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Differents topologies of three-phase grid connected inverter for photovoltaic systems, a review

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Abstract:
Three-phase inverters are widely used today as converters in many fields of application including renewable energies. Compared to single-phase inverters, three-phase inverters have a longer service life. This paper is essentially devoted to a review of the literature on the various topologies of three-phase inverters connected to the grid. The various power components of the inverters and the losses they generate have been described. Based on a few evaluation criteria, basic three-phase inverters such as Voltage source inverter, current source inverter and Z-source inverter were compared. Finally, the various three-phase inverter structures and their advantages and disadvantages are discussed.

Keyword: Keyword: Three-phase; grid connected; photovoltaic systems; Inverter; Power Components.

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1. Introduction

The constraints posed by fossil energies have gradually led to the development of alternative sources of energy, namely renewable energies. In particular, solar photovoltaic (PV) energy remains very promoter. Capturing solar energy through photovoltaic panels, in order to produce electricity is considered one of the most promising markets in the field of renewable energy. The performance of a solar photovoltaic system depends strongly on the quality, stability and reliability of the energy that it delivers [1, 2].

In recent years the interconnection of photovoltaic systems on grid has evolved to meet the demand of certain electrical charges that are only powered by alternative voltage and increased use of clean and carbon-free energy [3].Grid connected systems play an important role in the production of distributed energy. With the help of government incentives, their use is becoming more widespread within the community [4]. These systems consist of a photovoltaic generator for converting solar irradiation into direct current and an inverter for converting direct current to alternating current [5].

With regard to the grid connection, single-phase PV inverters and three-phase PV inverters are available on the market. In low-power photovoltaic systems connected to the domestic and medium power grid, chain converters within a power range of 1 to 5 kW are widely used. For a power range greater than 10kW, three-phase inverter topologies are mainly used [6].

Three-phase topologies compared to single-phase inverters have a longer service life, improved efficiency, smaller size and lower costs due to the absence of an electrolyte capacitor and reduced stress and dimensioning semiconductors and magnetic components [5]. Several topologies of three-phase inverters exist on the market and differ in their characteristics, structures and applications.

This paper first explains the various power components used as switches by the inverters and the most important losses generated by the latter, and then we will see the various topologies of three-phase inverters and their advantages and disadvantages. Finally, a discussion on the differents topologies and a conclusion will be given.

2. Power semiconductor switches for inverters

Power electronics is the application of power semiconductor devices for the control and conversion of electric energy. These semiconductor components are very widely used in many applications today such as the renewable energy applications, electric drives and power supplies [13]

1. – The power components

In recent years inverters are increasingly used in a large number of applications, for the following reasons: The increased power capabilities, ease of control, and reduced costs of modem power semiconductor devices.There are different types of switches generally used depending on the power range and frequency of use and can be classified into three groups according to their degree of controllability: Diodes, Thyristors and Controllable switches. The controllable switch category includes several device types including bipolar junction transistors (BJTs), metal-oxide-semiconductor field effect transistors (MOSFETs), gate turn off (GTO) thyristors, and insulated gate bipolar transistors (IGBTs) [7].

Among these different types of elements, the MOSFETs and the IGBTs are widely used more in the design of inverters. Power MOSFET can operate at somewhat higher frequencies (a few to several tens of kHz), but is limited to power ratings, usually 1000V, 50A. Insulated-gate bipolar transistor (IGBT) is used while voltage requirement increases and it also offers better speed than a BJT but is not quite as fast as a power MOSFET [8] .The IGBT still has the disadvantages of a comparatively large current tail and the lack of a body-drain diode [9] . For the MOSFET, it is almost invariably used in today's high-frequency power converter applications being a voltage controlled, fast switching and majority-carrier device [10].The drawbacks of the MOSFET are that: It requires a high base current to turn on, it has relatively slow turn-off characteristics (known as current tail), and it's susceptible to thermal runaway due to its negative temperature coefficient [9].

All these semiconductor devices are often the basis of enormous losses noticed in the inverters.

2. –Semiconductors power losses

The efficiency of inverters depends heavily on power losses that occur in its components. The two most important causes of power losses in components of an inverter that must be considered are conduction and switching losses. The evaluation of these losses depends strongly on the type of semiconductor component used by the inverter.

Conducting losses : The Conducting losses can be calculated using linear approximation of power switch static volt-ampere characteristic that corresponds to the switch on-state equivalent circuit represented by series connection of the voltage source with the known value of threshold voltage $V_{(TO)}$ and the resistor with the known value of differential resistance r_T.There to average I_{AV} and effective I_{RMS} currents of the power switch for the chosen type of power converter should be defined. The average power of static losses P_{cond} is:

$$P_{cond} = I_{AV} \cdot V_{(TO)} + I^2{}_{RMS} \cdot r_T \quad \text{[Eq. 1] [11].}$$

Switching losses: The share of switching losses in the total loss of inverter systems is not negligible. Therefore it is necessary to calculate them accurately. Switching loss is the powers dissipated during the turn on and turn off switching transitions. In PWM switching losses can sustainable and must be considered in thermal design. To estimate average switching power losses read the Esw (on) and Esw (off) values from the curve at the expected average operating current. Average power dissipation is then given by:

$$P_{sw} = F_{sw} \cdot \frac{E_{sw}(on) + E_{sw}(off)}{\pi} \quad \text{[Eq. 2]}$$

The main use of the estimated power loss calculation is to provide a starting point for preliminary device selection. The final selection must be based on the rigorous power and temperature rise calculation [12].

The total loss generated by the power component is given by:

$$P_{total} = P_{sw} + P_{cond} \quad \text{[Eq. 3]}$$

A simple mathematical scheme for estimating the losses in the IGBT proposed in [12] reveals that the accuracy of the resulting total losses depends strongly on the data sheets or experimental measurements.

3. Basic three-phase inverters

Inverter topologies can be basically divided into two main types: Voltage-Source inverters (VSI) and Current Source inverters (CSI). In recent years, the Zsource inverter [20-22] which is the combination of the both as a third type is considered to be used in systems connected to the photovoltaic grid.

1.-Voltage-Source Inverter (VSI)

Voltage source inverters (VSI) (Figure1) are commonly used in uninterruptible power supplies to connect the photovoltaic generator (GPV) to the AC power grid. This type of inverter at its AC output voltage always lower than the DC input voltage [14]. A VSI with neutral-point connection needs at least a dc-link voltage of 650V to feed into a three-phase 400V grid as each dc-link capacitor needs to have a voltage higher than the amplitude of the phase voltage. In the practical design, the dc-link voltage actually needs to be 700-750V due to a 10% grid voltage tolerance and some control reserve. The reason why the neutral point

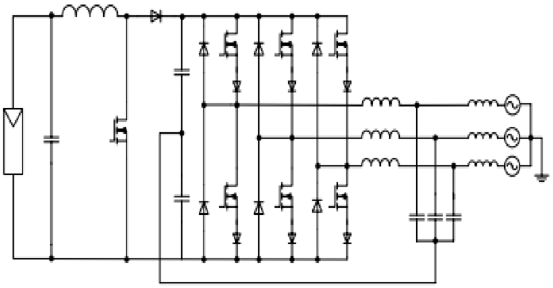

Figure 1 : Typical circuit diagram of a MOS-equipped VSI+BC for a PV module generation system

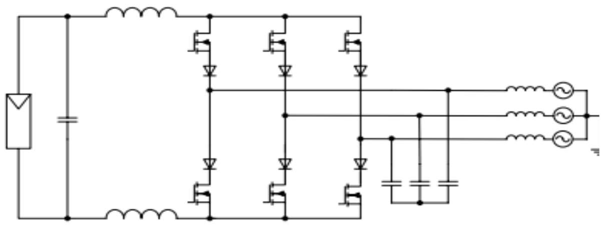

Figure 2: Circuit diagram of a MOS-equipped CSI for a PV module generation system

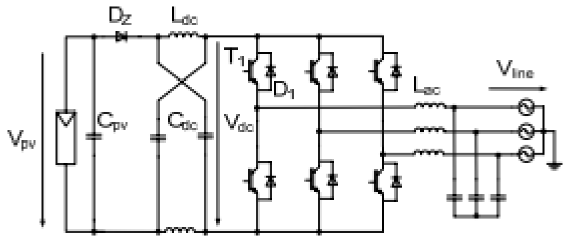

Figure 3: Z-Source inverter with voltage source bridge

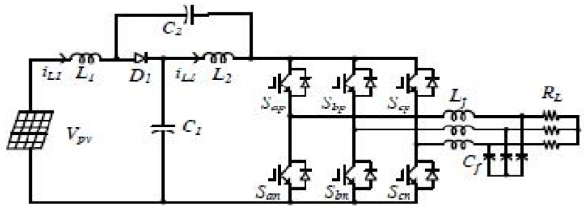

Figure 4: QZSI in the PV power generation system

should be connected to the dc-link is to minimise common-mode voltages at the PV module. This issue will be discussed in the following sections. A VSI directly connected to the PV module would even need a higher MPP voltage because of a module manufacturing tolerance. An additional dc-dc boost converter (BC) would be required which can work with lower MPP voltages [15]. The advantage of the VSI is that it has a common mode current across the potentially low GPV, standard IGBT modules / drivers can be used. However, VSI has some disadvantages such as: many passive components no short-circuit protection, need for an additional boost converter [6].

2.-Current-Source Inverter (CSI)

In the current source inverter (CSI), the input acts as a current source, the output current is kept constant regardless of the load on the inverter [16]. This type of inverter (Figure 2) increases the voltages to the mains supply. The inverter operates up to a maximum DC voltage not to exceed, if not beyond this voltage, it is out of control [17]. This inverter is a viable alternative to VSI + BC (Buck Converter) [18], [19]. The advantages of this inverter is that it requires fewer components and no AC current sensors needed .Unfortunately the input voltage range of this inverter is limited, it has No standard power modules/drivers applicable , not open-circuit proof [6], [15].

3.-Z-source Inverter (ZSI)

The Z-source inverter (ZSI) (Figure 3) was presented in [20]. The inability of the VSI and CSI inverters to act as buck-boost converters at the same time and their vulnerability to EMI noise in terms of reliability can be overcome by using a Z-Source inverter that employs two inductors and two capacitors. By selecting the suitable values of Inductors and capacitors it can be used as VSI or CSI. Therefore without changing the circuit it can work as both Buck/Boost inverters [21]. This inverter requires fewer semiconductor components, has a wide input voltage range, it can operate based on standard IGBT power modules. Its main disadvantage is the high voltage stress of the capacitors [6]. This problem has been solved in [22] which propose new inverter topologies similar to the Z-source inverter called quasi Z-source inverter (QZSI) (Figure 4) and reduces stress, number of components and simplifies control strategies.

A comparison between these basic concepts based on normalized stress factors presented in [6] reveals that The ZSI features a single-stage concept with buckand boost-capability, but it has high relative switching stress at low input voltage, which has a negative impact on partial load efficiency. This topology tends to require large passive components too. On the other hand The CSI has its benefits when switching stress and size of passive components is concerned at the cost of high semiconductor current stress. This means that it requires larger semiconductors than its counterparts. When a wide input voltage range is needed, the CSI also suffers the necessity of an additional Buck Converter and finally, The VSI+Boost Converter presents a good trade-off between wide input voltage range, low current stress and moderate switching stress. However, it requires more and larger passive components than the CSI and also two more semiconductor devices.

4. Three-phase inverters topologies

As we have seen above, three-phase inverters play an important role in the connection of PV systems to the grid. Several topologies have been proposed in the literature in recent years.

1.-Three-Phase three wire inverter topology

Three-phase inverters can be designed to have a three-phase system where the inverter itself does not provide a neutral point. Typically, a Δ/Y_g transformer is used with the secondary center grounded before the inverter powering the load or being connected to utility (Figure 5). In this topology, the three-wire system on the Δ-side only has two independent dimensions and 0-axis current, which makes the system relatively easy to control. The drawback is the existence of the costly, heavy, and bulky transformer [23].

2. - Three-Phase four wire inverter topologies

This topology is widely used to supply electrical energy to single-phase or three-phase loads. There are two types of four-wire inverter topologies: three legs with split DC bus and four legs.

2.1. - Three legs with split DC bus

A three-phase three-leg inverter with split dc bus is one topology to implement three-phase four-wire system with a neutral point seen by the load [25]. This topology is represented by Figure 6. The advantages of this topology are as follows: it is simpler and uses fewer semi-conductors; it does not have the isolation transformer and provides three-dimensional control [25, 26]. However, several problems are introduced when choosing the split-link topology. One of them is to ensure equal voltage sharing between the divided capacitors and the need to attenuate the voltage ripple. This results in the need for large and expensive dc-link capacitors or even extra balancing structures. Another disadvantage is caused by the fact that the split-link topology requires that the phase voltage peak is less than or equal to half the total dc-link voltage, whereas the four-leg inverter can follow a line-voltage peak equal to half the total dc-link voltage. This gives an approximately 15% advantage in dc voltage utilization in favor of the four-leg inverter [27, 28]. To overcome these problems, several solutions have been proposed in the literature: [27] uses a two quadrant chopper to regulate capacitor voltages in a two capacitor compensating structure. In [29] a control strategy has been proposed to force the neutral current, to flow through the inductor of the neutral leg so that the neutral point is maintained stable and balanced for an inverter, even when the neutral current is large. [30] Proposes a compensator with a voltage source inverter, two DC storage capacitors and a two quadrant chopper to equalize the capacitor voltages in the neutral shunt compensator for a 4-wire three-phase distribution system. The authors of [31], propose an algorithm based on Linear Matrix Inequalities (LMIs) for the selective compensation of the imbalance, the phase shift and the harmonic distortion of the load currents of a four-wire three-phase system. A modified UPQC topology for the four-wire three-phase system has been proposed in [32], which has the capability of compensating the load at a lower DC link voltage under a non-rigid source.

2.2.-Three-phase four legs inverter

The three-phase four-leg topology, illustrated in Figure 7, requires two additional power switches (Sn1 and Sn2). The advantages of this topology are the increased maximum output voltage value, reduction of neutral currents and the possibility of neutral point voltage control [33].However, this topology presents a serious disadvantage, which is that the extra two switches result in a complicated control which makes the

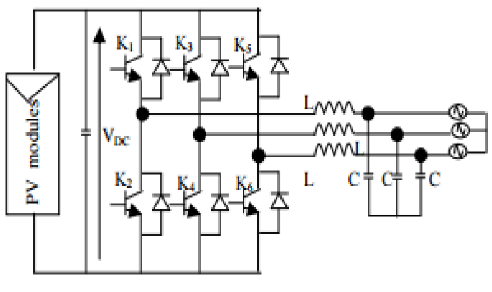

Figure 5: Topology of the three phase three-wire inverter

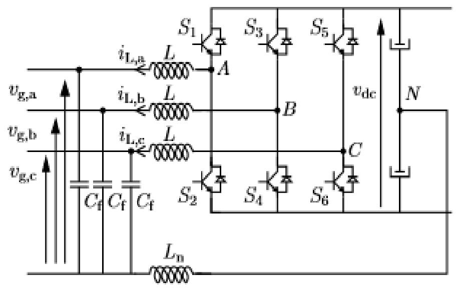

Figure 6 : Topology of the three phase four-wire inverter with split dc-link

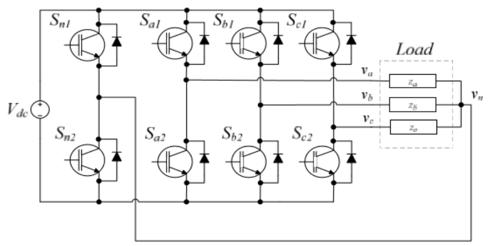

Figure 7: Toplogy of three phase four leg inveter

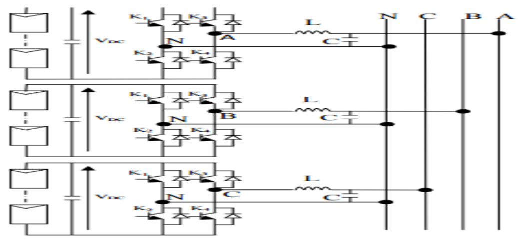

Figure 8 :Topology of the three phase four-wire multi-string inverter

topology less interesting [5]. The often used control techniques of this topology are referred to as spatial vector modulation (SVM), generally using complex mathematical algorithms based on three-dimensional geometric figures. To overcome this problem, new control techniques are proposed in the literature. An approach based on the separation of the control of the fourth leg from that of the other phases, allowing the application to the three-phase inverters of traditional SVM techniques and avoiding the use of complex procedures was proposed by [33]. [24] Proposes a modified *p–q–r* theory based digital current control in three-phase four-leg VSI to resolve the problems of harmonics elimination, reactive power compensation and symmetrisation of asymmetrical three-phase load. [34] Proposes a novel control strategy including an adaptive current-limiting scheme for grid-connected three-phase four-leg inverter. In [35] a three-dimensional (3-D) space vector pulse width modulation (SVPWM) technique via a 4 × 4 orthonormal transformation matrix that has been used as a new approach in controlling a three-phase four-leg

3.-Three-phase Multi-string Inveter

To achieve high power demand purpose, we need large space requirements; connections provide to the PV system become complex and high rating equipments are necessary. One of the important limitations is the single control for the whole photovoltaic system. This paved the way for the string inverter topology. It is not possible to extend the rated power of single strings by connecting more PV modules to the PV strings. So the next step in the evolution of string inverter topology is multistring inverters. Multistring topology is the symbiosis of two main competitors in the PV system- the central and string topology [36, 37]. Figure 8 illustrates a single-phase multistring inverter. This architecture, due to the individual and optimal exploitation of each string, allows the parallel connection of several chains and can be connected to single-phase or three-phase electrical networks [38].

4.-Multilevel inverter

The concept of multilevel converters has been introduced since 1975. The most common MLI topologies are classified into three types: neutral point clamped (NPCMLI) or diode clamped MLI (DCMLI), flying capacitor MLI (FCMLI), and Cascaded HBridge MLI (CHBMLI).

4.1. - Diode Clamped MLI (DCMLI)

A five-level three-phase DC-MLI topology is shown in Figure 9. Each bridge arm has eight switch tubes. DC capacitor is composed of four like capacitors connected in series, led D1, D2, D3, D1 ', D2 ' and D3 ' called the clamp diode, it can make the converter outputs five voltage waveforms: 0, E, 2E, 3E and 4E five levels. In every moment, the converter must have four on-off tubes. To A state as an example, the possible switch tube are the combination of (VT1, VT2,VT3 and VT4),(VT2,VT3,VT4 and VT1') (VT3,VT4, VT1' and VT2'),(VT4', VT1' VT2 and VT3') , (VT1' ,VT2 ',VT3 ',VT4') . Any other combinations are not allowed. In the process of commutation in across two levels above the switch state is not allowed [39]. The main advantages of this topology are: High efficiency for the fundamental switching frequency, the capacitors can be pre-charged together at the desired voltage level, the capacitance requirement of the inverter is minimized due to all phases sharing a common DC link. The disadvantages of this topology are : Packaging for inverters with a high number of levels could be a problem due to the quadratically relation between the number of diodes and the numbers of levels , Intermediate DC levels tend to be uneven without the appropriate control making the real power transmission a problem [40].

4.2.-Flying capacitor MLI (FCMLI)

The FCMLI requires a large number of capacitors to clamp the device (switch) voltage to one capacitor voltage level provided all the capacitors are of equal value, an n-level inverter will require a total number of (n-1)(n-2)/2 clamping capacitors per phase leg in addition to (n-1) main dc bus capacitors. Figure 10 shows the three phases six level flying capacitor based multilevel inverter. Let us consider the group of capacitors in a single clamping leg as one equivalent capacitor, which is also applicable for 'n' level inverter. If the voltage of the main dc –link capacitor is V_{dc}, the voltage of inner most capacitor, the inner most two devices is V_{dc}/ (n-1). The voltage of the inner most capacitor will be V_{dc}/ (n-1) + V_{dc}/ (n-1) = 2V_{dc}/ (n-1) and so on. Each next clamping capacitor will have the voltage increment of V_{dc}/ (n-1) from its immediate inner one voltage levels. The arrangements of the flying capacitors in the FCMLI structure assures that the voltage stress across each main device is same and is equal to V_{dc}/ (n-1) for an 'n' level inverter [41]. The most important advantages of FC-MLI topology are preventing the filter demand, and controlling the active and reactive power flow besides phase redundancies. Although these advantages, the increment of *m* level will restrain the accurate charging and discharging control of capacitors. The cost of inverter will increase and device will be more enlarged due to increased number of capacitors [38].

4.3. - Cascade H-bridge MLI

A cascade multilevel inverter made up of from series connected H-bridge inverter, each with their own isolated dc bus. Each level can generate three different voltage outputs +Vdc, 0, -Vdc by connecting the dc sources to the ac output side by different combinations of the four switches. The output voltage of m level inverter is the sum of all the individual inverter outputs. Cascade multi-level inverter consists of a number of H-bridge inverter units with separate dc source for each unit and it is connected in cascade or series as shown in Figure 11.

If the entire dc source equal to Vdc, the inverter is known as symmetrical multilevel inverter and the number of output phase voltage levels N_{step} in a

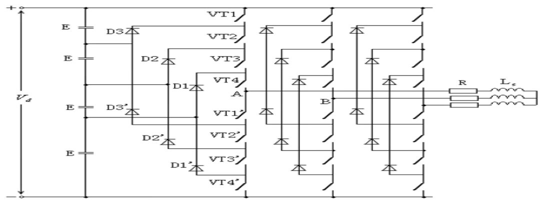

Figure 9 :Three-phase five-level topology of a diode clamped multilevel inverter.

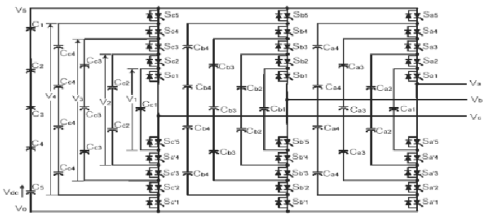

Figure 10 :Three phase Flying Capacitor based Multilevel Inverter

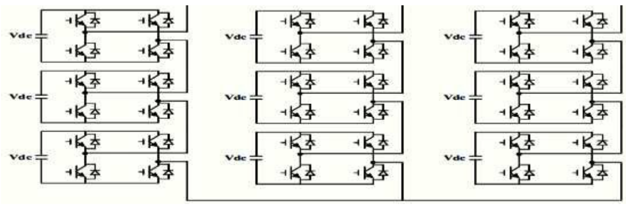

Figure 11 : Three phase structure of Cascaded Multilevel

cascade inverter is defined by:

$$N_{step}=2n+1 \qquad \text{[Eq. 4]}$$

Where n is the number of separate dc sources or the number of full bridges and the maximum output voltage (V_{max}) of this n cascade multi-level inverter is:

$$V_{max}=nV_{dc} \qquad \text{[Eq. 5] [42]}$$

This topology has several advantages: it does not have the voltage balancing problems, the modulation, control, and protection requirements of each bridge are modular [43]. Though it has wide application area and tremendous merits, it has greater disadvantage that it uses separate DC supply for each HBridge [44].

4.4.-Others Multilevel Inverter

There are other multilevel inverters topologies parts from the three base multilevel topologies seen above. However, most of them are combinations of the different basic topologies.

GENERALIZED MULTILEVEL INVERTER: This topology (Figure 12) is described in [45]. The generalized multilevel inverter topology can balance each voltage level by itself regardless of inverter control and load characteristics. The existing multilevel inverters such as diode-clamped and capacitor-clamped multilevel inverters can be derived from this generalized inverter topology. Moreover, the generalized multilevel inverter topology provides a true multilevel structure that can balance each dc voltage level automatically at any number of levels regardless

of active or reactive power conversion without any assistance from other circuits, thus in principle providing a complete multilevel topology that embraces the existing multilevel inverters.

REVERSING VOLTAGE MLI: This topology (Figure 13) is a hybrid multilevel topology. The output voltage is separated into two parts one part is for level generation part and is responsible for level generation in positive polarity. It requires high frequency power semiconductors switches to produce the required levels. In this part the switches should have high – switching frequency capability [46]. The main advantages of this topology are: easily extends to higher voltage levels by duplicating the middle stage, it requires fewer components in comparison to conventional inverters [47].

MODULAR MLI: It uses a setup of sub modules, which are either connected or by passed for generation of output voltage level. Every phase-leg consists of two arms where each arms has n number of sub-modules [48]. Figure 14 presents a three-phase modular multi-level inverter topology. A major advantage of the Modular MLI is its flexible module redundancy, which further increases reliability [49].

5. - Three-phase Inverter with stabilize

Another three-phase topology with stabilizer (Figure 15) has been proposed in [50]. The basic components of this topology are a stabilizer, a 6 IGBTs 3 arm bridge, a Filter LC and a 10KW load. The behaviour of the whole system would seem ideal if each of its parts were considered separately.The disadvantage of this topology is that when the Load is getting bigger the variation follows up and the sinusoidal characteristics are becoming worse off

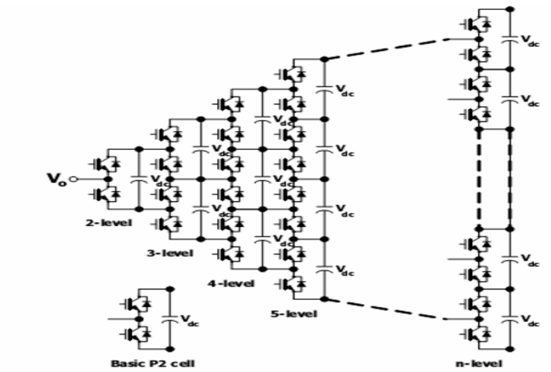

Figure 12: Generalized P2 multilevel converter topology for one phase leg.

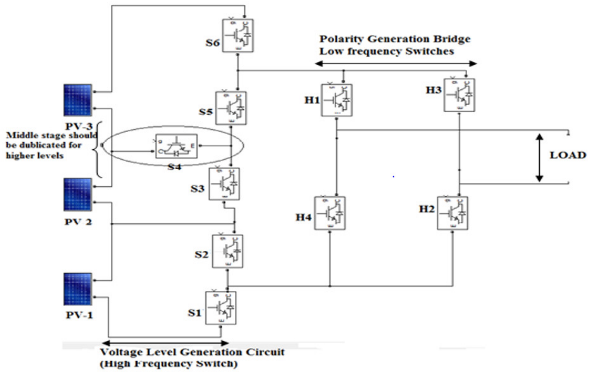

Figure 13: diagram of reversing voltage inverter topology in seven levels seven level inverter

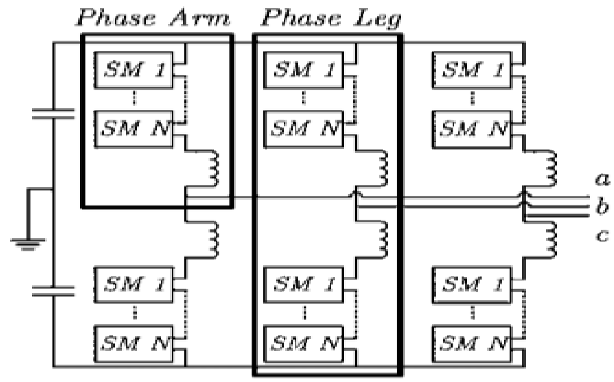

Figure 14: Three-phase modular multi-level inverter topology

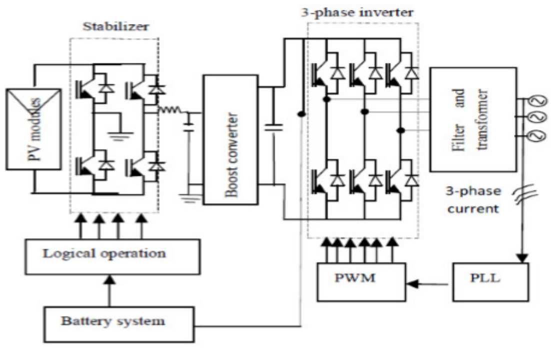

Figure 15 :Topology of three-phase inverter with stabilizer and transformer

5. Conclusion and discussions

In this paper devoted to the literature review, many three-phase inverter structures for photovoltaic systems connected to the network have been described.

In the first place we have presented the power components of the inverters and among these, it should be noted that the MOSFET and the IGBT are widely used more. These components are the basis of huge losses in the inverter, including conduction and switching losses, thus affecting the efficiency of the overall system.

The three types of basic three-phase inverters namely Voltage-Source Inverters (VSI), Current-Source Inverters (CSI) and Z-Source Inverter. The basics behaviors of these topologies are described. The advantages and disadvantages of each of them have been explained. It is apparent that in a practical design, a detailed optimization of each of the basic three-phase inverter types can give it overall performance similar to the other types, depending on the components available in the specific power range.

6.-Three-Phase Parallel Inverter

Parallel operation of inverters is a viable way to increase power. Each parallel module takes its share of load, so the current stress on power switch is reduced greatly. However, in the parallel inverter, in order to reduce the effect of current, the output voltage of all paralleled inverters must be strictly consistent in frequency, phase and amplitude to guarantee the output power sharing [51]. In parallel operation, two or more inverters are tied together to share the load. Figure 16 shows two inverters which are directly connected in parallel.

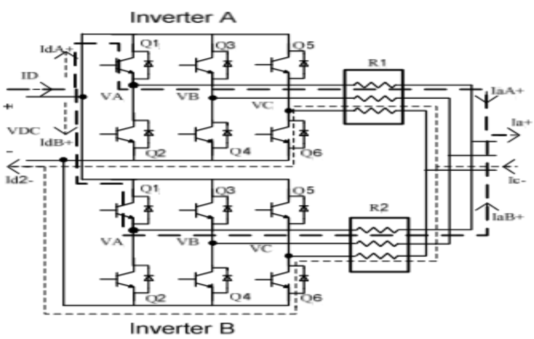

Figure 16: Parallel Connection of Two Three-Phase Inverters

Then, several topologies of three-phase inverters were clearly presented. For each topology the advantages and disadvantages have been listed.

Three-wire topologies require an expensive, heavy and bulky transformer. Because of their simplicity, this topology is the most interesting. It provides a three-dimensional control that is interesting in active filtering applications.

The multi-string inverter topology was also presented. Due to the individual and optimal exploitation of each string of this topology, it accepts the parallelization of several chains and can be connected to single-phase or three-phase electrical networks

The multi-level converters have also been presented in this paper. It offers the possibility of generating output voltages with extremely low distortion. A particular disadvantage is the greater number of power semiconductor switches required. Although nominal low voltage switches can be used in a multilevel converter, each switch requires an associated gate control circuit. This can make the overall system more expensive and complex.

In addition, another three-phase inverter topology with stabilizer and transformer also developed in the literature was seen. Its strong dependency seen from the load makes it less interesting compared to other topologies.

Finally, a topology realized by the parallelization of two inverters has been described. By comparing the THD (Total Harmonic Distortion) and the efficiency of the topology to a single inverter and that of two inverters in parallel, it emerges that the power of the inverter system is higher by connecting the inverters in parallel.

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