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Improved DC-Link Voltage Balancing Algorithms for Cascaded Solar Inverters

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ABSTRACT

The design and control issues associated with the development of single phase grid-connected photovoltaic system incorporating a multi-level cascaded inverter are discussed in this paper. The advantages of transformer less inverter over a full-bridge inverter in combination with a line frequency transformer which is a common topology has been described in this report. Attractive features of multi-level inverters have been studied and descriptive details of photovoltaic system along with control and grid synchronization has been given this paper. Simulation results are presented to demonstrate the suitability of the control method.

Keywords: fault-resilient, multilevel inverters, cascade h-bridge, grid-tied inverters, PV systems, renewable energy.

I. INTRODUCTION

Providing electrical energy access to rural zones is a fundamental requirement as a means of improving sustainable living standards topping the agenda in many developing countries [1]-[4]. Energy efficiency, electricity supply and sustainability are the most important research topics in society. The energy that is sustainable, renewable, cost-effective, reliable and secure is the fundamental requirement for economic growth, human and industrial development of a country. Ecological concerns, exhausting petroleum reserves and expanding reliance on fossil fuels from unstable locales have expanded the significance for more efficient use of energy. Sources like thermal, nuclear that has been used for some time now for the generation of electricity has its own merits and demerits.

The developing attention to decrease the carbon footprint (CO2) has added to the expanding interest for research on non-fossil based fuel as a source of energy. Thus, a more sustainable energy supply is required across all sectors viz. residential, transportation, industrialisation and agriculture. This impromptu pressure and challenge on the environment have encouraged the energy providers to develop further and transform the energy system in a much effective manner. During the most recent times, it has been witnessed the reduced complexity of different energy policies and investment options are increased across the globe in the energy sector [5].

Renewable energy can be termed as liveliness from unlimited natural resources. There are many sources of natural renewable energy resource like sunlight, water, air, biomass, and geothermal heat. Over a specified geographical area, the scope and opportunities for renewable energy

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resources are vast in contrast to other forms of energy like fossil fuels that are limited and concentrated to specific localities. With the rapid deployment of renewable energy, efficiency, economic benefits are immense and would result in significant energy security, while reducing the environmental effects. This include positive developments in improved healthcare and reduction in infant mortality rates due to reduced pollution effect and countries would save millions on healthcare [6]-[8]. Renewable energy often displaces convention energy requirements in generation of electricity, water heating, transportation, energy services at rural areas (off grid). Along these lines, it can securely be expected that renewable energy assets go about as an impetus to increment and improve energy access in rural areas [9].

II. SOLAR ENERGY

Solar energy is harnessed from the sun using PV technologies, solar heating, concentrated solar power, concentrated photovoltaics and are generally characterised based on the way the energy is captured, converted and distributed. They are either classified as active or passive. A PV system converts light into electrical energy taking advantage of the photoelectric effect. The PV system involves an array of silicon semiconductors that collect the photons and changes over to electrons. The generated DC is then convereted to AC using converters.

Therefore, it is essential to utilize specific MPPT system to maximise the energy captured from the sun. This is generally achieved by using sun-tracking PV's. The sun-tracking PV's achieve this goal by adjusting itself to the global solar insolation shifts and amplifies the captured sunlight radiation to generate maximum power at a steady voltage. Efficiency in the solar array is estimated by the capacity to change over daylight into energy and is an exceptionally unique factor in picking the right panel for the PV system. As a reliable RE source, solar PV's can be successfully integrated into the mainstream power supply. However, there are many challenges in the solar energy system in the form of mismatch of the generated power from the PV and the demand. This is primarily due to the stochastic generation in PV. It leads to numerous other challenges, and one such problem is voltage regulation [10].

Solar energy has attracted significant attention as an ecofriendly and sustainable means of generating electrical power. The utilization of cascaded multilevel inverters has seen a growing popularity in the conversion of solar energy into usable electricity, primarily due to their capability to produce high-quality voltage waveforms and counteract harmonic disturbances. Nevertheless, achieving an optimal power quality level remains a persistent challenge, particularly in the face of fluctuating solar irradiance and varying load conditions.

When a photovoltaic (PV) module is linked to a load, the resultant output voltage (V), current (I), and power (P) depend on the operational state of the PV module. Different types of loads display unique I-V and P-V characteristic curves, with each PV module having its own distinctive I-V and P-V characteristic curve. In the P-V characteristic curve, point A corresponds

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to the Maximum Power Point (MPP), aligning precisely with point B on the V-I characteristic curve.

III. PV ENERGY GENERATION CONCEPTS

Grid-Connected Applications: In this mode of solar power generation, the solar arrays are used in large capacities of the order of MW for the generation of bulk power at the solar farms, which are coupled through an inverter to the grid and feed in power that synchronises with the conventional power in the grid. The grid connected solar power operates at 33KV and at 50 Hz frequency through inverter systems, whereas the solar farms generate the average power output of about 5MW each. Owing to quite high power generations, the batteries are not used to store power as in the case of isolated power generation for economic concerns. 53 grid-connected solar projects were selected up to the end of 2010 comprising of total capacity of 704MW.

Stand Alone Applications:

This mode of energy generation from solar energy consists of systems which are not connected to the grid, i.e. off-grid applications (captive power). It is done especially in the places where there is acute scarcity of electricity derived from conventional sources. These stand-alone systems have a solar array coupled with a power conditioning device such as an inverter that converts the power from DC to AC to suit the load requirements, such as home power, and a battery to store the solar energy harnessed during the day which is to be consumed in the absence of solar energy. These decentralised systems of PV arrays operate at parameters below 33KV and 50Hz through the inverter. However, the higher capacities of the order of KW are usually sold to the grid to get paid with attractive tariffs. The heating systems concentrate the solar rays on heating water which can be used for cooking, washing, power generation, etc.

IV. CASCADED H-BRIDGE CONVERTERS

Although the proposed method is equally as effective in the inverter mode configuration, in order to test the capability of a DC-Link voltage balancing algorithm and avoid the necessity of isolated high voltage sources, the rectifier configuration is preferred. Referring to figure 1, the HBs are series-connected on the grid side and an inductive filter L, with a parasitic resistance rL, is used to facilitate the required connection between the converter and the grid.

In previous chapter a brief review is done on NPCMLI, FC-MLI and CHB-MLI. However, on comparing these three commercial topologies of multilevel voltage-source inverters, cascade multilevel inverter reaches the higher output voltage and power levels (13.8 kV, 30 MVA) and the higher reliability due to its modular topology. Cascade multilevel inverters are based on a series connection of several single-phase inverters.

This structure is capable of reaching medium output voltage levels using only standard low-voltage mature technology components. Typically, it is necessary to connect three to ten inverters in series to reach the required output voltage. These converters also feature a high

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modularity degree because each inverter can be seen as a module with similar circuit topology, control structure, and modulation [10].

Therefore, in the case of a fault in one of these modules, it is possible to replace it quickly and easily. Moreover, with an appropriated control strategy, it is possible to bypass the faulty module without stopping the load, bringing an almost continuous overall availability [11-15]. Numerous publications have been visible in the literature, particularly on this architecture. However, research on cascade multilevel inverter is a hot topic in multilevel based structures. So it's feasible to know the reason behind its significance.

In general inverters are compared in terms of feasibility of their utilization and applications. According to the MIL-HDBK-217F standards, the reliability of a system is indirectly proportional to number of its components, consequently less the components more reliable is the system [12]. Therefore, let's make the component verification of above mentioned inverters, so that it would be clear about the issues like; switching losses, reliability and cost factor. Compared to m-level DC-MLI, FC-MLI uses m-1 capacitors on the dc bus, the CMI uses only (m-1)/2 capacitors for same m-level. Clamping diodes are not required for FCMI and CMC. But balancing capacitors are must for FCMI. But for CMI such balancing – capacitors are completely absent. However, this is summarized in Table 1. After comparing CMI with DC-MLI, and FC-MLI, CMI requires least number of components and its dominant advantage is circuit layout with flexibility and outstanding availability due to their intrinsic component redundancy. Due to these features, the cascade multilevel inverter has been recognized as an important alternative for power market.

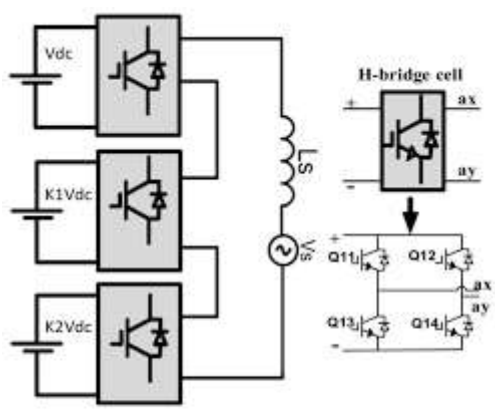

Fig.1. H Bridge.

TABLE 1 Comparison of Traditional Multilevel Topologies.

Converter Type	**DC-MLI**	**FC-MLI**	**CMI**
Main switching devices	(m − 1) × 2	(m − 1) × 2	(m − 1) × 2
Main diodes	(m − 1) × 2	(m − 1) × 2	(m − 1) × 2

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Clamping diodes	(m − 1) × (m − 2)	0	0
Balancing capacitors	0	(m − 1) × (m − 2) / 2	0
DC Bus Capacitors	(m − 1)	(m − 1)	(m − 1) / 2

In order to effectively harness and integrate the increasing energy capacity derived from solar power; grid-tied inverters prove to be of crucial importance. A grid-tied inverter represents a key component in the process of converting direct current (DC) generated by PV panels into alternating current (AC), which is compatible with the electrical grid. This conversion is of critical importance, given that the majority of electrical grids operate on alternating current power. In contrast to off-grid systems, whose energy storage is dependent on batteries [10, 11], grid-tied inverters facilitate the seamless integration of renewable energy into the grid. This optimizes the use of solar power while ensuring grid stability and reliability [12]. Among the various types of grid-tied inverters, multilevel inverters (MIs) have emerged as an innovative solution to produce a smoother output waveform, reducing harmonic distortion and improving overall power quality [13].

The ability of multilevel inverters to provide higher voltage outputs with lower switching losses makes them particularly advantageous for large-scale solar installations.

The MIs offers several advantages over a conventional two-level inverter such as: The generation of output voltages with minimal distortion and lower voltage variation, drawing of input current with minimal distortion, generation of smaller common mode (CM) voltages and the ability to operate with a lower switching frequency [14]. Among the various types of multilevel inverters, the cascaded H-bridge (CHB) [15] is another notable topology. It consists of multiple H-bridge inverters connected in series, offering a promising solution for a number of applications.

This configuration allows for modular design, scalability, and high efficiency. It is particularly well-suited for large-scale solar power plants, where higher voltage levels are required to interface directly with the grid without the need for bulky transformers. However, due to their complex structures, these inverters are also susceptible to various operational faults. It is therefore essential to address such faults in order to maintain the efficiency and reliability of both the inverter and the grid.

V. SIMULATION RESULTS AND INTERPRETATIONS

To validate the propose d control strategy, a simulation of a photovoltaic (PV) system connected to the grid through a three-phase seven-level Cascaded Multilevel Inverter (CMI) was developed code using MATLAB [10]. The parameters used in the simulation are detailed in Table 3. The Simulink block diagram of the studied PV system illustrates its operation under three different conditions: before the fault, during the fault, and after fault compensation.

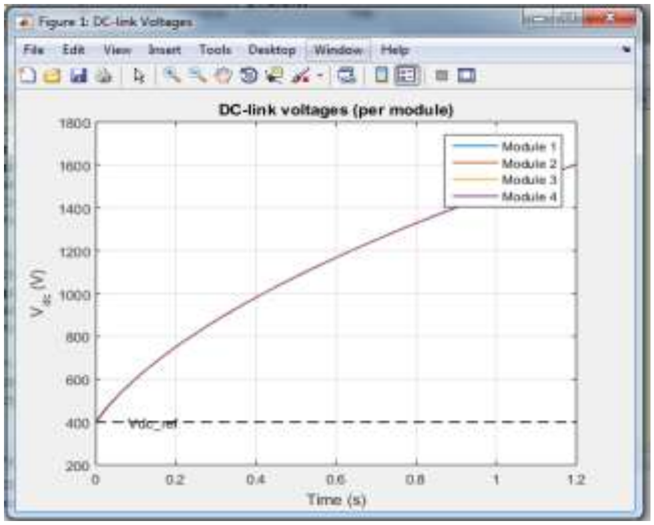

Fig.2 Voltage level.

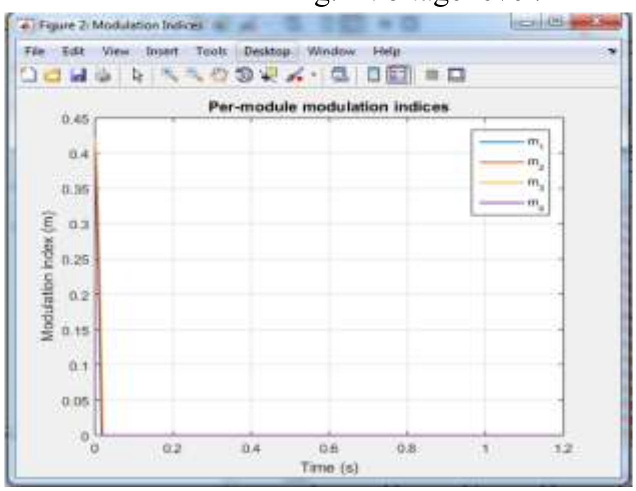

Fig.3 Inverter Modulation Index.

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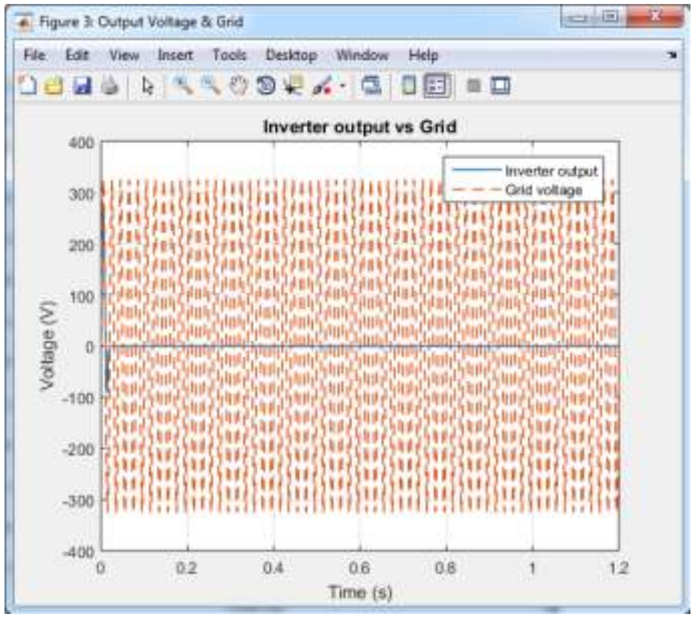

Fig.4 Grid Output.

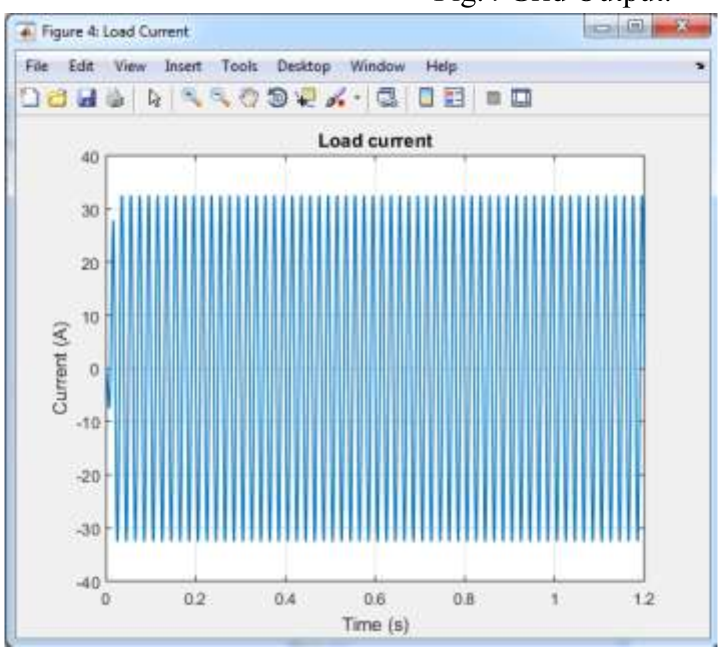

Fig.5 Current and Time.

VI. CONCLUSIONS

The proposed active voltage balancing is a very attractive alternative for balancing series connected electrolytic capacitors of power converters with DC voltage link to advantageously substitute the commonly used passive balancing resistors. The active system which preferably is realized by application of a cascode voltage-follower circuit topology is characterized by the following features in comparison to the resistor balancing:

- Significant reduction of balancing losses resulting in huge savings of energy cost considering the converter life cycle
- Stiffer balancing behavior (reduced output resistance)
- increased stationary balancing precision
- Low cost (similar to passive solution)

Finally, also the only attribute known at present which might be seen as drawback should be mentioned: The proposed system is not very well suited to perform the safety discharge of the DC voltage link after the power converter has been switched off. However, frequently alternative discharge paths will be present, e.g., the main load of the converter itself or the auxiliary power supply of the converter which more and more is realized using a small converter fed by the main voltage link. Future research in this area will focus on circuit extensions and topologies for balancing of series connections of more than two electrolytic capacitors.

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