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A Novel Method for on board Charger Using Three Phase Switched Coupled Inductor Quasi-Z-Source Inverter

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ABSTRACT: A new space vector modulation, for three-phase quasi-Z-source rectifier (qZSR) is proposed. All switches in the three-phase bridge can be turned on and turned off with zero-current or zero voltage using the proposed ZSVM3 without any auxiliary ciruit. The current through the inductors of the quasi-Zsource network operates in boundary conduction mode or discontinuous conduction mode to achieve all freewheeling diodes turned off with zero current- switching (ZCS). At the same time, the switch in the quasi-Z-source network can be turned on with ZCS. Besides, the voltage stress of all switches is equal to dc-link voltage. The operation principle of the qZSR is analyzed in detail and the calculated value of the quasi-Zsource inductor is given. The proposed theory in this paper is verified by a 2-kW prototype. Novel active clamping zero-voltage switching threephase boost pulse width modulation (PWM) rectifier is analyzed and a modified minimum-loss space vector modulation (SVM) strategy suitable for the novel zero-voltage switching (ZVS) rectifier is proposed in this paper. The topology of the novel ZVS rectifier only adds one auxiliary active switch, one resonant inductor, and one clamping capacitor to the traditional hard-switched threephase boost PWM rectifier. With the proposed SVM strategy, the novel ZVS rectifier can achieve ZVS for all the main and auxiliary Switches. In addition, the antiparallel diodes can be turned OFF softly, so the reverse recovery current is eliminated. Besides, the Voltage stress of all the switches is equal to the dc-link voltage. The Operation principle and soft-switching condition of the novel ZVS Rectifier is analyzed. The design guidelines of the soft switched Circuit parameters are described in detail. A DSP controlled 30 kW Prototype is implemented to verify the theory.

I. INTRODUCTION

Onboard charger plays a very important role in electric vehicles (EVs). While it increases space occupation, weight and costs of EVs, especially when quick charge is needed. Integrated charger solves these problems. It uses the traction hardware including an inverter, circuits, and motor windings, as the rectifier and grid-side filter inductors of the charger. Since the quasi-Z-source network can realize bi-directional energy flow and some electrical vehicle drives use quasi-Zsource network, three-phase qZSR is very suitable for integrated charger. Enhancing the efficiency of integrated charger is important. The switching loss and the freewheeling diode reverse recovery loss lower the efficiency of integrated charger. So it's necessary to realize the soft switching for a three-phase rectifier. Many researches on soft-switching for threephase rectifier have been done in recent years. In most soft-switching technologies, an auxiliary circuit is added to make switches turned on and turned off under zero-voltage-switching (ZVS) or ZCS condition. The resonant dc-link (RDCL) is one kind of dc-side soft-switching technologies. The auxiliary circuit of RDCL only needs one small capacitor and inductor. But the voltages across the switches will reach about 2.5 times the dclink voltage. The active clamped resonant dc-link (ACRDCL) is another dcside soft-switching technology. Compared to RDCL, the voltages across the switches are lower (about 1.4 times the dc-link voltage) using ACRDCL. However, the auxiliary circuit of ACRDCL needs one more power switch. Quasi-ACRDCL (qACRDCL) is proposed in. All switches can be turned on with ZVS and the reverse recovery loss of freewheeling diodes also can be eliminated. The auxiliary circuit of qACRDCL is simpler than ACRDCL and the grid-side harmonic current can be reduced by specific modulation, while the voltages across all switches are still higher than dc-link voltage. Modified qACRDCL uses a modified SVM to make the voltages across all switches equal to the dc-link voltage. The zero-voltage-transition (ZVT) and zero-current-transition (ZCT) converter proposed in use a small switch, a small inductor and a small diode to realize a wide load range soft-switching technology applies this technology to three-phase inverter and proposes a modified modulation. A high-power threephase rectifier using six auxiliary switches to achieve full zero-current switching for all switches is proposed. the simplified three-phase ZCT inverter only uses three auxiliary switches and LC resonant tanks and it can achieve soft switching with normal PWM algorithms.

II. EXISTING SYSTEM

The Z-source concept can be applied to all dc-to-ac,ac-to-dc,ac-to-ac,dc-todc power conversion. To describe the operating principle andcontrol,this paper focuses on an application example of the Z-source converter:a Z-source inverter for dc-ac power conversion needed for fuel cell application. Because fuel cells are usually produce a voltage that changes widely.(2.1 ratio) depending on current drawn from the stacks. For fuel-cell vehicles and distributed power generation, a boost dc-dc converter is needed because the V-source inverter cannot produce an ac source.

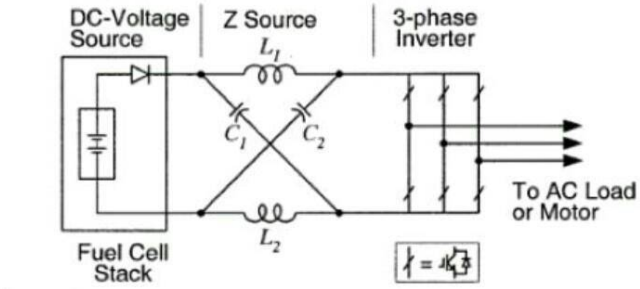

Fig1: Existing Proposed switched coupled-inductor quasi-Z-source inverter

III. PROPOSED SYSTEM

We propose, a combination of switched-capacitor (SC) and a three winding switched-coupled-inductor (SCL) is applied to the qZSI, and the topology obtained is termed as SCL-qZSI. The proposed SCL-qZSI retains all of the advantages of the classical qZSI topology such as continuous input current and a common ground between the dc-voltage source and the inverter-bridge; it can also suppress the start up inrush current. The integration of the SC with SCL is beneficial in that it significantly enhances the boost ability of the SCL-qZSI with a smaller component count and lower turn ratio. The proposed inverter adds only one capacitor and two diodes to a classical qZSI, and even with a turns ratio of 1, its voltage boost ability is higher than that of the existing high-voltage boost (q) ZSI and trans-ZSI, which were discussed before. Therefore, for the same input and output voltages, it can use lower and higher, which results in lower component-voltage stresses, a better output power quality, and a lower input current ripple.

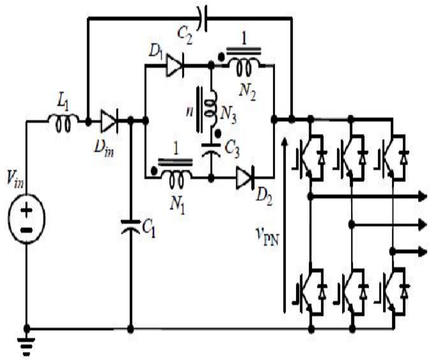

Fig 2: Proposed switched-coupled inductor quasi-Z-source inverter (SCLqZSI).

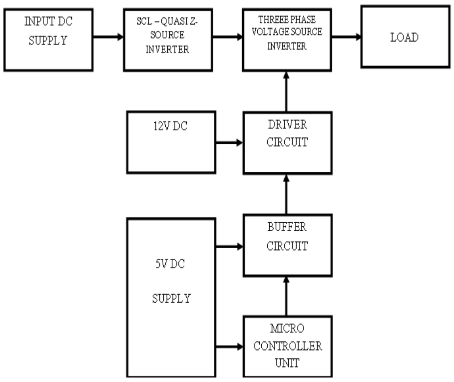

Fig 3: block diagram for proposed switched-coupled-inductor quasi-Z-source inverter

The three-phase six-switch boost pulse width modulation (PWM) rectifier as shown in Fig. 1, due to its remarkable features of high power quality and low electromagnetic interference (EMI) emissions, is widely chosen for medium and high power industrial applications. However, during the commutation from diode to transistor, the antiparallel diodes of the rectifier experience reverse recovery process, which will cause severe switching losses and EMI problems due to high di/dt and dv/dt. Considering these problems, the switching frequency of PWM converters is usually confined, which may result in higher current total harmonic distortion, larger passive components, and high switching noise. The soft-switching technique can make switches be turned ON and OFF under zero-voltage or zero-current condition, which will resolve the diode reverse recovery problems and reduce switching losses. Meanwhile, the rising and falling edges of switch current and voltage waveforms can be shaped so the di/dt and dv/dt are reduced as well. Many soft-switching techniques for three-phase PWM converter have been investigated. The general methodology is to add auxiliary resonant circuit to decrease or eliminate the overlap between voltage and current at switching transitions. According to the placement of auxiliary circuit, the soft-switching threephase PWM converters can be divided into two classes: the dc-side soft-switching converter and the ac-side soft-switching converter. The dc-side soft-switching converter uses one group of auxiliary circuits placed on the dc-side of the converter to produce high-frequency pulsating voltage across the main switch bridge. The switches are commutated at the instants when the bridge Voltage is zero so the corresponding devices can be zero-voltage switching (ZVS) switched. Among the various dc-side soft-switching topologies in the resonant dc-link (RDCL) converter in has the simplest topology, but it imposes 2–2.5 times voltage stress on all the switches. The active clamped RDCL (ACRDCL) converter in added one extra auxiliary clamping switch to decrease the device voltage stress by times. However, the RDCL and ACRDCL converters are both controlled by discrete pulse modulation (DPM), which will produce sub harmonics in the ac-side current waveforms. A partial PWM control technique for heRDCLand ACRDCL converters has been proposed in to overcome the drawbacks of the DPM but the device turn-off loss is increased and meanwhile the PWMrange is limited. To apply real PWM control techniques, many approaches have been presented in . These converters provide zero voltage intervals in the switch bridge of the PWM converter antiparallel diodes can be turned OFF softly, so the reverse recovery current is eliminated. Moreover, the voltage stress of both main and auxiliary switches is equal to the dc-link voltage. The turn-on losses of IGBTs and reverse recovery losses of antiparallel diodes can be avoided. But for ZVS switching, the turn-off losses of IGBTs can only partly be avoided because of the existence of the tail current.

IV. CONVERTER TOPOLOGY AND OPERATION ANALYSIS

Converter Topology Derivation

The topology of the ZVS-SVM-controlled threephase PWMrectifier proposed in which consists of a standard PWMrectifier and an auxiliary resonant branch. The auxiliary Branch consists of an auxiliary active switch S7, a resonant

Inductor Lr, and a clamping capacitor Cc. The auxiliary switch S7 is conducting for most of the switching period. When the auxiliary switch S7 is turned OFF, the energy stored in the resonant inductor Lr will discharge the parallel capacitors of the main switches. When the voltage of the capacitors paralleled With the main switches is discharged to be zero, the main switches can be turned ON under ZVS condition. Meanwhile, the current of the antiparallel diodes can be linearly decreased with the existence of Lr . Therefore, the reverse recovery current of the antiparallel diodes is effectively suppressed. For the topology shown in Fig. 2, the voltage stress of the Main and auxiliary switches is clamped to Vo + VCc, which will increase with the load power. With circuit parameter optimization, the voltage stress can be confined within 1.1 times of the dc-link voltage. To further decrease the voltage stress of the main and auxiliary switches, a novel active clamping ZVS three-phase boost PWM rectifier, as shown in Fig. 3 controlled by minimum voltage active clamping SVMmethod, is proposed in. Compared with the topology shown in Fig. 2, only the position of the clamping capacitor Cc is changed, which will decrease the device voltage stress to the dc-link voltage. In the existing ZVS-SVM control method proposed in is adopted to control the rectifier shown in Fig. 3. But there still exists some problems in the soft-switching condition. This paper will further discuss the rectifier shown in Fig. 3 and find the solution. B. Operation Analysis with Existing Modulation SchemeSince the novel topology shown in Fig. 3 is very similar to the topology shown in Fig.2; this paper will first discuss the operation principle of the novel ZVS rectifier adopting the existing ZVS-SVM control method proposed in.

The rectifier always works with unit power factor, so the three-phase grid voltage and current waveforms can be shown in Fig. 4. Based on the analysis in the traditional six voltage sectors can be further divided into 12 different smaller sectors according to the peak of grid current waveforms, as shown in Fig. 5. For example, sector SECT1 can be divided into SECT1-1 and SECT1-2. In SECT1-1, the current of phase A is the largest among three phases, and the switching status of phase A in the selected nonzero-vectors is “1” so that **U**7(111) is chosen as the zero-vector to make sure there is no commutation of phase A in one switching cycle. In SECT1-2, the current of phase C is the smallest among three phases, and the switching status of phase C in the selected nonzero-vectors is “0” so that **U**0(0 0 0) is chosen as the zero-vector to make sure there is no commutation of phase C in one switching cycle.

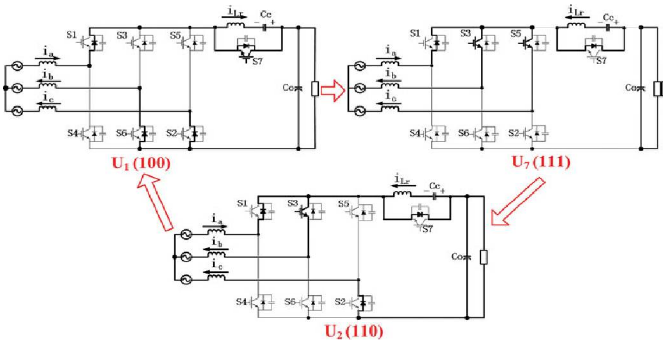

Fig. 4. Three switching states in the SECT1-1.

The auxiliary branch only operates once in each switching cycle to realize the ZVS of the main and auxiliary switches. Taking SECT1-1 as an example, the zero-vector**U**7 (1 1 1) should be placed after **U**1(1 0 0), and **U**2(1 1 0) follows **U**7(1 1 1), as shown in Fig. 6. As shown in Fig. 6, the antiparallel diode of switch S1 in phase A is always conducting, while the switches in the other two phases are controlled in PWMmanner. There are two kinds of commutations: one is from transistor to diode and the other is from diode to transistor. The switching state changing from **U**7(1 1 1) to **U**2(1 1 0) and from **U**2(1 1 0) to **U**1(1 0 0) are the former, in which the commutations are normally soft-switching and the auxiliary branch needs not act. Much more attention should be taken to the switching state changing from **U**1(1 0 0) to **U**7(1 1 1), which is the commutation from diode to transistor and needs to activate the auxiliary branch to realize ZVS. The three switching states shown in Fig. 6 can be simplified as shown in Fig. 7. The three-phase grid current can be represented by a current source during one switching cycle, and the equivalent circuits of switching states **U**1(1 0 0),

U7(1 1 1), and **U**2(110) can be shown in Fig. 7. With the existing ZVS-SVM controlmethod proposed in the operation principle of the novel ZVS rectifier in SECT1-1 is given as follows.
The auxiliary switch S7 is in conduction during most of the time in one switching cycle. When the switching state changes from **U**1(1 0 0) to **U**7(1 1 1), the auxiliary switch S7 is turned OFF first and then the resonance between Lr , C4 + C3 + C5 , and C7 is initiated. 2) The energy in the resonant inductor Lr will discharge the parallel capacitor of the switches S4 , S3 , and S5 , and make the bridge voltage resonant to zero so that S3 and S5 can be ZVS turned ON. 3) And Lr can suppress the reverse recovery currents of S6 ’s and S2 ’s antiparallel diodes. After these switch antiparallel diodes finish the reverse recovery, the current of the resonant inductor starts to flow through the antiparallel diode of the auxiliary switch S7 . So the auxiliary switch S7 is turned ON under ZVS condition.

V. DESIGN GUIDELINES

A. Resonant Parameters Optimization

In the novel ZVS three-phase boost PWM rectifier shown in Fig. 3, the resonant parameters include the inductance of the resonant inductor Lr , the resonant capacitors C1 = C2 =C3 = C4 = C5 = C6 = C, and C7 . These parameters have vmuch influence on the efficiency of the rectifier and must be optimized. Base on the previous theoretical analysis, the design guidelines of the novel ZVS three-phase boost PWM rectifier are presented as follows.

1) Choosing resonant cycle Tr according to dead time tdead. According to the switch driving signals shown in Fig. 13, the duration time of stage 2 (t1–t2) tstage2 should be less than dead time tdead.
2) According to Fig. 12(d), to effectively suppress the reverse recovery current of the antiparallel diodes, the di/dt of the diodes must be confined to less than 100 A/μs in stage 4, which requires the resonant inductor be large enough.
3) According to (17), the duration time of stage 5 must be larger than a value to realize ZVS of the main switches. On the other hand, the duration time of stage 5 also determines the additional current of the resonant inductor Iadd represented as (7), which should beminimized to decrease the turn-off losses of the main switches at t5 . The resonant tank impedance Zr is also determined to minimize current
Iadd.
4) According to the switch driving signals shown in Fig. 13,the auxiliary switch turn-off duty cycle D0 should be less than the duty cycle of zero-vector in a PWM period Dz . Otherwise, D0 will occupy the duty cycle of nonzerovector, which will distort the input current waveforms. 5) Combining all the aforementioned conditions, a feasible parameters region will be obtained. Considering turn-off
loss reduction, Cr is selected to be the maximum value of the feasible region. Then, a group of optimized resonant parameters will be confirmed. Fig. 15. Resonant cycle Tr versus Cr and Lr . The working condition of the novel ZVS three-phase boost PWM rectifier designed in this paper is given as follows.
1) input phase voltage Vsa : 220 Vrms ;
2) output dc voltage Vo : 700V;
3) switching frequency fs: 16kHz;
4) maximum output power Pomax: 30kW. Following the optimization steps mentioned previously, the resonant parameters can be designed as follows.
1) The dead time tdead is selected to be 3 μs, which is about 5% of the switching period. From the stage analysis, the maximum duration time of stage 2 (t1–t2) will be tstage2(max) =14Tr = πLr (3C + C7
Considering tstage2 should be less than dead time tdead,the resonant cycle Tr is confined to be less than 6 μs.The relationship between the resonant cycle Tr and theresonant parameters can be seen in Fig. 15, in which theparameter Cr is defined in (3).
2) According to Fig. 12(d), the di/dt of the resonant inductorshould be lower than 100 A/μs to suppress the reverse recoveryof the antiparallel diodes. Since the output voltageis 700VDC, the inductance of Lr should be larger than7 μH.3) According to the ZVS condition shown in (17), the duration time of stage 5 should be as long as possible to store enough energy in the resonant inductor.

VI. SIMULATION & EXPERIMENTAL VERIFICATION

The battery voltage of the electric vehicle usually vary from 360-V to 550-V according to different bands. And the input voltage is a three-phase 50-Hz 380-V. As the experimental platform is limited, a 2-kW scaling-down system is designed in this example. The parameters are: The input filter inductance is L=3mH. The capacitances of the quasi-Z-source network are c1=c2=550 uF. The switching frequency is 10-kHz. The input phase voltage amplitude is Vm=78V. The output
voltage is Vout=120V. The output load resistance is R=7.5Ω
through 4 d and 4 S (Iigbt, I4d), the voltage across 4S , the driving signal of 4S and 7.

VII. CONCLUSION

To enhance the efficiency of the threephase qZSR, a ZSVM3 is proposed. The switches in a three-phase bridge can be turned on and turned off under softswitching condition. When the quasi-Zsource inductor current operates in BCM or DCM, the current through freewheeling diode has enough time to decrease to zero, so all the freewheeling diode reverse recovery can be suppressed. And S7 can be turned on with ZCS. The value of the quasi-Z-source inductor can be fit for a wide range of load power. Besides, the voltage stress of the main switches is equal to dc-link voltage. Compared with ZSVM2 and ZSVM6, the proposed ZSVM3 can realize full softswitching and the efficiency of system increases significant. And the switching frequency of S7 using ZSVM3 is just 3 times the switching frequency of S1-S6, while using ZSVM2 is 4 times and using ZSVM6 is 6 times. However, ZSVM3 has its disadvantages. Because ZSVM3 is asymmetric, the THD of grid-side current is a little high. And the peak current through S7 is higher than ZSVM2 and ZSVM6 because of system working in BCM or DCM.

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