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A Survey on Multilevel Power Factor Correction Rectifier

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ABSTRACT—

Increasing concerns over the pollution caused by the tailpipe emissions from the internal combustion enginebased vehicles and the limited availability of fossil fuels have greatly paced up the adoption of Electric Vehicles (EVs). Recent advances in battery technologies, power electronics, digital controllers, electric machines and sensing technologies have laid the foundation for the development of the next generation EV technology. As such, power electronics interface plays a pivotal role in EV battery charging. The power electronics interface for both on-board and off-board EV charging generally comprises two stages: (a) AC-to-DC conversion stage with Power Factor Correction (PFC) and regulation of the intermediate DC link voltage; and (b) DC-to-DC conversion stage for regulating the charging current for the EV battery. This work deals with novel PFC converters for the AC-to-DC conversion in the futuristic and emerging EVcharging systems. Multilevel Rectifiers (MLRs) have been specifically investigated as they offer numerous advantages, such as: utilization of low voltage power switches, highly improved harmonic profile of the alternating voltage at the input terminals, low dv/dt stress, modularity and so on.

Keywords— Bidirectional, Buck-boost rectifier, Electric vehicle, Grid-to-vehicle, Multilevel converter, Power factor correction, Switched capacitor, Vehicle-to-grid, Wide output voltage range

Introduction

PFC rectifiers have a long history, dating back to the early days of AC power distribution. In the early 20th century, the power factor of AC power systems was typically low due to the use of inductive loads such as motors and transformers, which led to significant power losses and reduced efficiency in power transmission and distribution systems. The development of PFC rectifiers was driven by the need to improve power factor and reduce energy consumption. Early PFC rectifiers were based on passive circuits such as diode bridges and LC filters, which had limited PFC capabilities. However, in the 1970s, the development of active PFC rectifiers, using techniques such as boost converters, brought significant improvements in PFC [47]. One of the most important developments in PFC rectifiers came in the 1980s with the introduction of the Vienna rectifier [48]. This rectifier uses a three-phase input and a specially designed circuit topology to achieve near-unity PFC. The Vienna rectifier has been widely used in high-power applications, such as industrial motor drives and renewable energy systems [49]. For PFC rectification and improved power quality, the emergence of multilevel converters marked a turning point in the field of power electronics. By utilizing multiple levels of voltage, multilevel converters could significantly reduce switching losses, resulting in improved power quality and higher efficiency. One study by [50] compared a three-level NPC converter and a traditional two-level PFC converter for a 10 kW PFC rectifier, and found that the three-level NPC converter had lower harmonic distortion, lower switching loss, and higher efficiency. Multilevel converters can improve power quality in PFC rectifiers. Over the years, various multilevel topologies have been proposed and analyzed. The basic HB multilevel inverter was f irst introduced in the early 1980s [51]. This topology consists of a series of HB cells, with each cell containing four power switches and two capacitors. By controlling the switching of the power devices, the HB inverter can produce a staircase waveform with several voltage levels. The HB inverter is simple in structure and easy to control, making it a popular choice for low-voltage and low-power applications. The HB topology can also be implemented for bidirectional operation as a boost PFC rectifier.

The Flying Capacitor Multilevel Inverter (FCMLI) was introduced in the early 2000s as a modification of the NPC inverter [53]. The FCMLI topology reduces the number of components required in the converter by using flying capacitors to achieve the same number of output voltage levels. The FCMLI has a simpler structure compared to other multilevel topologies, making it suitable for high-frequency applications and achieve boost PFC rectification. The multilevel buck rectifier based on the Cascaded H-bridge (CHB) topology [41] provides multiple DC outputs. In the CHB structure, each module on the AC side interact with the others to obtain an almost sinusoidal current that is in phase with the grid voltage. There are two other topologies of multi-output buck MLR, five-level rectifiers with the possibility of two outputs [42], and a nine-level rectifier with three outputs [43]. In recent years, research has focused on improving the efficiency and performance of PFC rectifiers through the use of advanced semiconductor devices such as wide bandgap materials (silicon carbide and gallium nitride) and soft-switching techniques such as resonant converters. Overall, PFC rectifiers have become an essential component of modern power supplies, with significant improvements in efficiency and PFC being achieved through the use of active control techniques and advanced semiconductor devices

NON-MULTILEVELPFCRECTIFIERTOPOLOGIES

Based on the magnitude of output DC voltage, non-multilevel PFC rectifiers are classified into three categories: buck, boost and buck-boost PFC rectifiers. 'Boost' refers to the fact that in this class of rectifiers, the magnitude of output DC voltage is greater than the peak value of the input AC voltage [34, 36], which is found to be unsuitable to directly feed the DC-bus of EV battery, and hence requires either a subsequent step-down DC-DC converter at the DC side, or a step-down transformer at the AC side. Both these approaches add to the volume, costs and power losses in the system. However, the consideration of constant output DC voltage and PFC operation at the input do not require bulky filters either at the AC side or the DC side. 'Buck' refers to the fact that in this class of rectifiers, the magnitude of the output DC voltage is lower than the peak value of the input AC voltage. Such rectifiers provide a wider control range for the output DC voltage, as compared to the boost rectifiers [64, 68]. PFC buck rectifiers, however, generally exhibit Discontinuous Conduction Mode (DCM), due to which the regulation of output voltage becomes difficult and necessitates large filters on the DC side. 'Buck-boost' type of rectifiers can operate in buck as well boost modes [69]. Many a times, they employ a low number of switches and integrate the magnetic elements to reduce the total size and volume of the converter [70, 71]. In many cases, however, bridge-less buck-boost rectifiers do not offer bidirectional power flow and easy extension to three-phase module.

MULTILEVELPFCRECTIFIERTOPOLOGIES

Another categorization of PFC rectifiers is based on the fact that a grid-connected voltage source rectifier synthesizes a voltage to control the grid current. If the synthesized voltage is improved by increasing the number of voltage levels, the grid current can be consequently improved. These rectifiers are known as MLRs, and the synthesized terminal voltage can be as high as 'N' levels, as shown in Fig. 1 Multilevel converters offer numerous advantages, some of which are [42.41,15]

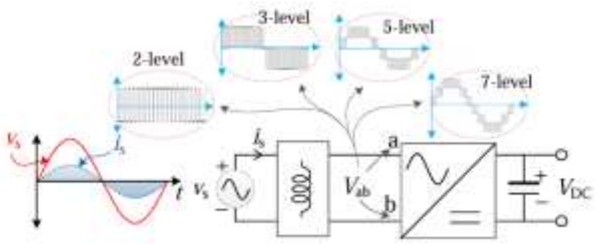

Fig.1 : Possibility of multilevel voltage at the terminal of Vab

Multilevel boost PFC rectifier topologies

Three-level H-bridge:

The HB rectifier generates three levels at the terminals 'a' and 'b', resulting in a voltage Vab consisting the levels +VDC, 0, and-VDC [34], where VDC is the regulated output DC voltage. In HB rectifier, the modulation index M is defined as M = $vmax$ '1' and $vmax$ s s βVDC where β is is the peak grid voltage in this topology. In the modulation range (0.5<M

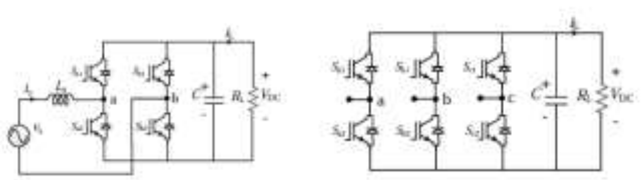

Fig.2: Three level H-bridge boost PFC rectifier topology

Three-level T-type topology:

The T-type rectifier produces three distinct voltage levels at the 'a' and 'b' terminals, resulting in a voltage Vab of +VDC 2 ,0, and-VDC , where VDC is the regulated output DC voltage [35]. In T-type rectifier, the modulation index M is defined as M = $vmax$ s βVDC where β is '0.5' in this topology. As compared to the H-bridge topology, under the same modulation range of (0.5<M

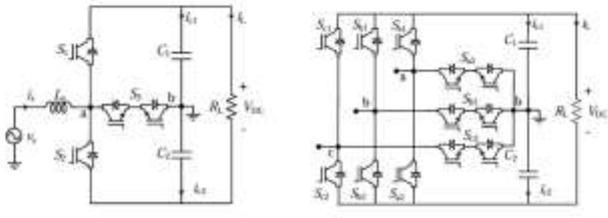

Fig.3:Three levelT-TypeboostPFCrectifiertopology

Five level FC topology:

The FC based rectifier generates five voltage levels at the terminals of‛ a and ‘b’, voltage levels In FC rectifier, modulation index M is defined as M= $vmax$ s VDC where $\beta$is‘1’ in this topology.Under the modulation range(0.5<M

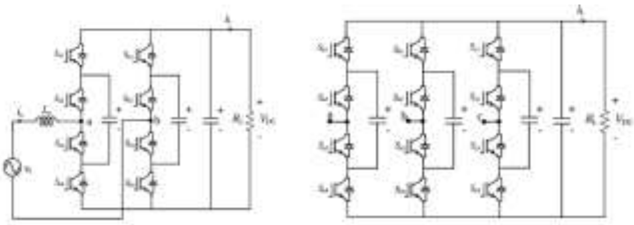

Fig.4 :Five level flying capacitor boost PFC rectifier topology

MultilevelbuckPFCrectifiertopologies

Very limited literature is available on multilevel buck rectifiers [41–43]. These topologies proposed in [41–43] single-phase, Continuous Conduction Mode (CCM) and generate a multilevel voltage wave form at the input terminals. Due to CCM operation, commonly used AC-side capacitive and DC-side inductive filters are removed. The buck rectifier proposed in [41] is based on the CHB topology and provides multiple DC outputs this topology each output terminals regulated for VDC and generates voltage levels at the terminal of ‘a’ and ‘b’, voltage levels Vab can be +2VDC, +VDC, 0,-VDC and-2VDC. In [41], the modulation index M is defined as M = $vmax$ s βVDC where β is ‘2’ in this topology. For the CHB structure, on the AC side, each module must interact with the others to obtain an almost sinusoidal current in phase with the grid voltage [89]. On the DC side, each capacitor’s voltage must be stable and controlled. Balancing the capacitor output voltage requires multiple voltage sensors and a complex control strategy.

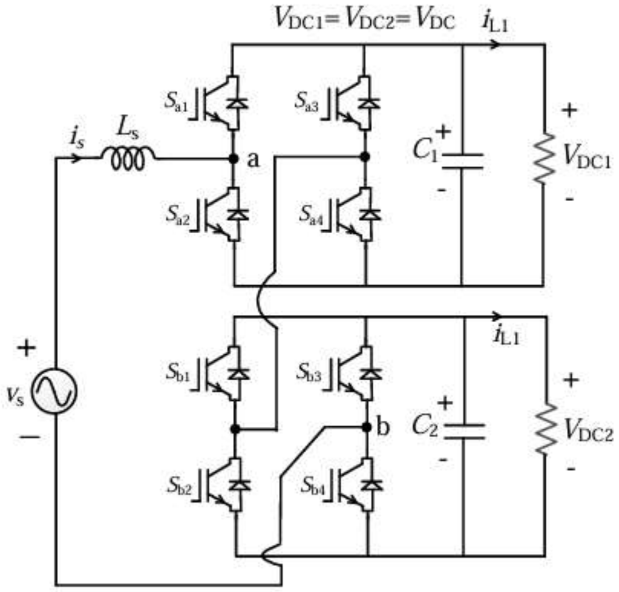

Fig. 5: Five level cascaded H-bridge buck PFC rectifier

Another buck topology proposed in [43] is a nine-level converter, which is primarily based on the original inverter topology described in [90]. The voltage balancing of capacitors and control methodology is challenging in [43]. Voltage levels at the terminal of ‘a’ and ‘b’, voltage levels Vab can be +2VDC, +3VDC 2 , +VDC, +VDC 2 , 0,-VDC 2 ,-VDC,-3VDC 2 and-2VDC. In [43], the modulation index M is defined as M= $vmax$ s βVDC where β is ‘2’ in this topology. In [43], the authors use Finite Switching Set Mode Predictive Control to regulate the DC voltages and to track the desired reference of the input AC current. This requires four voltage sensors and four current sensors to balance the capacitor voltage and improve the PFC. Another drawback of the topology in [43] is the requirement of high voltage rated power switches and difficulty in extension to three-phase version. Hence both these rectifiers of [42] and [43] are characterized by three important limitations: voltage ratings of the switches are different and higher, balancing of voltages is extremely complex (involving multiple sensors and cumbersome real-time computation) and three-phase extensions are not possible directly. This topology functions as a buck PFC rectifier and is challenging to implement in a three-phase configuration due to its complexity.

Table2.2.Comparison of multilevel PFC rectifier topologies based on various features

Reference	Work	F#1	F#2	F#3	F#4	F#5
[36]	T-type boost PFC rectifier	×	✓	✓	×	✓
[39]	Three-phase three-level ANPC rectifier	×	✓	✓	×	✓
[40]	Three-phase flying capacitor PFC rectifier	×	✓	✓	×	×
[41]	Cascaded H-bridge PFC rectifier	✓	✓	×	×	×
[42]	Bidirectional five level buck PFC rectifier	✓	✓	×	×	×
[43]	Triple output nine level buck PFC rectifier	✓	✓	×	×	×

CONCLUSION

The existing multilevel PFC rectifier topologies discussed so far have been compared based on these features and a summary is presented in Table 1. It is noted that most of the research on multilevel PFC rectifiers focuses on the single output boost mode of operation, and is designed for either single-phase or three-phase power supply. As EV technology continues to evolve, we can expect to see even more innovation and variation in battery voltages, charging infrastructure, and other components, which will shape the future of electric mobility. Given the different aspects of power converters, the scope of this work is identified as the development of a single and three-phase multilevel PFC rectifier with a wide output voltage range for EV charging, taking the following considerations into account: A multilevel PFC rectifier is classified by the number of levels in the input side voltage waveform. Compared to non-multilevel rectifiers, MLRs offer several advantages such as lower voltage ratings for power switches, a much better harmonic profile of the input waveform, reduced dv/dt stress, and the possibility of fault-tolerant operation. Therefore, the scope is identified to investigate the multilevel PFC rectifier. Existing buck PFC rectifiers require multiple capacitors for voltage regulation. Balancing these capacitors necessitates the use of multiple sensors, which adds to the complexity of controller in signal processing. Therefore, the scope is identified to develop a voltage balancing technique that can reduce the sensor requirements and the controller complexity.

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