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Multilevel Inverters: Literature Survey – Topologies, Control Techniques & Applications of Renewable Energy Sources - Grid Integration

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ABSTRACT
Multilevel inverters are in favor of academia as well as industry in the recent decade for high-power and medium-voltage applications. In addition, they can synthesize switched waveforms with lower levels of harmonic distortion compared to a two-level converter. Multilevel converters have received increased interest recently as a result of their ability to generate high quality output waveforms with a low switching frequency; the multilevel concept is used to decrease the harmonic distortion in the output waveform without decreasing the inverter power output. This paper presents a review on most important topologies, control techniques of multilevel inverters and also the applications powered by multilevel inverters which are becoming an enabling technology in many industrial and research areas.
***Keywords* -** Multilevel inverter, Neutral point clamped, CHB, FACTS and Renewable energy sources.

I. INTRODUCTION

In recent years, multilevel inverters have gained popularity with medium and high power ratings. Renewable energy sources such as photovoltaic, wind, and fuel cells can be interfaced to a multilevel converter system [1]. Many multilevel converter topologies have been proposed during the last two decades. Research has engaged novel converter topologies and unique modulation schemes. The three types of multilevel converter structures reported in the literature are: cascaded H-bridge converter with separate dc sources, diode clamped (neutral-clamped), and flying capacitors (capacitor clamped). Modulation techniques and control paradigms have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. Many, multilevel converter applications include industrial medium-voltage motor drives, renewable energy systems with utility interface, flexible AC transmission system (FACTS), and traction drive systems. The common multilevel converter topologies are the neutral-point-clamped converter (NPC), flying capacitor converter (FC) and Cascade H-Bridge (CHB) have developed from last two decades. Multilevel inverters are best for medium and high power applications [2].

II. MULTILEVEL INVERTER-OPOLOGIES AND CONTROL TECHNIQUES

2.1 DIODE CLAMPED INVERTER

Effective control technique for medium-voltage high-power induction motor fed by cascaded neutral-point-clamped inverter [3]. [4], five/nine-level twelve-switch inverter for three-phase high-speed electric machines having a low per-unit leakage reactance is described. [5], used a new single-inductor multi-output dc/dc converter that can control the dc-link voltages of a single-phase diode-clamped inverter asymmetrically to achieve voltage quality enhancement. [6], comparative analysis between the classical structure of Neutral Point Clamped (NPC) and the emerging Active NPC converters. [7], DC bus short circuit protection is usually done using the sensed voltage across collector and emitter (i.e., *VCE* sensing), of all the devices in a leg. [8], introduced a new nine-level active neutral point- clamped (9L ANPC) converter for the grid connection of large wind turbines (WTs) to improve the waveform quality of the converter output voltage and current. [9], investigations of dc-link voltages balance with the use of a passive RLC circuit in a single-phase diode clamped inverter composed of two three-level legs. [10], three-level active neutral point- clamped zero-current-transition (3L-ANPC ZCT) converter for the sustainable energy power conversion systems. [11], new modulation techniques for three-phase transformer less neutral point clamped inverters to eliminate leakage currents in photovoltaic systems without requiring any modification on the multilevel inverter.[12], comparison between three level diode neutral-point-clamped zero-current transition (DNPC-3L ZCT) inverter and three-level active neutral-point clamped zero-current-transition (ANPC-3L ZCT) inverter, with respect to switching energy, volume, as well as parasitic inductance influence, the topologies are compared.

2.2 CASCADED MULTILEVEL INVERTER

[13], Cascaded H-bridge multilevel inverter can be implemented using only a single dc power source and capacitors.[14], cascaded H-bridge multilevel boost inverter for electric vehicle (EV) and hybrid EV (HEV) applications implemented without the use of inductors. [15], new feedback control strategy for balancing individual dc capacitor voltages in a three-phase cascade multilevel inverter-based static synchronous compensator. [16], single-phase cascaded H-bridge converter for a grid-connected photovoltaic (PV) application. The independent control of each dc link voltage, for the tracking of the maximum power point of each string of PV panels is carried out. [17], direct torque control (DTC) scheme for electric vehicles (EVs) or hybrid EVs using hybrid cascaded H-bridge multilevel motor drive based on DTC operating principles is implemented.[18], generalized multiband hysteresis modulation and its characterization have been proposed for the sliding-mode control of cascaded H-bridge multilevel-inverter (CHBMLI)-controlled systems. [19], symmetric hybrid multilevel topologies are introduced for both single- and three-phase medium-voltage high power systems. [20], the impacts of the connected load to the cascaded H-bridge converter as well as the switching angles on the voltage regulation of the capacitors are studied. [21], used a new topology of a cascaded multilevel converter based on a cascaded connection of single-phase sub multilevel converter units and full-bridge converters then, the structure is optimized.

2.3 FLYING CAPACITOR MULTILEVEL INVERTER

[22], mathematical analyses of the balancing process in boost and buck–boost converters and investigations of voltage sharing stabilization with the use of passive *RLC* circuit in switch-mode flying capacitor dc–dc converters are presented. [23], topology of flying capacitor multilevel converter which has several terminals of different dc voltage and an ac voltage terminal proposed to utilize the topology as an integrated power conversion module.[24], control strategy of flying capacitors multilevel inverters. The analysis of the permissible switching states, especially the possibility of the multiple commutations is carried out. [25], the stabilization of the input DC voltages of five level flying capacitors (FLFC) voltage source inverters (VSI). A feedback control algorithm of the rectifier is proposed. [26], an experimental photovoltaic (PV) power conditioning system with line connection in which the conditioner consists of a flying capacitors multi-cell inverter fed by a dc-dc boost converter is carried out. [27], two active capacitor voltage balancing schemes are proposed for single-phase (H-bridge) flying-capacitor multilevel converters, based on equations of flying capacitor converters. The methods are effective on capacitor voltage regulation in flying-capacitor multilevel converters.

2.4 SINUSOIDAL PWM

[28], multicarrier sub-harmonic pulse width modulation (PWM), called disposition band carrier and phase-shifted carrier PWM (DBC-PSC-PWM), method is developed to produce output voltage levels of ($n \times m + 1$) and to improve the output voltage harmonic spectrum with a wide output frequency range. [29], carrier-based closed-loop control technique has been developed to reduce the switching losses based on insertion of ‘no switching’ zone within each half cycle of fundamental wave. [30], five-level pulse width modulation inverter configuration, including chopper circuits as DC current-power source circuits using small smoothing inductors, is verified through computer simulations and experimental tests. [31], designed a seven-level flying capacitor multilevel inverter by using sinusoidal pulse width modulation technique. [32], addressed a modified Sinusoidal Pulse Width Modulation (SPWM) modulator with phase disposition that increases output waveform up to 7-level while reducing output harmonics.[33], pulse-width modulation (PWM) for single-phase five-level inverter via field-programmable gate array (FPGA) is carried out.

2.5. SPACE VECTOR PWM

[34], two discontinuous multilevel space vector modulation (SVM) techniques are implemented for DVR control to reduce inverter switching losses maintaining virtually the same harmonic performance as the conventional multilevel SVM for high number of levels. [35], two carrier-based modulation techniques for a dual two-level inverter with power sharing capability and proper multilevel voltage waveforms were introduced. Their main advantage is a simpler implementation compared to SVM. [36], focused a novel 3-D space modulation technique with voltage balancing capability for a cascaded seven-level rectifier stage of SST.

2.6 SHE-PWM

A method to obtain initial values for the SHE-PWM equations according to the reference modulation index *M* and the initial phase angle of output fundamental voltage is investigated thoroughly. [37], the elimination of harmonics in a cascade multilevel inverter by considering the non-equality of separated dc sources by using particle swarm optimization is presented. [38], new formulation of selective harmonic elimination pulse width modulation (SHE-PWM) technique suitable for cascaded multilevel inverters with optimized DC voltage levels. [39], neutral point voltage control strategy for the three-level active neutral point clamped (ANPC) converter using selective harmonic elimination pulse width modulation (SHE-PWM). [40], a control strategy is proposed to regulate the voltage across the FCs at their respective reference voltage levels by swapping the switching patterns of the switches based on the polarity of the output current, the polarity of the FC voltage, and the polarity of the fundamental line-to-neutral voltage under selective harmonic elimination pulse width modulation. [43], suggested a novel space vector modulation (SVM) technique for a three-level five-phase inverter, based on an optimized five vectors concept.

2.7 SPACE VECTOR CONTROL

[41], switching strategy for multilevel cascade inverters, based on the space-vector theory. The proposed switching strategy generates a voltage vector with very low harmonic distortion and reduced switching frequency. [42], PWM technique for induction motor drives involving six concentric dodecagonal space vector structures is proposed. [43], novel space vector modulation (SVM) technique for a three-level five-phase inverter is based on an optimized five vectors concept. [44], switching strategy for multilevel cascade inverters, based on the space-vector theory. The proposed high-performance strategy generates a voltage vector across the load with minimum error with respect to the sinusoidal reference.

III.APPLICATION-RES-GRID INTEGRATION

A permanent-magnet synchronous generator wind turbine as shown in Fig.1 is a simplified diagram of a 3L-NPC back-to-back configuration. The gearbox can be avoided by electromechanically achieving the speed conversion between the low-speed rotor shaft (about 15 r/min) and the grid frequency (usually 50 or 60 Hz), for multi-pole generators. The hybrid 5L-ANPC been proposed in back-to-back configuration in [45 - 46]. The use of a 3L-NPC at the grid side and a three-phase diode full-bridge rectifier with a boost converter dc–dc stage at the generator side is proposed [47].

In this, boost converter performs the MPPT of the generator side, whereas the NPC regulates active and reactive power. The boost naturally elevates the voltage, which is suitable for Medium Voltage operation of the NPC. The main advantage over the back-to-back NPC is a simple, low-cost, and reliable front end with the expense of current harmonics at the generator side and lower dynamic performance.

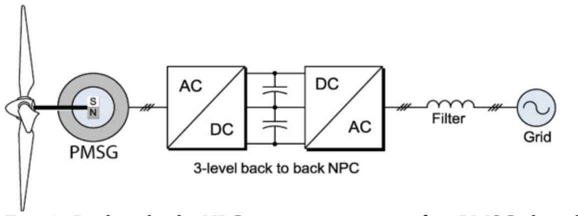

Fig 1 Back-to-back NPC power converter for PMSG based variable - speed wind turbine.

The Cascaded H Bridge on the other side requires multiple isolated dc sources, and therefore, its application is not straight forward. But, some interesting concepts based on rectifiers fed from independent generator stator windings of a permanent-magnet synchronous generator have been proposed, with each one rectified and used to provide the dc source for each H-bridge of the CHB converter [48].With the increase in the number of levels of the converter will allow lower switching frequency operation, improving grid side power control performance and grid code compliance without filters. However, due to the reduction in the cost of photovoltaic modules (among other factors); grid-connected photovoltaic power plants are consistently increasing in power rating mainly now, hundreds of large photovoltaic-based power plants over 10 MW [49], are operating, and even more are under development. In addition, one of the fastest developing renewable energy sources in the last years is photovoltaic grid-connected systems [50].

Centralized and multistring configurations are used with a central dc–ac converter that interfaces the power to the grid, for large photovoltaic power plants. With more demand of grid code requirements for photovoltaic systems, multilevel topologies become more attractive. In [51], has been proposed a dc–ac converter stage in a multistring photovoltaic configuration, in which a five-level converter is formed by a three-level H-bridge with a bidirectional switch arrangement that can clamp two additional levels to the output. In [52]–[53], Cascaded H Bridge based grid interfaces are proposed with their respective control scheme.

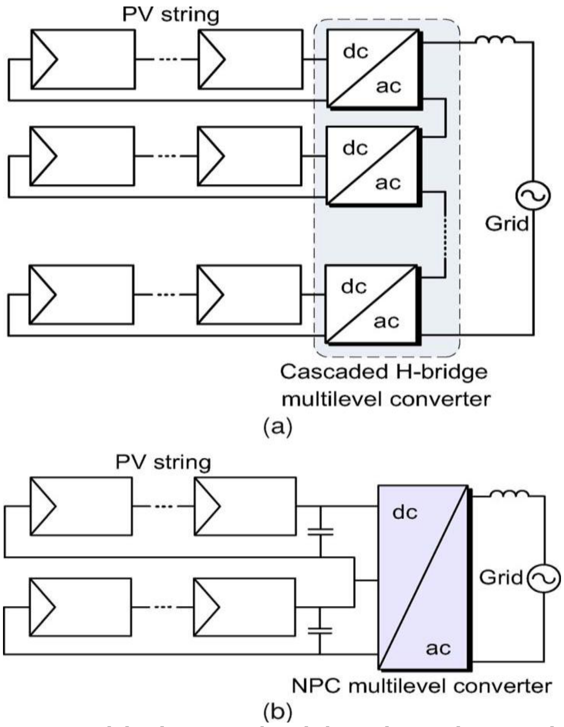

Fig 2.Multilevel-converter-based photovoltaic grid-connected systems. (a) CHB based. (b) NPC based.

Fig.2 (a) and (b) shows a CHB-based and an NPC-based multilevel multistring photovoltaic topology respectively. The series connection of the H-bridge makes CHB very impressive, as the strings naturally elevate the voltage, eliminating the need for a boost stage or step-up transformer. Enabling a reduction in the average device switching frequency, it increases the apparent switching frequency of the total converter waveform. The higher amount of voltage levels produces an intrinsic reduction of all the harmonics, which reduces the need for grid side filters, along with the efficiency improvement. A trend clearly shows an exponential growth of grid tied photovoltaic systems, compared with the evolution of the stand-alone technology due to improved efficiency (no losses in energy storage and additional converter stages). A recent application of multilevel converters is hydro-pumped energy storage. A large-scale energy storage system in which water is pumped from a lake, river, or even ocean to a higher located reservoir; at the time of requirement and the same water is used for hydropower generation. Hydro-pumped storage is especially useful for nuclear power plants since the reactor operation level cannot abruptly be changed, and during low power demand, the excess energy can be used to pump water to the reservoir. It can also be applied for wind power plants, when the wind energy surpasses the consumption demand.

In the high-power-demand period (peak hours), water from the reservoir is used to generate the additional required energy also.

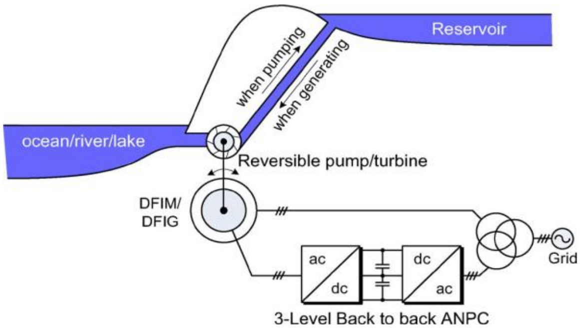

Fig 3. Back-to-back ANPC doubly fed induction generator/motor for hydro pumped energy storage application

A simplified overview of a hydro-pumped energy storage system is illustrated in Fig. 3. The system uses a reversible Francis hydro-pump or turbine that can be used for either water pumping or generation. These systems are usually operated at fixed speed with synchronous motor or generator due to their high power rating. In a doubly fed induction generator, with a partially rated converter interconnecting the rotor to the grid a small percent of variable-speed operation above or below synchronous speed can improve efficiency at different load and operating conditions; thus, can provide a percentage of variable speed for a much higher power rated pump or turbine [54].To enhance the controllability and the power transfer capability of the network, Flexible AC Transmission Systems (FACTS) have been introduced as the solution. Different technologies that are considered as FACTS are AFs, static compensators (STATCOM), dynamic voltage restorers (DVRs), unified power flow controllers (UPFCs), and unified power quality conditioners. All these systems can, in one way or another, provide instantaneous and variable reactive power compensation in response to grid voltage transients (voltage sag, swell, harmonics, etc.), enhancing the grid voltage stability [55],These devices (AF, STATCOMs, DVRs, and UPFCs) are currently gaining importance due to more demanding grid codes [56], which even require low voltage-ride-through capability during voltage sags. Several multilevel converter applications for these systems have been proposed, the CHB and NPC topologies seem to be the most suited for STATCOM applications.

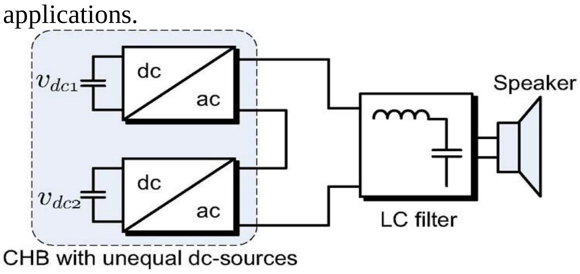

Fig 4. Nine-level asymmetric fed CHB class-D digital audio Amplifier.

3.1. OTHER APPLICATIONS

Class-D digital audio power amplifiers are not in the high-power and medium-voltage range, the improved power quality (mainly reduced THD) and the possibility of reaching higher apparent switching frequencies, without increasing the average device switching frequency, have led to the research lines to apply multilevel technology in this field [57]–[59]. Here, the cascaded topologies, particularly the Cascaded H Bridge fed with unequal dc sources, seem more attractive since they can easily reach a high number of levels (less THD), improving audio quality while facilitating high-frequency filtering. Fig.4 shows a nine-level class-D digital audio amplifier proposed in [58]. Large conveyor systems are one of the standard applications of multilevel converters, not necessarily demanding high performance and high dynamic control. In Grid-connected PV applications [60], the primary issue of solar PV energy is its generation variability where large-scale PV systems are considered, which presents a great challenge to the power system operator. Energy storage is a key component in improving energy efficiency, security and reliability [61]. As the power level of the PV systems increases and the grid connections takes place at medium voltages, the system can benefit from the utilization of multilevel converters due to the lower EMI, reduced switching frequency, increased efficiency and improved waveform quality [62-63]. The multilevel concept is used to decrease the harmonic distortion in the output waveform without decreasing the inverter power output using renewable energy sources like Wind, PV etc. [64-65]. For hybrid photovoltaic and wind energy system connected to the grid, the method allows the renewable energy sources to deliver the load together or independently depending upon their availability. The usage of five-level inverter reduces Total Harmonic Distortion (THD) in output voltage and helps in eliminating bulk filters required at the output side [66].

IV. CONCLUSIONS

In this paper many topologies and control techniques have been reviewed, which helps the researchers to use proper techniques to control multilevel converters for renewable energy sources grid integration. The elimination of the transformer implies significant cost, volume, and weight reduction, and it also would reduce system complexity and losses. There are now several commercial products available for wind power converters, centralized photovoltaic converters, STATCOMs hydro pumped storage, etc. It can be seen that a clear trend in the diversification of multilevel powered applications are increasing. It is expected that this trend will continue, and more applications will be enabled by this technology, due to more grid codes, continued increase in power demand of the applications, increasing development of power semiconductors, and the benefits of multilevel technology. In this respect, the application of multilevel converters to FACTS systems is very promising. For, a distributed generation system involving multiple energy sources and networks of different voltage levels, multilevel voltage source converters can effectively be used as a power management system. ng system may be installed instead of storage system.

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