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A simple modular multilevel inverter topology for the power quality improvement in renewable energy based green building microgrids

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ABSTRACT

The advent of multilevel inverter topologies paves path for the realization of renewable energy based microgrids for various classes of consumers. But, these topologies are offering concerns with design complexity, power quality, *dv*/*dt* stresses, capacitor voltage balancing, etc. In view of these challenges, this paper proposes a simple Modular Cascaded Multilevel Inverter with modified Uni-Polar Shifted Carrier Pulse Width Modulation (MCMI-mUPSC PWM) topology for microgrids. The proposed MCMI topology eliminates the use of clamping diodes, capacitors, and requires only 1/4th (25%) of the DC input voltage that is used in any conventional topology to produce the same amount of output voltage. This leads to the reduction in switching devices' rating and *dv*/*dt* stresses. The proposed mUPSC PWM reduces the magnitude of hazardous lower order harmonics by shifting them to higher order components around the region of integral multiples of switching frequency. Thus, the proposed MCMI-mUPSC PWM topology simplifies the design of multilevel inverters along with aforesaid advantages. For the analysis, microgrid modelling and simulations are carried out in MATLAB/Simulink®. The effectiveness of the proposed topology is evaluated by calculating various power quality indices under dynamic and non-linear loading conditions. These indices are compared with the conventional topology with respect to standard tolerances. From results, it is observed that the proposed topology has improved the power quality along with the elimination of some of the inherent problems of the multilevel inverters. This enhances the plausibility of microgrid installations towards smart and net-zero energy buildings.

1. Introduction

The present utility grid is distressed from the increased burden of consumers, fossil fuel depletions, lower generation efficiencies, transmission/distribution losses, etc. These are leading to frequent grid outages that became an obstacle for economic growth of a country. Also, the government regulations for the reduction of carbon emissions pushes to think towards the use of alternative or renewable energy sources (RES). With this intent, many decentralized RES based microgrids are being formed all over the world with the use of power electronic conversion devices [1–6]. Microgrids augment the conventional power systems by the philosophy of onsite power generation and also enables selling the excess power back to the utility grid. However, power quality issue raised by the intermittent RES and harmonic prone power electronic inverters is the critical concern that denies the microgrid's fruitfulness [7,8]. Power quality issue is defined as "any problem manifested in voltage, current, or frequency that results in deterioration of consumers' equipment" [9]. Integration of energy storage units with RES is identified as a potential solution to mitigate RES intermittencies [10,11]. But, the usage of inverters in variety of applications draws nonlinear current that distorts supply voltage waveform, which leads to failure of load.

On the other hand, substantial evolution has been made in the power electronic inverter design from early 2-level to multiple levels in output voltage to approximate it to sinusoidal shape [12,13]. There are three basic multilevel inverter topologies available in technology, viz. diode clamped multilevel inverter (DCMI), flying capacitor multilevel inverter (FCMI), cascaded H-bridge multilevel inverter (CHBMI). DCMI produces better voltage waveform, but, needs more number of clamping diodes and special methods for capacitor voltage balancing [14]. FCMI does not need any clamping diodes, but, it requires more capacitor banks, whose voltages should be regulated within allowable ripples [15]. CHBMI eliminates clamping diodes required in DCMI and additional capacitors required in FCMI. But, it needs more number of isolated DC voltage sources [16]. Thus, the basic multilevel inverters are limited in

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design due to complexity with lots of switches, clamping diodes, capacitor voltage balancing, dv/dt stresses [17,18].

In order to address the aforementioned issues in microgrids for the improved quality power generation, the contemporary research work focuses majorly on 3 aspects viz., (i) designing energy storage units for energy uncertainty management [19–28], (ii) revised inverter topologies and control by modern modulation techniques to address the demerits of traditional topologies [29–40], (iii) replacing power electronic inverters with alternative conversion systems [41–43]. Symmetric and asymmetric sources based cascaded multilevel inverter topologies presented in [29–36] to reduce number of switching devices require switches of high-voltage withstanding capability. The topologies presented in [30,31,34,35] require different values of DC voltage sources. The H-bridge based topologies given in [29–33] demand its four switches should be able to withstand the inverter's maximum operating voltage. Similarly, the topologies based on combined bidirectional and unidirectional switches presented in [34,35] demand all its bidirectional switches have to withstand the major portion of the inverter's maximum operating voltage. Similar issues exist in the topology given in [36]. These drawbacks make the topologies presented in [29–37] inappropriate for medium-to-high voltage applications. Thereupon, a topology of series connected multilevel inverters presented in [38] has limitations in its use for high power applications due to the necessity of differently rated switches and change in polarity of voltage in every half cycle. Similarly, DC motor and synchronous generator based energy conversion scheme presented in [41] to replace the power electronic inverter has limitations in efficiency, space requirement, and deployment cost.

As a whole, handling of inverter design complexities (for scalability, replicability, and modularity), power imbalances, harmonics, electromagnetic emissions, etc., are yet suboptimal in microgrids' research. This requires more focus to enhance the plausibility and fruitfulness of microgrids' deployment.

In view of all the aforesaid challenges in state-of-the-art practices for obtaining quality power generation in microgrids, this paper proposes the design of a simple and single sourced "Modular Cascaded Multilevel Inverter with modified Uni-Polar Shifted Carrier Pulse Width Modulation (MCMI-mUPSC PWM) topology" as shown in Fig. 1. The main focus of this work is to realize dual functionality by the proposed inverter topology that can provide improved power quality for microgrid applications and also to eliminate some of the inherent problems of the conventional multilevel inverter topologies.

2. Description of the microgrid system

The schematic shown in Fig. 1 represents centralized DC bus architecture of microgrid. Photovoltaic (PV), Wind power (WP), Fuel cells (FC) along with respective DC/DC (and/or AC/DC) conversion units and storage batteries are considered as the local energy sources that are integrated to form DC bus.

2.1. Microgrid architecture description with conventional and proposed inverter topologies

2.1.1. Conventional DCMI/FCMI/CHBMI based microgrid

The DC bus energy is fed to the building loads via a 3-phase DCMI/FCMI/CHBMI power electronic inverter. It is further integrated with utility grid via point of coupling (PCC). The PCC facilitates bi-directional power flow; one in forward direction for export and other in reverse direction for import with respect to excess and deficit power conditions. It has a combination of circuit breaker and 3-phase transformer operating 11 kV at high voltage side and 440 V at low voltage side to meet the voltage levels accordingly in both the directions.

5-Level inverter is usually preferable to produce reasonable quality power. However, this is inadequate explicitly in utility grid connected mode and hence invites for improved quality power generation that adheres the regulations/standards set by various international forums such as IEEE, IEC, etc. [44–55]. One way of achieving this is by increasing number of inverter output levels or looking for new and innovative topologies and modulation techniques. However, increasing the number of levels again increases the inherent issues of the multilevel inverters.

2.1.2. Proposed MCMI based microgrid

In order to overcome the above mentioned issue with conventional topologies, this paper proposes the design of MCMI-mUPSC PWM inverter topology that replaces a conventional 5-level inverter. This leads to the improved power quality and reduced problems of multilevel inverters.

Proposed 5-level MCMI inverter topology is derived with the combination of four 2-level 3-phase inverters. Corresponding microgrid's architecture uses a multi-winding transformer for each phase as shown in Figs. 1 and 3 instead of using the conventional 3-phase transformer at PCC. It can serve two purposes, one side of the transformer cumulates the four inverters' output voltages and another side produces 11 kV voltage (A_{ug}, B_{ug}, C_{ug}) for utility grid integration and 440 V supply (A_{bl}, B_{bl}, C_{bl}) to building loads. The detailed description of MCMI-mUPSC PWM topology design and features is given in Section 3.

2.2. Modelling details of the microgrid constituents

Microgrid model is obtained by integrating three major subsystems viz., RES with DC/DC (or AC/DC) converters, 3-phase inverter, and loads. This paper emphasizes modelling of the proposed MCMI-mUPSC PWM topology. Models of RES and associated converters that are presented in [41–43] are used directly. The building loads are segregated into primary (or base) and secondary (or controllable) loads. Primary load must be served by the power system at all the time and secondary load can be varied usually based on the power availability. In this paper, secondary load is considered as the test load to evaluate the performance of proposed inverter topology as mentioned in Section 4. Constant impedance R, L, C load models in Simulink library are taken for simulating various types and combinations of the building loads.

A 3-phase 5-level diode clamped multilevel inverter with sine-triangle pulse width modulation (DCMI-STPWM) is modelled as shown in Fig. 2 in order to simulate conventional microgrid architecture. There are 4 carrier signals (triangular) each with frequency of 1 kHz and amplitude of 2.5 and 1 modulation signal (sinusoidal) with frequency of 50 Hz and amplitude of 10. This combination produces an amplitude modulation index of 1 and frequency modulation index of 20. Modulation signal is continuously compared with each of the carrier signals and produces the firing pulses required for the inverter operation.

3. Description of proposed MCMI-mUPSC PWM topology

3.1. Description of proposed Modular Cascaded Multilevel Inverter (MCMI) topology

The MCMI is derived with the back-to-back connection of 2 pairs of 2-level 3-phase inverters as shown in Figs. 1 and 3. All these four 2-level inverters will act as four limbs of the MCMI that can mimic the functionality of a 5-level inverter. All the limbs are connected to a same DC source of $V_{dc}/4$ magnitude (where V_{dc} is the DC voltage required in the case of microgrid architecture with any

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