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Study of Inverter for High Efficiency Photovoltaic Module using MPPT

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ABSTRACT: With the increased energy demand in the world, the new renewable energy sources must be found in order to meet the future energy demand, since the conventional sources are on the verge of exhaustion. Photovoltaic (PV) cell is one such type of renewable energy source, which converts sunlight to electrical current, without any form for mechanical or thermal interlink. The electrical infrastructure around the world is based on AC voltage, with a few exceptions, with a voltage of 120 Volt or 230 Volt in the distribution grid. Therefore an inverter is needed as an interlink if a PV module is to be connected onto the grid. The two main tasks for the inverter are (1) to inject a sinusoidal current into the grid and (2) to load the PV module optimally, in order to harvest the maximum energy . Of many methods for making solar power more competitive, one of the way is to develop the interlinking inverters that are inexpensive, reliable and efficient at the same time. The aim of this paper is therefore to study high efficiency inverter design and further develop new and cheap concepts for converting electrical energy, from the PV module to the grid.

I. INTRODUCTION

This paper introduces a study on inverter concept for photovoltaic (PV) applications .i.e. the 'direct current' to 'alternating current' (DC-AC) inversion. The PV module is capable of generating electric DC power, when exposed to sunlight. To generate a D.C voltage of 23-45 volts and maximum power of 160 watt, around 72 PV cells are connected together to form a PV module (depending upon the solar irradiation and temperature). The focus of this paper is especially on inverters where the source is a single PV module and the load is the low-voltage AC public utility network. Power generated by PV modules and injected into the grid is gaining more and more visibility in the area of PV applications, This is mainly due to steadily increasing global energy demand. Not many PV systems have so far been put into the grid . This is due to a relatively high cost, compared with the more traditional energy sources, such as oil, gas, nuclear, hydro, wind, etc. Compared to other resources the cost for a PV module is quite high. The lowest price for a PV module, inclusive inverter, cables and installation, is approximately Rs. 4000, or about Rs 60000 for a standard PV module and inverter with a nominal power of 160 Watt. However for domestic purposes its profitable, since its free from considerations like duty, taxes, wages for maintenance. A PV module does not contain any moving parts.

A long lifetime is therefore guaranteed, without almost any tear-and-wear and maintenance. For example, BP SOLAR gives the following warranties: 25-year on 80% power-output, 12-year on 90% power-output, and 5 years on materials and workmanship. Gradually now a downward tendency is seen in the cost of the modules, due to a rapid increase in production capacity, The cost of the inverters is therefore becoming more visible in the total cost. Inverters & MPPT are used for following tasks:

- To amplify and invert the generated DC power into a suitable AC current for the grid. A standard PV module generates approximately 100 W to 150 W at a voltage around 20 V to 32 V, whereas the grid mostly requires 110V at 60 Hz or 230 V at 50 Hz.
- To control the PV module so as to track the Maximum Power Point (MPP) for maximizing the energy capture.

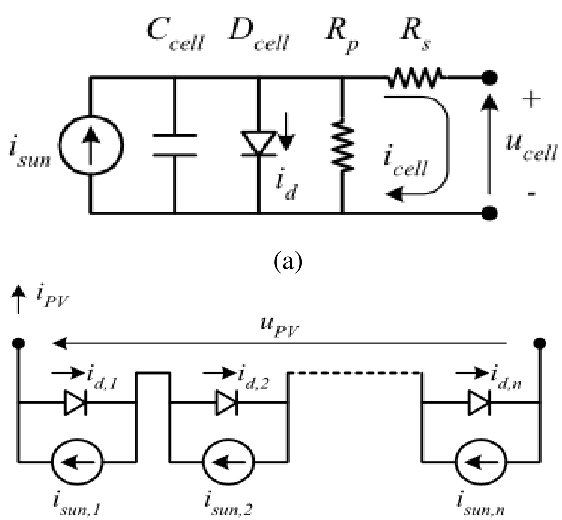
Both tasks must be made at the highest possible efficiency, over a wide power range, due to the morning-noon-evening and winter-summer variations. The MPP is tracked by means of a MPP Tracker (MPPT) device.

The power injected into a single-phase grid follows a sinusoidal waveform raised to the second power, if the voltage and the current are in phase and with no harmonics (the power injected into a three-phase grid is constant). The PV module cannot be operated at the MPP if this alternating power is not decoupled by means of an energy buffer.

In this paper we study inverter designs for PV system. In section II we see the model of PV cell and section III describes the different inverter topologies for PV system. After the study of inverter we see the designs of inverter and study the algorithm for inverter with MPPT. Implementation of the system is under progress and some aspects of the experimental result are given in section VI.

II. MODEL OF THE PV CELL

An electrical model of the PV cell is shown in Fig-1(a). The PV module is composed of n number of these cells in series, as shown in Fig-1.b, in order to reach a high voltage at the terminals. The connection of PV cells in series is named a string. From Fig-1.b and the theory of superposition, it becomes clear that the current generated by the PV module is determined by the lowest $i_{sun,}$ this is the principle of the weakest link. Thus, care must be taken when selecting the PV cells for a PV module. So that the cells have same characteristics



(a)

(b)

Fig. 1. Electrical model of a PV cell (a), and of a PV module made up around n cells (b).

A. Light Dependent Current Source
The current source in Fig. 1, i_{sun}, is proportional to the amount of irradiation, and linear with respect to the PV cell temperature. According to (1), an increase in temperature involves a decrease in band gap energy, which results in more current generated by the incoming photons. The current is given as [28].

$$\boldsymbol{i_{sun}} = \left(\boldsymbol{i_{sun,STC}} + \boldsymbol{k_{temp}}.\left(\boldsymbol{T_{cell}} - \boldsymbol{T_{cell,STC}}\right)\right)\cdot\frac{\boldsymbol{P_{SUN}}}{\boldsymbol{P_{sun,STC}}} \quad \text{...(1)}$$

where i_{sun} and $i_{sun,STC}$ is the short circuit current at the given working point and STC, respectively. The constant k_{temp} is the temperature coefficient of i_{sun}. T_{cell} and $T_{cell,STC}$ are the actual and STC cell temperatures, respectively. Finally P_{sun} and $P_{sun,STC}$ are the irradiations at the present operating point and at STC, respectively.

B. Diode
The current through the diode, $i_{d,}$ is described by the well-known diode-equation:

$$\boldsymbol{i_d} = \boldsymbol{i_{rs}}.\left(\boldsymbol{exp}\left(\frac{\boldsymbol{q.u_d}}{\boldsymbol{k.A.T_{cell}}}\right) - \boldsymbol{1}\right) \qquad (2)$$

where i_{rs} is the reserve saturation current, A is the diode quality factor, and u_d is the voltage across the diode. The reverse saturation current increases with temperature.

C. Resistances
The two resistors included in the model, R_s, and R_p, describe the power losses due to resistance in the current-collecting bus-bars, fingers and connections between modules and the inverter, the purity of the semiconductor material and the regularity of the semiconductor lattice. The parallel resistance is high; it does therefore not have much influence on the PV cell characteristic.

$$\boldsymbol{R_{PN}} = \frac{du_{PV}}{di_{PV}} = \frac{k.A.T_{cell}}{q.(I_d+i_{rs})} = \frac{k.A.T_{cell}}{q.((i_{sun}-i_{cell})+i_{rs})} \approx \frac{k.A.T_{cell}}{q.(i_{sun}-i_{cell})} \quad \text{...(3)}$$

D. Capacitance
The two layers of the PN junction form a capacitor. If the layers are regarded as being a plate capacitor without end-effects, the capacitance can be stated as:

$$\boldsymbol{c_{cell}} = \varepsilon_0.\,\varepsilon_r.\frac{a_{disc}}{d} \qquad \textbf{(4)}$$

Where ε_0 is the permittivity (dielectric constant) of free space (8.85x10-12 F/m), ε_r is the relative permittivity of the semiconductor material, a is the area of the discs and d is the distance between the two discs.

The area of the discs is easily measured with a ruler, but the distance between the two plates is more difficult to measure! The distance depends on the applied voltage, doping, and temperature.

III. INVERTERS FOR PV APPLICATIONS

In this paper we study different types of multilevel inverters which we use in PV cell system that are as follows:

A. Diode Clamped multilevel inverter

The main concept of using diodes in this inverter is to limit voltage stress. The voltage over each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources, 2(n-1) switching devices and (n-1) (n-2) diodes. In a 5-level diode clamped multilevel:

n = 5

Therefore:

Number of switches = 2(n-1) = 8

Number of diodes = (n-1) (n-2) = 12

Number of capacitors = (n-1) = 4

A 5-level diode clamped multilevel inverter is shown in Fig. 2. Switching states are shown in Table.1. For example to have $V_{dc}/2$ in the output, switches S_1 to S_4 should conduct at the same time. For each voltage level four switches should conduct. As it can be seen in Table 1 the maximum output voltage in the output is half of the DC source. It is a drawback of the diode clamped multilevel inverter. This problem can be solved by using a two times voltage source or cascading two diode clamped multilevel inverters. The output voltage of a 5-level diode clamped multilevel inverter is shown in Fig-3. As can be seen in Fig-3 all of the voltage level should have the same voltage value. The switching angles should be calculated in such a way that the THD of the output voltage becomes as low as possible. The switching angle calculation method that is used in this paper is the harmonic elimination method. In this method the lower dominant harmonics can be eliminated by choosing calculated switching angles

Table 1. The switching states of Diode clamped multilevel inverter.

V_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc}/4$	0	0	0	1	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

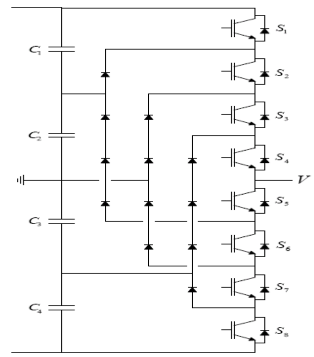


Fig. 2. One phase of a diode clamped inverter.

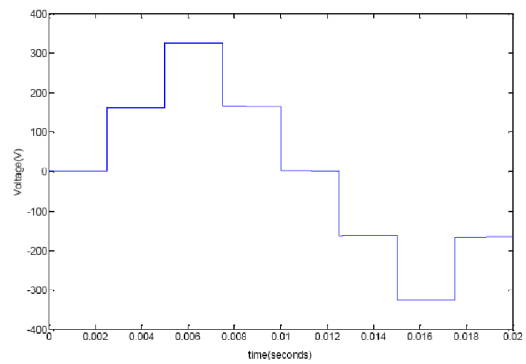


Fig. 3. Output voltage of a 5-level multilevel inverter.

B. Flying capacitor multilevel inverters

This inverter uses capacitors to limit the voltage of the power devices. The configuration of the flying capacitor multilevel inverter is like a diode clamped multilevel inverter except that capacitors are used to divide the input DC voltage. The voltage over each capacitor and each switch is V_{dc}.

For a 5-level flying capacitor multilevel inverter:

N = 5

Therefore:

Number of switches = 8

Number of capacitors = 10

Fig. 4 shows a five level flying capacitor multilevel inverter. The switching states in this inverter are like in the diode clamped multilevel inverter. It means that for each output voltage level 4 switches should be on. Table 2 shows the switching states for a 5 level flying capacitor clamped multilevel inverter.

The output voltage was shown before in Fig. 3. The switching angles like the diode clamped multilevel inverter should be calculated in such a way that the THD of the output voltage becomes as low as possible. The method is the same as the diode clamped inverter.

Table 2. The switching pattern for capacitor clamped multilevel inverter.

V_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	1	1	1	0	1	0	0	0
0	1	1	0	0	1	1	0	0
$-V_{dc}/4$	1	0	0	0	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

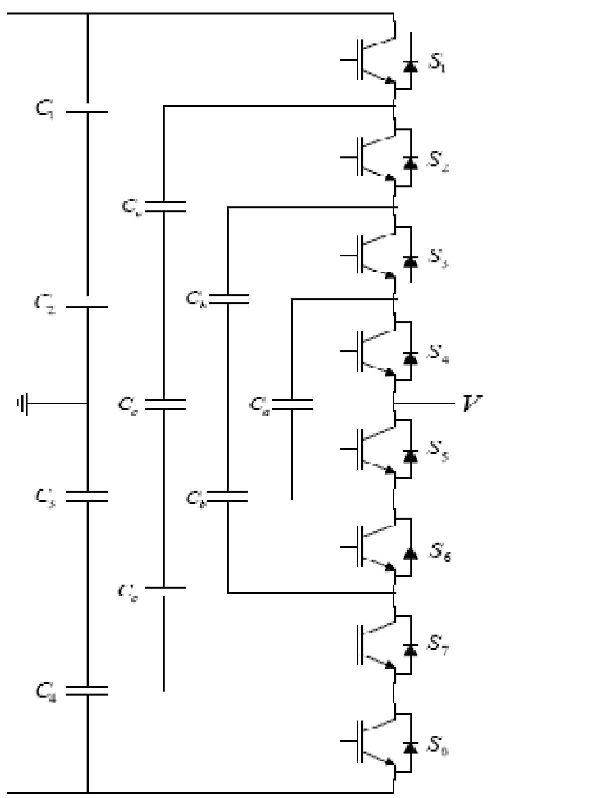


Fig. 4. One phase of a 5-level Flying capacitor multilevel inverter.

C. Cascaded H-bridge multilevel inverter

The concept of this inverter is based on connecting H-bridge inverters in series to get a sinusoidal voltage output. The output voltage is the sum of the voltage that is generated by each cell. The number of output voltage levels are 2*n*+1, where *n* is the number of cells. The switching angles can be chosen in such a way that the total harmonic distortion is minimized. One of the advantages of this type of multilevel inverter is that it needs less number of components comparative to the diode clamped or the flying capacitor, so the price and the weight of the inverter is less than that of the two former types. Fig. 5 shows an *n* level cascaded H-bridge multilevel inverter. The switching angles calculation method that is used in this inverter is the same as for the previous multilevel inverters.

An *n* level cascaded H-bridge multilevel inverter needs 2(*n*-1) switching devices where *n* is the number of the output voltage level.

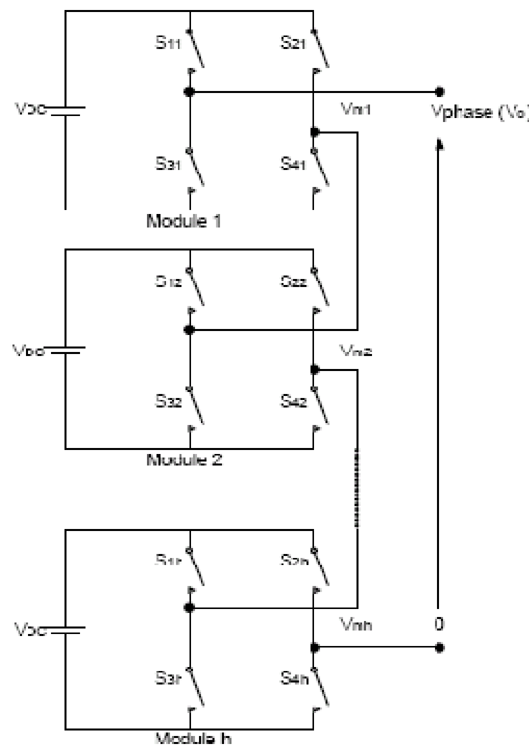


Fig. 5. One phase of a cascaded H-bridge multilevel inverter.

IV. DESIGN OF THE PHOTOVOLTAIC INVERTER

The design of a power-electronic inverter depends on many issues, such as silicon devices; capacitors; gate drives; grid performance; current, voltage and temperature-sensing; protection and control strategies; implementation, etc., which all must be taken into account.

The DC-AC inverter is depicted in Fig 7. The inverter is fabricated around a DC-link capacitor C_{DC}, four MOSFETs with freewheeling diodes S_{AC1} – S_{AC4}, and an LCL filter composed by $L_{grid,1}$, C_{grid}, and $L_{grid,2}$. The four MOSFETs are operated with PWM, in what is called uni-polar mode. This operation scheme benefits from an apparent doubling of the switching frequency, seen by the grid [30].

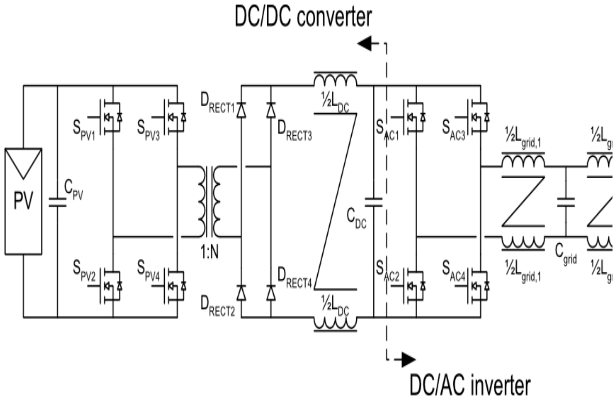


Fig. 6. Power circuit of the photovoltaic inverter.

A doubling of the frequency leads to halving of the current ripple on the grid side. Therefore, smaller filter components are required to meet the electrical-noise reduction specifications.

$u_{LCL,on} = U_{DC} - u_{grid}$, when S_{AC2} and S_{AC3} are conducting,
$u_{LCA,on} = -U_{DC} - u_{grid}$, when S_{AC1} and S_{AC4} are conducting,
$u_{LCL,on} = -u_{grid}$, when S_{AC1} and S_{AC3},or S_{AC2} and S_{AC4} are conducting

where U_{DC} is the voltage across the DC-link capacitor (assumed constant), and u_{grid} is the instantaneous grid voltage. The change in the grid current per switching cycle is then computed as

$$\Delta \boldsymbol{i}_{grid} = \frac{(U_{DC} - u_{grid}).D}{2.L_{grid}.f_{new}} + \frac{(0 - u_{grid}).(1-D)}{2.L_{grid}.f_{sw}} = \frac{U_{DC}.D - u_{grid}}{2.L_{grid}.f_{sw}} \quad \ldots (5)$$

where L_{grid} is the sum of the two inductors included in the grid-connected filter, f_{sw} is the switching frequency, and D is the duty cycle defining the on-durations of S_{AC3}, compared with the switching period, i.e. $D = T_{on, SAC3} / T_{sw}$. It becomes in this way possible to control the grid current.

The controlling IC is a phase shift PWM controller that implements control of a full-bridge power stage by phase shifting the switching of one half-bridge with respect to the other. It allows constant frequency switching pulse-width modulation in conjunction with resonant zero-voltage switching to provide high efficiency at high frequencies. This part can be used either in a voltage mode or as in a current mode controller. The input voltage from the PV module is given in the range from 20V to 32 V, and the output voltage across the DC-link is defined from 300 V to 400 V.

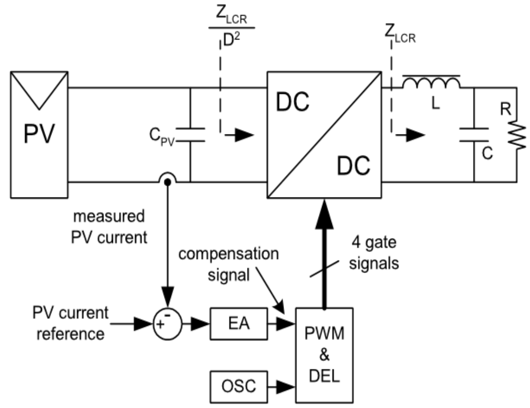


Fig. 7. Block diagram of the DC-DC converter with the proposed controllers.

Besides this, the DC-AC inverter controls the magnitude of the output voltage, so the task for the controller is to regulate the input current of the PV-module.

A block diagram of the PV module, with DC-DC converter, measuring circuit and controller is illustrated in Fig.7. It consists of an Error Amplifier (EA), a PWM block together with the oscillator (OSC) and blanking time circuit (DEL).

The aim of the PI controller is to regulate the PV-module current, even that the DC-link and the PV module voltages are non-constant in order to operate the module at the desired working point. A small signal model is needed of DC-DC converter in order to design a feasible controller.

V. MAXIMUM POWER POINT TRACKER (MPPT)

The operating point where the PV module generates the most power is denoted the Maximum Power Point (MPP) which co-ordinates are: UMPP, IMPP. The available power from the PV module is a function of solar irradiation, module temperature, and amount of partial shadow, thus the MPP is never constant but varies all the time. Sometimes it changes rapidly due to fast changes in the weather conditions, other times it is fairly constant when no clouds are present. Four major types of tracking algorithms (MPPT) are available, they are (in order of complexity, simplest first):

- Constant fill-factor (voltage or current)
- Sweeping
- Perturb and observe (hill-climbing)
- Incremental conductance

Other types of algorithms also exist, e.g. fuzzy-logic, neural-networks, monitor/reference cells, etc. They are however not reviewed here, due to their elevated complexities, or the need for additional PV cells for monitoring purpose

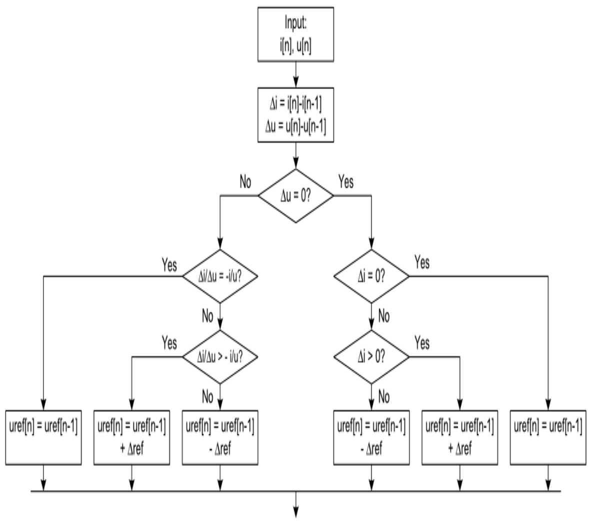


Fig. 8. Flow chart of the incremental conductance MPPT algorithm.

The algorithm is bypassed by the conditions: Δi = 0 and Δi/ Δu + i/u = 0, when the MPP is tracked, thus the power is no more fluctuating around the MPP. The largest disadvantage with this algorithm, depicted in Fig-8, as compared with the other algorithms, is the problem of tracing the global maximum when the module is partial shadowed. Adding a scan mode to the algorithm can solve this. This is done in [28] where the voltage/current characteristic is scanned, during 40 ms, every 12 second, with a high amplitude signal to increase the signal-to-noise ratio.
This also helps to increase the resolution of the sensed current, which can be a problem at low irradiance. The output from the scan is the co-ordinates for the global MPP, which then is used as the new reference before the algorithm is turned on again. This approach does not require any additional hardware**.** This helps to track the global MPP, even under severe partial shadow.

VI. EXPECTED RESULT

The above paper includes the study of dynamic nature of the PV cell, current and voltage. Also the interfacing of an inverter and PV module is studied.
With the study of MPPT algorithm it is seen that the output voltage is compatible with load. Multilevel inverter is used and the wave shape obtained is non sinusoidal. Due to the use of multilevel inverter the lower harmonics is reduced. By using different voltage levels the required output voltage is generated, thus by reducing harmonics and a more efficient Photovoltaic system can be designed.

VII. CONCLUSION

The photovoltaic (PV) module is an all-electrical device that converts sunlight into electrical DC power. Solid-state power electronic inverters have been used to connect PV modules to the AC utility grid since the early seventies. The inverter has two major tasks: to inject a sinusoidal current into the grid, and to optimize the operating point of the PV modules, to capture the maximum amount of energy.
Large, megawatt, PV systems were connected to the grid in the eighties, but the trend is now to connect smaller systems to the grid, in order to overcome certain problems, like non-flexible designs, mismatch losses between the PV modules, etc. These systems are either based on the string-concept, with multiple modules connected in series, or on a single PV module.

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