line transformer in the power-conversion stage, which guarantees galvanic isolation between the grid and the PV system, thus providing personal protection. Furthermore, it strongly reduces the leakage currents between the PV system and the ground, ensures that no continuous current is injected into the grid, and can be used to increase the inverter output voltage level. Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility, while the world’s power demand is increasing. Not many PV systems have so far been placed into the grid due to the relatively high cost, compared with more traditional energy sources such as oil, gas, coal, nuclear, hydro, and wind.

II. PHOTOVOLTAIC SYSTEM

A. THE NEED FOR RENEWABLE ENERGY

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike dwindling conventional fossil fuels. The global energy crunch has provided a renewed impetus to the growth and development of Clean and Renewable Energy sources.

B. PHOTOVOLTAIC TECHNOLOGY

A PV array consists of a number of PV modules, mounted in the same plane and electrically connected to give the required electrical output for the application. The PV array can be of any size from a few hundred watts to hundreds of kilowatts, although the larger systems are often divided into several electrically independent sub arrays each feeding into their own power conditioning system.

Photovoltaic’s is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation.

Figure 2.1: photovoltaic systems
C. PV CELL

PVs generate electric power when illuminated by sunlight or artificial light. To illustrate the operation of a PV cell the p-n homo junction cell is used. PV cells contain a junction between two different materials across which there is a built in electric field. The absorption of photons of energy greater than the band gap energy of the semiconductor promotes electrons from the valence band to the conduction band, creating hole-electron pairs throughout the illuminated part of the semiconductor [6]. These electron and hole pairs will flow in opposite directions across the junction thereby creating DC power.

![Figure 2.2: Structure of a PV cell](image)

The cross-section of a PV cell is shown in Figure 1.3. The most common material used in PV cell manufacture is mono-crystalline or poly-crystalline silicon. Each cell is typically made of square or rectangular wafers of dimensions measuring about 10cm x 10cm x 0.3mm [6]. In the dark the PV cell’s behaviour is similar to that of a diode and the well known Shockley-Read equation can be used to model its behaviour i.e.

\[
i = I_s \left( e^{\frac{qV}{n kT}} - 1 \right)
\]

D. PV MODELING

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 modelled 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.

![Figure 2.3: Single diode model of a PV cell](image)

In this model we consider a current source (I) along with a diode and series resistance (R_s). The shunt resistance (R_SH) in parallel is very high, has a negligible effect and can be neglected. The output current from the photovoltaic array is

\[
I = I_{sc} - I_d
\]

\[
I_d = I_0 \left( e^{\frac{qV_d}{n kT}} - 1 \right)
\]

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 (1.38 * 10^-19 J/K) and T is the junction temperature in Kelvin (K).

Using suitable approximations,

\[
I = I_{sc} - I_0 \left( e^{\frac{q(V+IR_s)+nkT}{n kT}} - 1 \right)
\]

where, \( I \) is the photovoltaic cell current, \( V \) is the PV cell voltage, \( T \) is the temperature (in Kelvin) and \( n \) is the diode ideality factor. In order to model the solar panel accurately we can use two diode model but in our project our scope of study is limited to the single diode model. Also, the shunt resistance is very high and can be neglected during the course of our study.

II. POWER ELECTRONIC CONVERTERS

A. POWER SEMICONDUCTOR DEVICES

Power electronic circuits require high-power semiconductor switches and diodes. An ideal switch should have the following characteristics: full control over switch state (on/off), very low voltage drop during on state, infinite impedance during off state, and instantaneous transition between states. Diodes should have very low voltage drop during conduction, infinite impedance in off-state, and instantaneous transition. Practical devices have non-ideal characteristics, and different devices capitalizing on one advantage while sacrificing some other have been developed.

B. DIODES

Line frequency, fast recovery, ultra-fast recovery, and schottky—in increasing order of switching speed, and decreasing order of reverse voltage rating. There are essentially two types of power semiconductor diodes: PN junction, and metal semiconductor junction (schottky).

C. MOSFETS (METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR)

Good for low voltage 100s of volts, high switching frequency (~ 100 kHz). MOSFETS are voltage-controlled switches. Unlike triacs, MOSFETS have the capability of being turned on and turned off. They also switch much faster than triacs. The MOSFET acts as a unidirectional switch between the drain and source terminals, and has an internal antiparallel diode. An applied gate-to-source voltage of approximately 4 or 5 V is sufficient to turn on the MOSFET.

D. IGBTs (INSULATED GATE BIPOLAR TRANSISTORS):
Good from a few hundred Volts to about 6 kV, currents upto 1.2 kA, and switching frequency upto 30 kHz. The insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch and in newer devices is noted for combining high efficiency and fast switching. It switches electric power in many modern appliances: variable-frequency drives (VFDs), electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers.

E. THYRISTORS OR SCRS (SILICON-CONTROLLED RECTIFIERS)

Good for very high voltage and current (kVand kA), and low power moderate performance applications. A thyristor is a two- to four-lead solid-state semiconductor device with four layers of alternating N and P-type material.

IV. TRANSFORMERLESS INVERTERS

Transformerless topologies have several associated benefits against designs using topologies with line or high frequency transformers. From a practical perspective, transformerless topologies reduce the size and mass of inverters. The initial cost of the inverter is also typically reduced. Perhaps the most advantageous aspect of transformerless inverters is their increased efficiency at low and partial load.

A. COMMON-MODE SYSTEM DESCRIPTION

When no transformer is used, a galvanic connection between the ground of the grid and the PV array exists. Under these conditions and because of the high stray capacitance between the PV generator and the ground, large ground leakage currents can appear. The amplitude of these currents can exceed the legal norms. In [4], a model is proposed for the analysis of the common-mode system behaviour. This model determines the effect, on ground currents, of the conversion topology and the arrangement of its elements.

![Common-mode currents in a transformerless conversion stage](image)

Figure 4.1: Common-mode currents in a transformerless conversion stage

![Difference Between Transformer and Transformerless inverters](image)

Table 1: Difference Between Transformer and Transformerless inverters

V. SINGLE PHASE TRANSFORMERLESS INVERTER FOR GRID-CONNECTED PV SYSTEMS

A. INTRODUCTION
Transformerless photovoltaic (PV) grid-connected inverters have the advantages of higher efficiency, lower cost, less complexity, and smaller volume compared to their counterparts with transformer galvanic isolation. High frequency common-mode (CM) voltages must be avoided for a transformerless PV grid-connected inverter because it will lead to a large charge/discharge current partially flowing through the inverter to the ground. This CM ground current will cause an increase in the current harmonics, higher losses, safety problems, and electromagnetic interference (EMI) issues. For a grid-connected PV system, energy yield and payback time are greatly dependant on the inverter’s reliability and efficiency, which are regarded as two of the most significant characteristics for PV inverters.

B. H5 TOPOLOGY

One commercialized unipolar inverter topology, H5, as shown in Fig.6.1, solves the ground leakage current issue and uses hybrid MOSFET and IGBT devices to achieve high efficiency. The reported system peak and CEC efficiencies with an 8-kW converter system from the product datasheet is 98.3% and 98%, respectively, with 345-V dc input voltage and a 16-kHz switching frequency.

![Figure 5.1: Single-phase transformerless PV inverters using super junction MOSFETs: H5 Topology](image)

However, this topology has high conduction losses due to the fact that the current must conduct through three switches in series during the active phase. Another disadvantage of the H5 is that the line-frequency switches $S_1$ and $S_2$ cannot utilize MOSFET devices because of the MOSFET body diode’s slow reverse recovery.

C. H6 TOPOLOGY

Replacing the switch $S_4$ of the H5 inverter with two split switches $S_4$ and $S_5$ into two phase legs and adding two freewheeling diodes $D_3$ and $D_4$ for freewheeling current flows, the H6 topology was proposed. The H6 inverter can be implemented using MOSFETs for the line frequency switching devices, eliminating the use of less efficient IGBTs. The reported peak efficiency and EU efficiency of a 300 W prototype circuit were 98.3% and 98.1%, respectively, with 180 V dc input voltage and 30 kHz switching frequency.

D. DUAL-PARALLELED-BUCK INVERTER TOPOLOGY

Another high-efficiency transformerless MOSFET inverter topology is the dual-parallelled-buck converter. The dual-parallelled-buck converter was inversely derived from the dual-boost bridgeless power-factor correction (PFC). The dual-parallelled-buck inverter eliminates the problem of high conduction losses in the H5 and H6 inverter topologies because there are only two active switches in series with the current path during active phases.

E. PROPOSED TRANSFORMERLESS PV INVERTER AND ITS ANALYSIS

Fig.5.2 shows the circuit diagram of the proposed transformer less PV inverter, which is composed of six MOSFETs switches ($S_1$–$S_6$), six diodes ($D_1$–$D_6$), and two split ac-coupled inductors $L_1$ and $L_2$. The diodes $D_1$–$D_4$ perform voltage clamping functions for active switches $S_1$–$S_4$. The ac-side switch pairs are composed of $S_5$, $D_3$ and $S_6$, $D_6$, respectively, which provide unidirectional current flow branches during the freewheeling phases decoupling the grid from the PV array and minimizing the CM leakage current.

![Figure 5.2: Proposed high efficiency and reliability PV transformer less inverter topology](image)

Fig.5.3 shows the gating signals of the proposed transformerless PV inverter.
Fig.5.3 illustrates the PWM scheme for the proposed inverter. When the reference signal \( V \) control is higher than zero, MOSFETs \( S_1 \) and \( S_3 \) are switched simultaneously in the PWM mode and \( S_5 \) is kept on as a polarity selection switch in the half grid cycle; the gating signals \( G_2, G_4, \) and \( G_6 \) are low and \( S_2, S_4, \) and \( S_6 \) are inactive. Similarly, if the reference signal \(-V \) control is higher than zero, MOSFETs \( S_2 \) and \( S_4 \) are switched simultaneously in the PWM mode and \( S_6 \) is on as a polarity selection switch in the grid cycle; the gating signals \( G_1, G_3, \) and \( G_5 \) are low and \( S_1, S_3, \) and \( S_5 \) are inactive.

VI. SIMULATION RESULTS

Simulation of the 1-ph transformerless inverter for PV system is performed in MATLAB SIMULINK using the control technique. MATLAB SIMULINK is a very popular tool for mathematical computation and model-based design and SIMULINK Model is in generally pictorial representation of an application created using blocks provided by MATLAB as well as third parties.

A. MATLAB/SIMULINK RESULTS (VERIFICATIONS)

The experimental gating signals in the grid cycle and in the PWM cycle are shown in Fig. 6.1(a) and (b), respectively. It can be seen that the experimental gating signals \( G_1, G_3, \) and \( G_5 \) agree with the analysis results of the PWM scheme and the gating signals of \( G_1 \) and \( G_3 \) are synchronized well.

Figure 6.1: Switch gating signals: in (a) grid cycle and (b) PWM cycle

The drain–source voltage waveforms of the switches \( S_1, S_3, \) and \( S_5 \) in the grid cycle and in the PWM cycle are shown in Fig. 6.2(a) and (b), respectively. The voltage stresses of \( S_1, S_3, \) and \( S_5 \) are well clamped to the dc bus voltage, 380 V, without any voltage overstress. It can be seen from Fig. 6.2(b) that the switches \( S_1 \) and \( S_3 \) almost evenly share the dc-link voltage when they switch OFF simultaneously, effectively minimizing the ground loop leakage current.

Figure 6.2: Drain–source voltage waveforms of the switches \( S_1, S_3, \) and \( S_5 \): in (a) grid cycle and (b) in PWM cycle

Simulation result for M72_Final2-Scope1

VII. CONCLUSION AND FUTURE SCOPE OF WORK

A. CONCLUSION

The simulation of the high reliability & efficiency of single phase transformerless inverter for grid-connected photovoltaic system is done in Matlab Simulink. The main characteristics of the proposed transformerless inverter are summarized as follows:

- Ultra high efficiency can be achieved over a wide output power range by reliably employing superjunction MOSFETs for all switches since their body diodes are never activated.
- No shoot-through issue leads to greatly enhanced reliability.
- Low ac output current distortion is achieved because dead time is not needed at PWM switching commutation instants and grid-cycle zero-crossing instants.
- Low-ground loop CM leakage current is present as a result of two additional unidirectional-current switches.
decoupling the PV array from the grid during the zero stages.

- Higher switching frequency operation is allowed to reduce the output current ripple and the size of passive components while the inverter still maintains high efficiency.
- The higher operating frequencies with high efficiency enables reduced cooling requirements and results in system cost savings by shrinking passive components.

From the simulations we can conclude that the experimental results tested on a 5 kW hardware prototype verify the effectiveness of the proposed converter and show 99.0% CEC efficiency. With the super high efficiency, low leakage ground loop CM current, high quality of output current and greatly enhanced reliability, the proposed topology is very attractive for transformerless PV inverter applications.

B. FUTURE SCOPE

Transformerless topologies for PV-inverters are an upcoming technology. This is due to the fact that transformers operated at grid frequency are bulky and expensive and produce losses. In addition the transformer limits the freedom to control the grid current of the inverter. PV-systems offer a wide range of possibilities and configurations for the use of power electronic converters. An overview over technologies and transformerless topologies is given and the technology is presented as promising for the future. In addition some problems from the application side are given.

Future work will be to compare the transformerless topologies with special respect to the induced ground-leakage currents by simulation and measurements on an experimental setup. Experimental measurements are important, which are difficult to understand only by simulation, play a role for the paths of the leakage currents at higher frequencies.

Extension of my project is three phase high efficiency and high reliability transformerless inverter connected to grid system. In single phase we will get pulsating waveforms, if we implement it a three phases then we can get constant pure sinusoidal waveforms. With these we can achieve ultra-high efficiency and the life of machine will be increased and harmonic content reduced, noise will be decreased.

REFERENCES