Role of Power Converters in Distributed Solar Power Generation

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***Abstract*—All the RE systems require specific power electronic converters to convert the power generated into useful power that can be directly interconnected with the utility grid and/ or can be used for specific consumer applications locally. The roles of these power converters become very critical, particularly when it is used in one of the most expensive energy generating sources such as solar PV. Since power converter/inverter are the interface of the distributed power system, any premature failure of such system will make the entire system defunct and thus need to be selected appropriately. These power converters need to be selected and designed optimally in order to provide maximum energy efficiency, ensuring reliability and safety of the overall solar PV system, required for different applications. This paper focuses on classification of inverters and present how an best fit inverter can be selected for a particular distributed solar PV applications based on its control scheme, PV array configurations, operational and safety features etc. The paper also covers the review of inverters and brings out few findings on the performance of various existing inverters available in the market based on a systematic analysis done by the author.**

***Index Terms*—solar photovoltaic, inverter, control scheme, central inverter, string inverter, review of inverter**

I. Introduction

Solar Photovoltaic (SPV) technology is one of the most matured renewable energy (RE) technologies and there is an increasing demand of SPV installation both in grid-connected as well as off-grid stand-alone modes. Although in recent years, the penetration of solar PV installation has increased substantially due to several initiatives, it is yet to be considered as one of the mainstream renewable energy technologies. The main drawbacks of solar PV system is its high cost of installation for producing desired power level of electricity which is due to the high manufacturing cost of solar modules compounded with its low conversion efficiency [1], [2]. Most of the times, the power conversion system associated with the solar PV generating unit can cost up to 40% of the total cost. PV system, in general, is designed to deliver a specific amount of energy as per the requirement of the applications [3]. Therefore, purchase and installation of all PV system will eventually be based on predicted or guaranteed energy production. To make the solar PV system commercially viable, the cost of unit generation of electricity from solar PV system needs to be reduced which, in turn, calls for the development of a low cost, high efficient power conversion systems or schemes for delivering required electrical power. Hence it is always critical to design the most appropriate power converters and to assess their performance to ensure maximum power capture from solar modules along with impeccable power quality, reliability and efficiency. A major challenge that needs to be addressed by the DC-DC converters is to take the non-linear output characteristic of the solar PV sources which varies with solar insolation and temperature and convert it in to appropriate level of voltage [4]. During recent years, different DC-DC converter topologies have been investigated for their applicability, safety and protection issues in SPV power generating system [5]-[8]. Since there are several DC-DC converter and inverter topologies available, it is important to assess the performance of those topologies or system configuration under different operating conditions [9]-[11]. Again the size of the distributed PV plant varies from few kW to several MW for which the type and configuration of the inverter also changes. Therefore the inverter has to be properly selected as the design and performance of the overall system depends mainly on the inverter. So there is a need of reviewing the type of inverter available mainly for off-grid application so that a judicious decision can be taken by the project developers and implementers for designing and developing efficient system.

The paper is structured as follows: different type of inverters are classified in section II whereas section III to VI focuses on selection of inverter based on different aspects such as control scheme, power rating and configuration, switching device, operational perspective, efficiency, system weight and cost etc. Finally the conclusion of the paper is brought in section VII.

II. Classification of Different Types of Solar Inverter

The solar inverter are classified based on the (i) number of energy processing stages i.e single, dual or multi-stage inverter, (ii) presence of transformer the use of a LF or HF transformer, (iii) position of power decoupling capacitors used to decouple the primary

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source and inverter and (iv)the type of inverters used: voltage or current source. Further the choice of conversion topology is highly dependent on the SPV field configuration and its peak power [12]-[16].

III. Selection of Inverter Based on Control Scheme

There are various types of inverters available in the market as shown in Fig. 1.The self-commutated inverter can freely control the voltage and current waveform at the AC side, and adjust the power factor and suppress the harmonic current, and is highly resistant to local grid or utility grid disturbance .Line-commutated inverters are not suitable for use in standalone systems because AC voltage is required to turn off thyristors. Due to advances in switching devices, most Inverters for distributed power sources such as photovoltaic power generation now employ aSelf-commutated inverter.

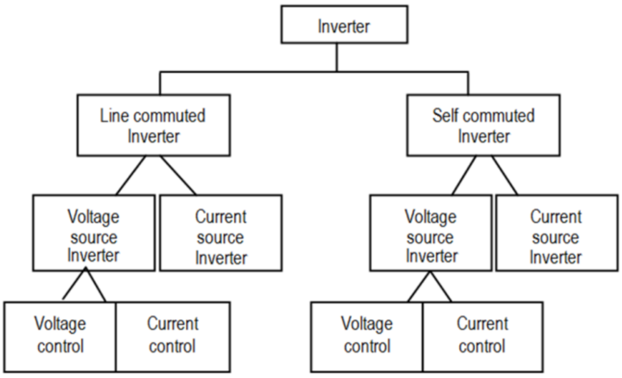

Figure 1. Classification of inverter type

Again, the self-commutated inverters can be a voltage source or a current source inverter In the case of photovoltaic power generation, the DC output of the photovoltaic array is the voltage source, thus, in general a voltage source inverter is employed rather than a current source inverter. However, the voltage source inverter can be operated as both the voltage source and the current source when viewed from the AC side, only by changing the control scheme of the inverter. Therefore the control scheme (i.e voltage control scheme and current control scheme) of the inverter plays a very crucial role in the inverter and needs to be employed appropriately. In a case of the isolated power source without any grid interconnection, voltage control scheme should be provided. However, both voltage-control and current-control schemes can be used for the grid interconnection inverter.

IV. Selection of Inverter Based on Power Rating and Array Configuration

The size and capacity of the distributed solar PV system varies very widely from few kW to MW scale and thus it is important to know whether selection on type of inverters is different for different capacity of the PV system. The section below describes the different configurations that exist and its significance for PV system.

A. *Single Stage/Central Inverter*

The single stage inverter (central inverter) is widely used for large scale power applications. Here, the single power processing stage takes care of all the tasks of MPPT, voltage amplification and grid side current control. In this configuration, the solar modules are connected in series to create strings with output voltage high enough to avoid an additional voltage boost stage. In order to obtain the desired power level, the strings are connected in parallel through interconnection diodes (string diodes) as shown in Fig. 2 below.

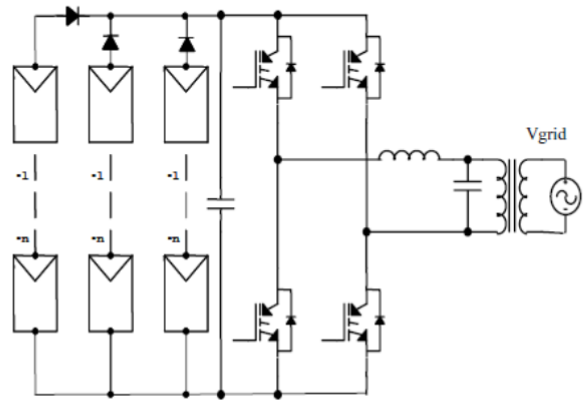

Figure 2. Single stage/ central inverter

Although this configuration is widely used, the global efficiency of the generation system is effectively reduced. The main reason of reduced performance is due to the centralized MPPT control that fixes a common operating point for all PV modules (shaded as well as un-shaded) whereas different operating point should be adopted for each module in order to extract the maximum power from the source. The presence of string diodes, further introduce additional losses, and the use of a Low Frequency (LF) transformer determining an increase of cost and weight of the converter. Because of these limitations, more advanced inverter topology is used based on the use of photovoltaic fields arranged in strings rather than arrays.

B. *Double or Multi-Stage Inverter*

Here each string is connected to a double- or a single-stage inverter. If a large number of modules are connected in series to obtain values of open circuit voltage higher than 360V, the DC/DC converter can be omitted. On the other hand, if a few number of PV modules are connected in series; a DC/DC boost converter is used. The DC-DC converter is responsible for the MPPT and the DC-AC inverter controls the grid current.

C. *Multi-string Multi-stage Inverters with High Frequency Transformer*

Another topology adopted is multi-string; multi stage inverter. The Multi String inverter has been developed to combine the advantage of higher energy yield of a string inverter with the lower costs of a central inverter. Lower power DC/DC converters are connected to individual PV strings. Each PV string has its own MPP tracker, which independently optimizes the energy output from each PV string. All DC/DC converters are connected via a DC bus through a central inverter to the grid. Depending on the size of the string the input voltage ranges between 125V to 750V. Here system efficiency is higher due to the application of MPPT control on each string and higher flexibility comes from the ease of extensions for the photovoltaic field [12]-[15]. This topology is more convenient for power levels below 10 kW. The multi-string inverters have provided a very wide input voltage range (due to the additional DC/DC-stage) which gives the user big freedom in design of the PV-system. However the disadvantages are that it requires two power conversion stages to allow individual tracking at the inputs.

V. Selection of Inverter Based on Switching Devices

To effectively perform Pulse Width Modulation (PWM) control for the inverter, Insulated Gate Bipolar Transistor (IGBT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET) are mainly used for switching devices. *IGBT is used in more than 70% of the surveyed inverter products and* MOSFET *is used in around remaining 30% of the inverter*. As far as differences in characteristics between IGBT and MOSFET are concerned, the switching frequency of IGBT is around 20 kHz and it can be used for large power capacity inverters of exceeding 100 kW. On the other hand although the switching frequency of MOSFET can go up to 800 kHz, but its power capacity is reduced at higher frequencies and MOSFET are used for output power range between 1 kW to 10 kW. So in nutshell, both IGBT and MOSFETs are used for small to medium range PV system with power capacity of 1 to 10kW whereas IGBTs are used for large scale power plant with power rating equal or more than 100 kW. High frequency switching can reduce harmonics in output current, size, and weight of an inverter and thus now a day High Frequency (HF) inverter with a compact size is available and widely used.

VI. Selection of Inverter from Operational Perspective

In order to assess the inverter's performance in terms of operational perspective, a literature review and collection of secondary information was carried out by the author. For the analysis purpose, information about 200 models of different inverters with different capacity and types were collected. The following sections bring the findings from the survey.

A. Features of Grid Connectivity

The distributed or off-grid inverter should have the feature for grid connectivity (both incoming and outgoing) so that these solar PV systems would not be completely obsolete when grid extension reaches. With the massive, aggressive plan of conventional rural electrification, it is always wise to select an inverter having grid connectivity features from the beginning with some incremental cost than completely changing the inverters later on with a high replacement cost.

B. AC Voltage and Frequency Range

For the standard values, the inverter can be operated substantially without any problems within the tolerance of +10% and –15% for the voltage, and ±0.4 to 1% for the frequency, specified by grid standards of any country. For example In India, where the single phase AC line is specified as 230V, 50Hz, the inverter should work any voltage value between 253V to 198V and any frequency value between 49.5 to 50.5 Hz without any problem. Any inverter which does not have this wide range, might not be considered, particularly for distributed power system which are installed in relatively remote and rural locations where wide fluctuation of voltage and frequency is prevalent.

C. Operational DC Voltage Range

The operable range of the DC voltage differs according to rated power of the inverter, rated voltage of the AC utility grid system, and design policy. In this survey, the operable range of the DC voltage for a capacity in the range of 180-500W includes 14-35V, 30-60V. Similarly the operable DC voltage range for a capacity of 10 kW or over includes 330-1000. Hence depending upon the operable range of the inverter the size and configuration of the solar PV modules should be done. So while designing or sizing the solar PV system, this is one of the criteria which decided how many modules need to be connected in series or parallel to get the required DC operating voltage.

D. AC Harmonic Current from Inverter

Minimization of harmonic current production is required as harmonic current adversely affects load appliances connected to the distribution system, and can impair load appliances when the harmonic current is increased. The results of this survey show that Total Harmonic Distortion (THD), the total distortion factor of the current normalized by the rated fundamental current of many of the inverter, is 3 to 5%.However , there are certain inverters in the power rating of 10-100kW, has THD in the range of 1-5%.

E. Inverter Conversion Efficiency

Fig. 3 shows the graph between power rating and euro efficiency of different inverters.

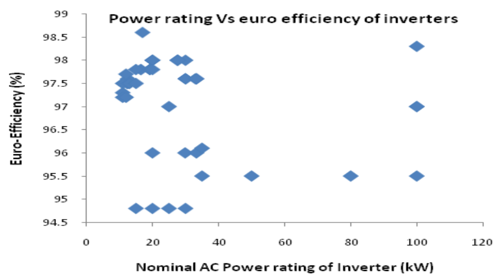

Figure 3. Power rating Vs euro efficiency of inverters

As per the graph, it shows that the efficiency range for all the inverters varies from 94.5 to 98.7%. In the medium scale range (10-20kW), there are several inverters available with the euro efficiency range of 97-98% and the incremental cost of these inverter are not much than that of the low efficiency inverter (generally USD 50/kW).Thus the project designer can see and evaluate the cost Vs benefit of the inverter in terms of its enhance efficiency.

F. Operational Environment

The installation conditions of the inverter (the indoor installation specification or the outdoor installation specification), the ambient temperature condition, the requirements for water proofness and dust proofness, actual audible noise level of the inverter, and applicable regulations for EMC (electro-magnetic compatibility), etc. needs to be seen carefully. As per the survey (Fig. 5), the maximum acceptable ambient temperature (in 0C) at nominal AC power is in the range of 40 to 75 0C. Whereas this range is relatively wider for 10-40kW inverter, it is narrow and in the range of 40-50 0C for large inverter.

G. Required Protection Devices or Functions

Protective functions include protection for the DC side, protection for the AC side, and others. The protective functions for the DC side include those for DC overpower, DC overvoltage, DC under voltage, DC over current, and detection of DC grounding faults. Protective functions for the AC side include AC overvoltage, AC under voltage, AC over current, frequency increase, frequency drop, and detection of AC grounding etc. Most of the inverters include these basic protections.

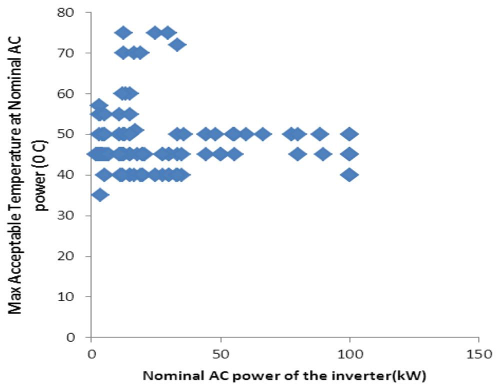

Figure 4. Maximum acceptable temperature at nominal AC power.

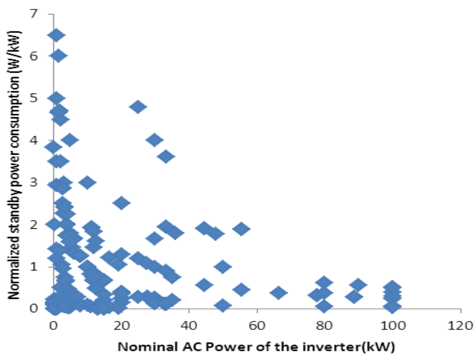

Figure 5. Normalized standby power consumption of different inverter

H. Standby Power Consumption

The standby power consumption of the inverter is a very important parameter to check, particularly for off grid PV applications where the only source for providing power is solar PV. So, by practice the lesser the standby power consumption is, better it is for distributed PV applications. As per Fig. 5, it is observed that there is a wide range of product available with normalized standby power consumption for inverter <20kW. So, the inverter can be judiciously selected so that self consumption of these inverter would not be much.

I. Inverter System Cost, Size and Weight

The cost of the inverter system is very crucial when considering the economy of a photovoltaic power system. Although the cost of the inverter varies from country to country as well as with make and model, the average cost range of the inverter is found to be USD 600-1000 per kW. The weight of the inverter system differs considerably according to presence/absence of the isolating transformer. However from the project developer's point of view it is very critical parameter to judge as the weight of system affects the total transportation cost, handling and installation cost. In the inverter for a household photovoltaic power system, weight reduction is important when the inverter is installed indoors or is mounted and thus appropriate inverter with less weight can be preferred.

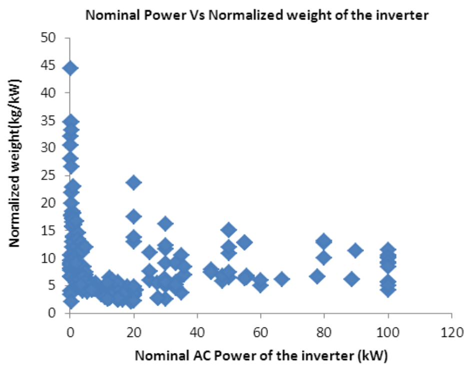

Figure 6. Normalized weight of different inverters

J. System Guarantee

Again system guarantee plays very crucial role as it decided the entire economics followed by business model of the system. Although the cost data for each of the inverter is not available, it is observed that, there are certain inverters where extended guarantee of 25 years is available.

VII. CONCLUSIONS

It is found that currently PV inverters available in the market have fairly good performance. They have high conversion efficiency while maintaining current harmonics THD less than 5%. Cost, size, and weight of a PV inverter have been reduced recently, because of technical improvements and advances in the circuit design of inverters and integration of required control and protection functions into the inverter control circuit. The control circuit also provides sufficient control and protection functions such as maximum power tracking, inverter current control, and power factor control. So if the inverters are chosen properly, substantial cost saving in terms of reduced but appropriate PV system sizing can be achieved.

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