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Review Article

Integration of Multilevel Inverter with Photovoltaic Systems to Enhance Grid Performance: A State-of-Art Review

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***Abstract* - *Multi-Level Inverters (MLI) have their applications in high-power medium-voltage control systems, which is mainly due to their numerous advantages viz., improved power quality, lesser dv/dt stress on the switches, lesser switching losses, reduced total harmonic distortion, reduced electromagnetic interference, better efficiency, smaller common-mode voltage, etc. A state-of-art review on the integration of multilevel inverters with photovoltaic systems to enhance the grid performance is presented in this paper. A deliberation on various topologies is presented here. The desired DC output voltage is obtained from the converter, which is then fed to MLI to convert into AC power with better quality and reduced harmonics. It is then fed to the AC utility grid. Depending upon the AC output voltage levels, MLIs have various switching devices. The application of MLIs to distribution generators and Photovoltaic systems (PV) is on the rise due to numerous advantages. Maximum power from the PV arrays is drawn using Maximum Power Point Tracking (MPPT). The generated AC power from the PV system is fed to the local isolated load or can be fed to the grid. A complete model of PV systems is also presented.*

Keywords* - *DC/DC power converters, Multi-Level Inverters, Photovoltaic systems, PV array, Phase locked loop.

1. Introduction

In recent times to meet the upsurge demand in electrical power, Renewable Energy Sources (RES) are immensely replacing Non-Renewable Energy Sources (NRES) for electrical power generation, but these suffer from various dis-advantages like air pollution, faster depletion of fossil fuels stock, fall in foreign reserves, various health issues, etc., Solar Photovoltaic (PV) system generates electric power from solar energy, i.e., a RES, its infinite resource, abundantly available, eco-friendly, renewable in nature, available all seven days a week and three hundred sixty five days a year throughout the globe [1-5]. Single-phase inverters operate with a 230V rms application, rectifiers operate with a DC-side voltage of 400V and achieve good efficiency with a basic 2-level inverter topology, as the losses are very low with this configuration at the said voltage level, and the peak-to-peak voltage can be doubled, which is generated on the DC-side for a particular DC-link voltage. For definite applications [6-9] like photovoltaic systems connected to the grid, chargers for Electric Vehicle (EV), DC drives, etc., three-phase converters are required, hence a higher magnitude of three-phase DC-link voltage, line-to-line voltage magnitude generally set to 800V for 230Vrms phase voltage systems. AC/DC and DC/AC power converters are vital for various emerging applications. Right from converters for renewable energy, electric vehicle drives, Power-Factor-Correction (PFC) rectifiers, etc., Single-phase inverters and rectifiers operate at 50 Hz, the effective output voltage can be doubled without increasing the semiconductor or capacitor voltage stresses, single-phase designs for 230V rms lines to work with DC-link voltages around 400V. For higher power ratings applications such as residential PV inverters, EV chargers and machine drives, a three-phase 230Vrms line is required. For medium and high power applications, a conventional inverter is not appropriate due to a number of causes, such as being expensive, total harmonic distortion is high in the output and switches are subjected to high stress of dv/dt. Multilevel Inverters (MLIs) have been introduced to overcome the above-mentioned issues. MLIs have several advantages over two-level traditional inverters, viz, low dv/dt stress on switches, low common mode voltage, low switching losses, high quality output, etc, and also they enable the usage of various renewable energy sources. MLIs have widespread applications in the areas of PV systems [10-12], Flexible AC Transmission Systems (FACTS), Electric Vehicles (EV), micro grids, electric traction, etc. A tree diagram for MLIs is depicted in Figure 1 below.

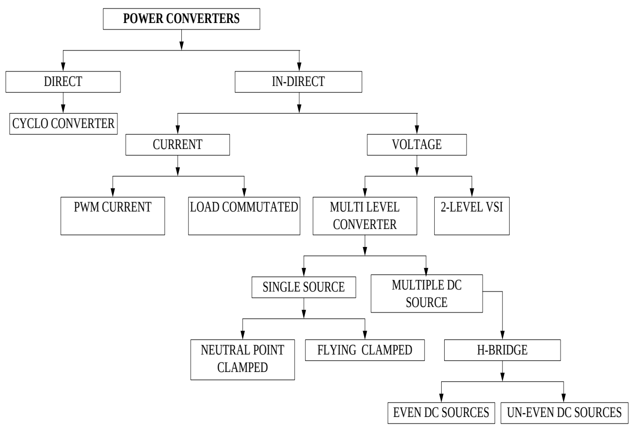


Fig. 1 Tree diagram for multi-level inverters

The paper is structured as mentioned. Section II provides briefs about multilevel inverters, solar photovoltaic systems are deliberated in Section III, Grid-connected solar photovoltaic systems integrated with multilevel inverters are deliberated in Section IV, and the paper is finally concluded in Section V.

2. Multilevel Inverters

MLI are used to attain higher power by using switches and DC voltage sources to accomplish power transformation by combining a voltage waveform of staircase shape. The DC sources used in MLI can be placed by renewable energy voltage sources like batteries and capacitors [13-16].

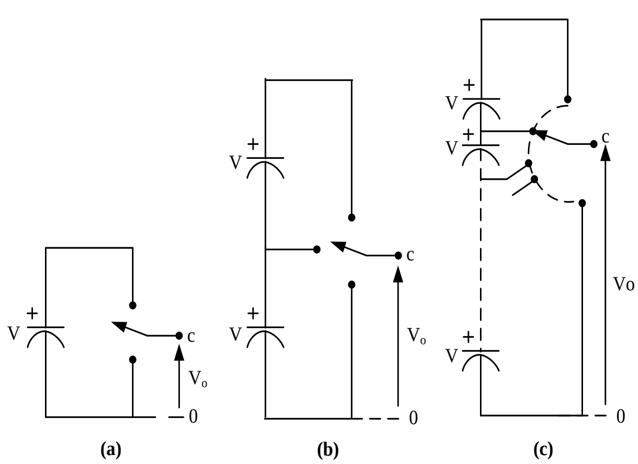


Fig. 2 One leg branch of MLI (a) Two-level, (b) Three-level, and (c) ‘n’ level.

Two values of voltages are generated by a two-level MLI, a three-level MLI with output voltages with three values, n level MLI with output voltages with n values, and so on. Figure 2 below depicts one leg branch of MLI for different levels of voltages with respect to the negative terminal, with a number of switches and input DC voltage sources. The phase voltage with respect to the negative terminal of the inverter is ‘m’. And ‘n’ is the load voltage steps between two phases, given as

$$n = 2m + 1 \quad (1)$$

The star-connected three-phase load with phase voltage for ‘p’ steps is given as

$$p = 2n - 1 \quad (2)$$

With respect to the number of sources, single DC source-based MLI and multiple DC source-based MLI are two types of MLIs. Subjected to the input DC source magnitude, MLI’s topologies can be symmetrical and asymmetrical. According to generation, MLIs can be used for level generation and polarity generation. The number of output levels can be generated by the different arrangements of switches and DC sources; its output is unipolar. Positive and negative H-bridge MLIs are used to produce a bipolar output. PV systems applications use these topologies, as a number of DC voltage sources are required on the input side. MLIs involve three basic topologies; further, four subtypes of multilevel inverters are formed by combining these three topologies. Various control topologies for MLIs are multi-level sinusoidal Pulse-Width Modulation (PWM), Space Vector Modulation (SVM), Selective Harmonic Elimination (SHE), etc.

2.1. Diode-Clamped (Neutral Point Clamped) MLI

A diode-clamped (neutral clamped) MLI consisting of two capacitors, two diodes and four switches for a three-level MLI topology shown in Figure 3 below.

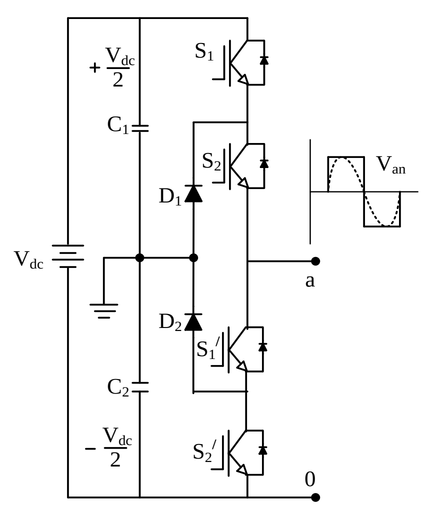


Fig. 3 Diode clamped multi-level inverter circuit topology for three-level

Three levels of output voltages can be obtained by the series connection of two capacitors. 'C_1' and 'C_2'. The neutral point, 'n', is at the center of two capacitors, and the three levels of output voltages are 'V_{an}' are '$V_{dc}/2$', '0' and '$-V_{dc}/2$' respectively. By turning 'ON' switches 'S_1' and 'S_2' and output voltage '$V_{dc}/2$' will be obtained by turning 'ON' either pair switches 'S_1' and 'S_1'' or switches 'S_2' and 'S_2'' and output voltage '0' will be obtained, by turning 'ON' switches 'S_1'' and 'S_2'' and output voltage '$-V_{dc}/2$' will be obtained. The blocking diodes and the active device have the same voltage rating; the number of diodes required for each phase is $(m-1)*(m-2)$.

2.2. Capacitor Clamped (Flying Capacitor) MLI

A capacitor-clamped (flying capacitor) MLI consisting of two capacitors, two diodes and four switches for a three-level MLI topology is shown in Figure 4 below.

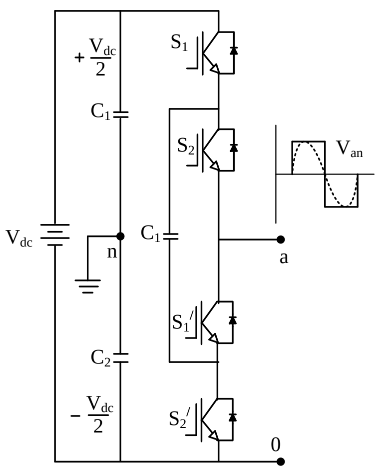


Fig. 4 Capacitor clamped multi-level inverter circuit topology for three-level

Three levels of output voltages can be obtained by the series connection of two capacitors 'C_1' , and 'C_2'. The neutral point, 'n', is at the center of two capacitors; the three levels of output voltages generated are '$V_{dc}/2$', '0' and '$-V_{dc}/2$' respectively. By turning 'ON' switches 'S_1' and 'S_2' and output voltage '$V_{dc}/2$' will be obtained by turning 'ON' either pair switches 'S_1' and 'S_1'' or switches 'S_2' and 'S_2'' and output voltage '0' will be obtained, by turning 'ON' switches 'S_1'' and 'S_2'' and output voltage '$-V_{dc}/2$' will be obtained. Capacitors 'C_1' gets *charged* by turning 'ON' switches 'S_1' and 'S_1'', and when switches 'S_2' and 'S_2'' are turned 'ON' it gets discharged. The capacitor used has the same voltage rating as that of the main power switch. For an 'm' level inverter, the number of clamping capacitors per phase is '$\frac{1}{2}*[(m-1)*(m-2)]$'.

2.3. Cascaded Multi-cell Inverters

A number of *single*-phase inverters with a separate DC source are connected in series to form a cascaded H-bridge MLI. The total phase voltage is obtained by adding the voltage produced by different cells. Each single-phase full-bridge inverter generates three voltages, '$+V_{dc}$', '0' and '$-V_{dc}$'. The final output voltage lies in the range of '$-4V_{dc}$' to '$+4V_{dc}$' for a nine-level MLI, obtained by connecting capacitors on the AC side, including four power switches. A nine-level inverter with four cells per phase and one leg is depicted in Figure 5 below.

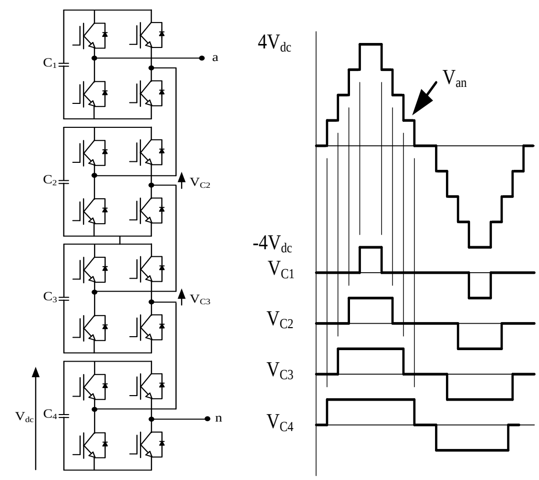


Fig. 5 Cascaded multi-cell inverter topology and its waveform

3. Solar Photo-Voltaic Systems

Researchers are working on the utilization of solar energy for the generation of electrical power as it is an alternative option to the conventional energy sources like coal, gas, and petrol, which are being exhausted at a faster rate due to the growing demand for electric power. A solar Photovoltaic (PV) system consists of PV arrays, Power converters and controllers.

3.1. PV Array

The basic element of a PV system is a PV cell, the input power is solar radiation, and it is converted to electrical power using a PV cell. The practical PV cell is depicted in Figure 6 below. Each PV cell produces an output voltage of around 0.5V and a current of around 25 mA/cm2. They are connected in series and parallel combination to achieve higher voltages and current [17, 18].

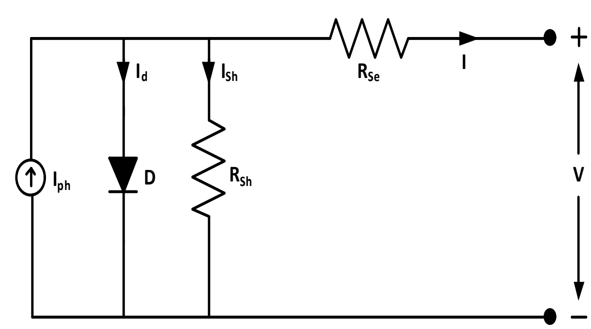


Fig. 6 Practical PV cell

The output load current 'I ' is,

$$I = I_{Ph} - I_d - I_{Sh} \quad (3)$$

$$I = I_{Ph} - I_o\left[exp\left(\frac{V+IR_{Se}}{aV_T}\right) - 1\right] - \left(\frac{V+IR_{Se}}{R_{Sh}}\right) \quad (4)$$

Load current and voltage are represented by "I" and "V" respectively. Photon-generated current, diode current and shunt current are represented by "I_{Ph}", "I_d" and "I_{Sh}" respectively. A PV system consists of blocking diodes and bypass diodes. Blocking diodes block the flow of current back to the PV panels from the batteries, and allow current flow from the PV panel to the batteries. Bypass diodes connected in parallel to the PV array provide an alternate path for current flow in case of the malfunctioning of the PV array for any reason. Figure 7 below depicts a PV system with uniform illumination over it.

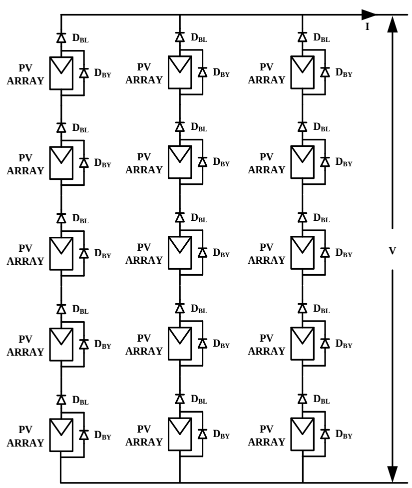


Fig. 7 Photovoltaic system exposed to uniform illumination

The number of PV arrays located in the PV system is subjected to uniform illumination. The output load current 'I' for a PV array with uniform illumination is

$$I = N_{Sh}I_{Ph} - N_{Sh}I_O\left[exp\left(\frac{V/_{N_{Se}} + {IR_{Se}}/_{N_{Sh}}}{aV_T}\right)\right] - \left[\frac{V/_{N_{Se}} + {IR_{Se}}/_{N_{Sh}}}{R_{Sh}}\right] \quad (5)$$

The solar illumination on overall PV panels may not always be uniform due to obstacles for several reasons, like passing clouds, bird droppings, and shadows of various particles flying over the panels, leading to a significant drop in the generating voltage. The Figure 8 below depicts a PV system with non-uniform illumination over it. A number of PV arrays located in the PV system are subjected to partial shading, hence illumination is not uniform all over the PV system.

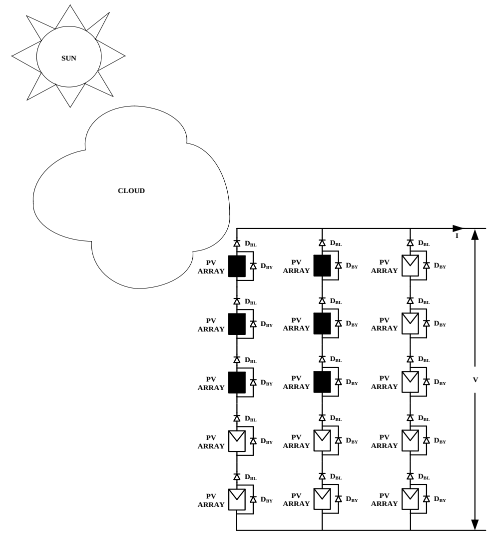


Fig. 8 Photovoltaic system with non-uniform illumination

The effective illumination 'G_e' on each of the PV arrays diverges and is given as

$$G_e = (1 - S)G \quad (6)$$

'G' is the illumination on the unshaded PV array, and shading ratio 'S' is defined as the ratio of PV array shaded area to the total area of PV array. The photo generated current 'I_{Ph}', for a shaded and unshaded PV array is

$$I_{Ph(G1)} = \left(I_{SC,Ref} + K_{ISC}\left(T - T_{Ref}\right)\right) * \frac{G_1}{G_{Reg}} \quad (7)$$

$$I_{Ph(G2)} = \left(I_{SC,Ref} + K_{ISC}\left(T - T_{Ref}\right)\right) * \frac{G_2}{G_{Reg}} \quad (8)$$

Here, $I_{Ph(G1)}$, $I_{Ph(G2)}$ is the photo-generated current due to illumination on the PV array, K_{ISC} The current coefficient, short circuit current, is $I_{SC,Ref}$. At standard test conditions, at standard test conditions the temperature is T_{Ref}. At standard test conditions, the Irradiance is G_{Reg}, illumination on individual PV arrays is G_1, G_2.

The output load current 'I' for a PV array with uniform illumination is

$$I = N_{Sh}I_{Ph} - N_{Sh}I_O\left[exp\left(\frac{V/_{N_{Se}} + {IR_{Se}}/_{N_{Sh}}}{aV_T}\right)\right] - \left[\frac{V/_{N_{Se}} + {IR_{Se}}/_{N_{Sh}}}{R_{Sh}}\right] \quad (9)$$

3.2. DC-DC Converter

A boost converter is depicted in Figure 9 below. It is used for modulation of the DC input voltage to a desired level [19, 20].

A diode and an n-channel MOSFET in a converter serve as energy-storing elements. In the course of its operation, they complement one another. During the diode in ON operation, MOSFET will be OFF, and when the diode is in OFF, MOSFET will be ON.

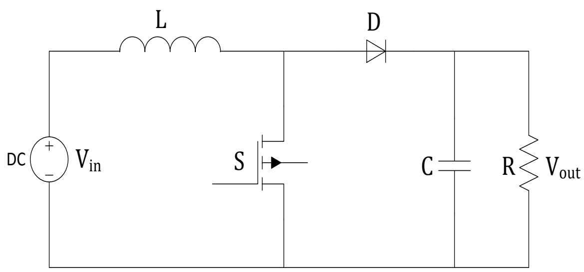


Fig. 9 DC-DC boost converter

The capacitor current and inductor voltage are,

$$i_c = c\frac{dv_c}{dt} \tag{10}$$

$$v_L = L\frac{di_L}{dt} \tag{11}$$

The boost converter operation is illustrated in the two Figures below. Figure 10 depicts the MOSFET during ON operation, and Figure 11 depicts the MOSFET during OFF operation.

Mode I - MOSFET during ON operation

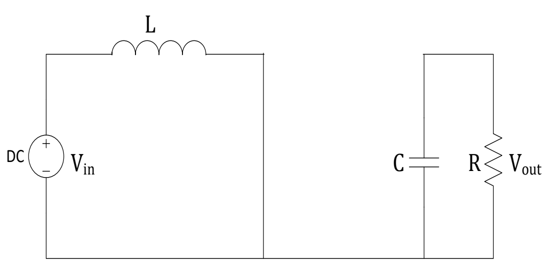


Fig. 10 MOSFET during ON operation

The inductor voltage '$\boldsymbol{v_L}$', during the OFF operation of the MOSFET.

$$\boldsymbol{v_L = v_{in} * PWM} \tag{12}$$

Mode II - MOSFET during OFF operation,

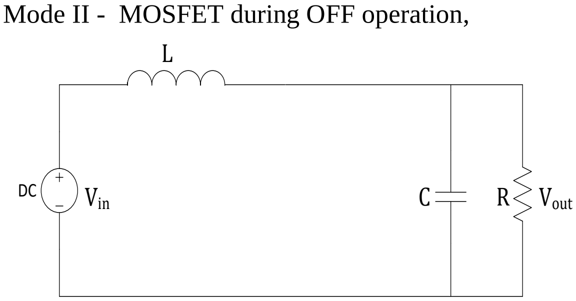


Fig. 1 MOSFET during OFF operation

The inductor voltage 'v_L', during the OFF operation of the MOSFET

$$v_L = (v_{in} - v_{out}) * \overline{PWM} \tag{13}$$

The switching frequency, PWM, is,

$$PWM = \frac{(v_{out} - v_{in})}{v_{out}} f_{pwm}^{-1} \tag{14}$$

The inductor current is,

$$i_L = \int v_L dt \tag{15}$$

The capacitor current is,

$$i_C = i_L - i_R \tag{16}$$

Finally, the capacitor voltage is,

$$v_C = \frac{1}{C}\int i_C dt \tag{17}$$

Duty cycle is

$$D = 1 - \frac{v_i}{v_o} \tag{18}$$

The inductor and capacitor value are,

$$L_{min} = \frac{D(1-D)^2 R}{2f} \tag{19}$$

$$C_{min} = \frac{v_o D}{\Delta v_o R f} \tag{20}$$

$$R_{in} = (1-D)^2 R \tag{21}$$

4. Grid-Connected Solar Photovoltaic Systems Integrated with Multilevel Inverter

The power generated from the PV system is DC; it has to be inverted to AC to feed the generated power to the utility grid. The generated DC power has to be stepped up before connecting to the common DC bus to avoid any mismatch in the PV-generated voltage, and this common DC bus power has to be inverted; MLIs do this job as they have numerous advantages over the conventional two-level inverters. DC to DC and AC to DC power conversion has to be done efficiently to avoid power loss.

MLIs with high voltage levels have good conversion efficiency as harmonic content and electromagnetic interference are reduced to a great extent [21, 22]. The block diagram of grid-connected solar PV systems integrated with MLI connected to the AC utility grid and to local isolated load is shown in Figure 12 below.

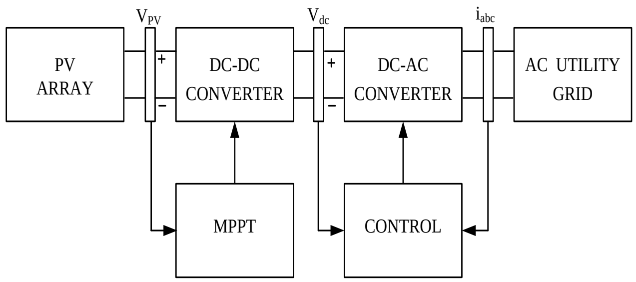
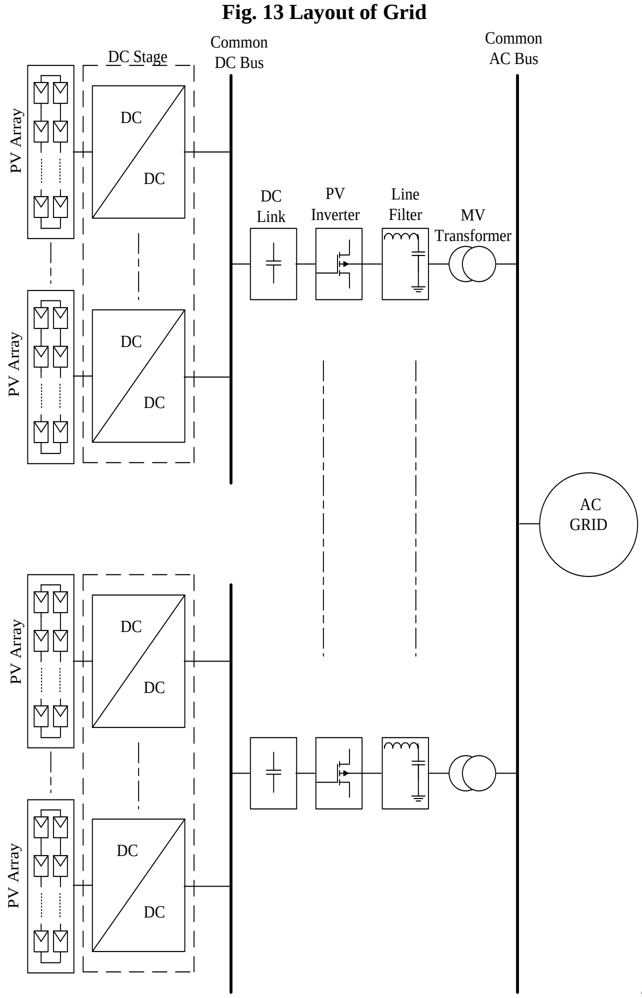


Fig. 12 Grid-Connected solar PV systems block diagram

The typical voltage and frequency fed to the AC grid or the utility are controlled by the inverter controller. A typical layout of the PV system connected to the grid is shown in Figure 13 below.

Fig. 13 Layout of Grid



Connected PV system

5. Controlling the Multilevel Inverter

The PV system generates voltage after power transformation by various controlling devices and is fed to the utility grid after [22-25].

5.1. Power Control From the Grid Side

Conventional PI controllers are used to control output currents of the inverter in the abc synchronous frame using current control and voltage control loops. Unity power factor can be achieved by obtaining voltage and current phasors in phase with respect to each other using a reference reactive power.

5.2. Inverter Control

The inverter switching characteristics are controlled using the controller. DC-link voltage is sent to the voltage regulator, and the PLL is fed with the remaining two inputs to retain a similar phase and frequency of current and grid voltage. The d-q axis frame is produced by the PLL and is fed to the current controller. The output parameters are again transferred to the abc frame, and the inverter pulse width can be calculated for each arm.

5.3. Inner Current Loop

The inverter current is controlled by the current loop function, and the voltage is controlled by the grid. The active power 'P' and the reactive power 'Q' are injected by the PV inverter and are given as

$$P = V_d I_d + V_q I_q \tag{22}$$

$$Q = -V_d I_q + V_q I_d \tag{23}$$

The d,q components voltages and currents are spelt above. The PLL fixes the grid frequency so that the grid side transformer q-axis voltage will be forced to zero, $V_q = 0$. The above active power 'P' and the reactive power 'Q' will be modified as

$$P = V_d I_d \tag{24}$$

$$Q = -V_d I_q \tag{25}$$

5.4. Outer Voltage Loop

The grid-interfacing inverters use a transformer and PI controller to maintain a constant DC voltage, which is essential for better functioning. The transfer function relating 'I' and 'I^*' is a first-order transfer function.

5.5. Phase Lock Loop (PLL)

The primary function of PLL is to make sure that the output of the inverter injects power to the grid at the proper phase angle and frequency, and synchronize the output of the inverter with the grid to maintain a reliable and stable connection. PLL generates a control signal to maintain the inverter's output with the grid parameters. The phase and frequency are monitored by the internal frequency oscillator, so as to maintain a phase difference of '0' by adjusting the internal oscillator frequency. The internal structure of a PLL is depicted in Figure 14 below.

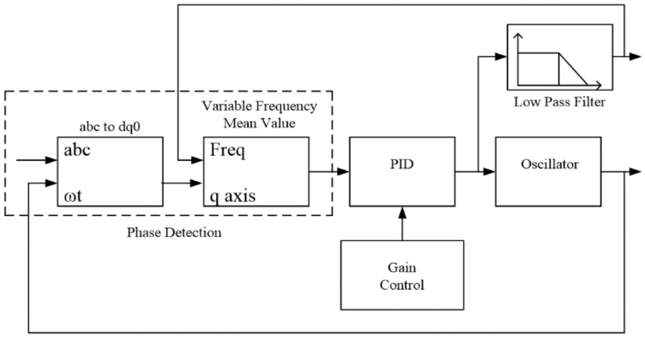


Fig. 14 Internal structure of a PLL

A set of variable frequency, three-phase sinusoidal signals is synchronized by the PLL.

6. Conclusion

The source of power generation is moving towards the usage of renewable energy sources, and the grid-connected PV system is in high demand in the present situation. The MLI have numerous advantages over the conventional two-level converter; hence, this paper presents a comprehensive review of integrating MLI with the grid-connected PV system. A wide review of its various components is provided. MLI advantages, classification is deliberated. PV array and its modelling under uniform and non-uniform conditions are discussed. DC-DC converter operating modes are also briefed. The controllers for MLI to maintain proper synchronization with the grid are also expressed. This article would serve as a guide for scholars working in the area of grid-connected PV systems, as a complete state-of-the-art review is provided.

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