Review of Three-phase Soft Switching Inverters and Challenges for Motor Drives

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***Abstract*—For electric vehicles (EVs), it is necessary to improve endurance mileage by improving the efficiency. There exists a trend towards increasing the system voltage and switching frequency, contributing to improve charging speed and power density. However, this trend poses significant challenges for high-voltage and high-frequency motor controllers, which are plagued by increased switching losses and pronounced switching oscillations as consequences of hard switching. The deployment of soft switching technology presents a viable solution to mitigate these issues. This paper reviews the applications of soft switching technologies for three-phase inverters and classifies them based on distinct characteristics. For each type of inverter, the advantages and disadvantages are evaluated. Then, the paper introduces the research progress and control methods of soft switching inverters (SSIs). Moreover, it presents a comparative analysis among the conventional hard switching inverters (HSIs), an active clamping resonant DC link inverter (ACRDCLI) and an auxiliary resonant commuted pole inverter (ARCPI). Finally, the problems and prospects of soft switching technology applied to motor controllers for EVs are put forward.**

***Index Terms*—Soft switching inverters, Zero-voltage switching, Electric vehicles, Motor drives.**

I. Introduction

With energy and environmental issues highlighted, EVs have gained popularity as sustainable modes of transportation, with their production and sales increasing annually. Nevertheless, the development of EVs is impeded by several challenges, including high cost of batteries, low energy density, and slow charging speed. To overcome these obstacles, two methods are proposed: firstly, the advancement of power battery technologies that feature both high energy density and affordability; secondly, the enhancement of system efficiency within EVs, which encompasses improvements in battery efficiency, controller efficiency, and motor efficiency [1].

Recently, with the rapid development of wide band gap (WBG) semiconductor devices (such as SiC MOSFETs), it has been expected to raise the voltage level of EVs motor controllers to 800 V and increase the switching frequency above 10 kHz. Some automakers such as Tesla and BYD are already using SiC devices for EVs motor controllers to cut costs and improve efficiency significantly [2]. However, aiming for higher voltage and frequency, hard switching leads to non-negligible switching losses and more severe noises at high frequency. These problems reduce the system efficiency and improve the requirements for electromagnetic compatibility of motor controllers [3]-[5].

Soft switching technology copes well with the problems caused by hard switching. According to switching type, soft switching is divided into zero-voltage switching (ZVS) and zero-current switching (ZCS). Ideal ZVS and ZCS ultimately reduce the switching losses to zero. Therefore, the integration of soft switching technology into EVs motor controllers helps reduce switching losses, permitting operations at higher frequencies and improving system efficiency [3]. It also helps reduce electromagnetic interference (EMI) and noises.

Originally, soft switching inverters (SSIs) were mostly series or parallel resonance inverters [6]-[7], which were highly load-dependent resulting in the limitation of their utility in variable conditions. Subsequently, there emerged a series of advancements, including active clamping ZVS inverters [7]-[10], quasi-resonant converters/multi-resonant converters [11]-[13], ZCS/ZVS pulse width modulation (PWM) inverters [14]-[16], and phase-shifted full-bridge inverters [17]-[19]. These technologies expanded the soft switching range and reduced the operation time of resonant circuits. Particularly, ZCS-PWM/ZVS-PWM technology solved the problem of unfixed switching frequency, realizing PWM control. Then, zero voltage transition (ZVT) / zero current transition (ZCT) PWM inverters were proposed [16], [20]-[24], which reduced losses caused by auxiliary circuits and further expanding soft switching range, even under light or heavy load.

Subsequent researches have focused on soft switching technology from some aspects, including control methods, circuit topologies, performance comparisons, and practical implementations. In terms of control methods, many optimized PWM strategies were proposed to achieve constant switching frequency control and reduce losses, such as soft

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switching vector control, edge-aligned PWM (EAPWM), ZVS space vector PWM (SVPWM), etc., [25]-[36]. For circuit topologies, some soft switching circuits for DC/AC converters have been proposed. Also, there were various studies on circuit improvements, trying to reduce the additional cost of the auxiliary circuit and the stresses of the switches [22], [37]-[42]. Besides, advantages and disadvantages of various SSIs were compared regarding switching frequencies, stresses, control methods, and other aspects. Methodology of parameter design and circuit evaluation methods for different dimensions were discussed [10], [39], [43]-[48]. For practical applications, the design methods and prototype verification were presented towards on-board chargers, uninterruptible power supplies, grid connected inverters, and photovoltaic inverters. Finally, with the development of WBG semiconductors, SiC or GaN devices have been gradually used in soft switching technology.

This paper reviews soft switching technology three-phase inverters in Sections II, including the topologies, performance, applications, etc. Several control methods are summarized in Section III. Section IV shows the simulation results of the conventional hard switching inverter (HSIs) and two SSIs, with the characteristics of two SSIs compared. Section V introduces the challenges and prospects of soft switching technology for EVs motor controllers. Finally, Section VI summarizes the full text.

II. Circuit Topology

This section classifies SSIs according to the distinct characteristics of various soft switching technologies. The first type includes SSIs based on passive devices (SSIs-PD), such as inductors and capacitors in their auxiliary circuits. The second comprises active-clamping resonant DC link inverters (ACRDCLIs), which feature auxiliary circuits equipped with large capacitance clamping capacitors on the DC side. The third is represented by quasi-resonant DC inverters (QRDCLIs) with auxiliary circuits that operate intermittently. The fourth type consists of resonant snubber inverters (RSIs), which achieve soft switching by introducing snubber circuits in parallel with the main switches. The fifth encompasses auxiliary resonant commutated pole inverters (ARCPIs), where each phase leg is equipped with an auxiliary circuit to help transfer energy to the respective auxiliary circuit during soft switching operations. The final type is ZVT-PWM/ZCT-PWM inverters, which share similarities with the aforementioned inverters, so they are briefly introduced.

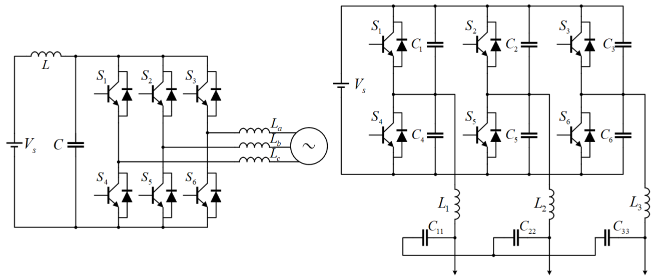
A. *Inverters Based on Passive Devices*

SSIs-PD forms a series/parallel resonant loop by connecting passive devices (such as inductors and capacitors) in series/parallel. The resonance exists voltage or current zero crossing points, making the inverter realize ZVS or ZCS at these zero crossing points. Incipiently, LC filter was directly implemented. Fig. 1(a) depicts LC link on the DC side, while Fig. 1(b) illustrates three-phase LC link on the AC side [6]-[7]. The LC link on the DC side generates voltage zero crossing points through the filter capacitor, enabling ZVS. Similarly, the AC side's LC link utilizes inductors to discharge the parasitic capacitance of the main switches. Both configurations present the following drawbacks:

1) There are at least twice the voltage/current stresses during the resonance process.

2) The inductor operates at a high switching frequency, leading to a pronounced skin effect.

3) There is a significant production of harmonics at the half switching frequency.

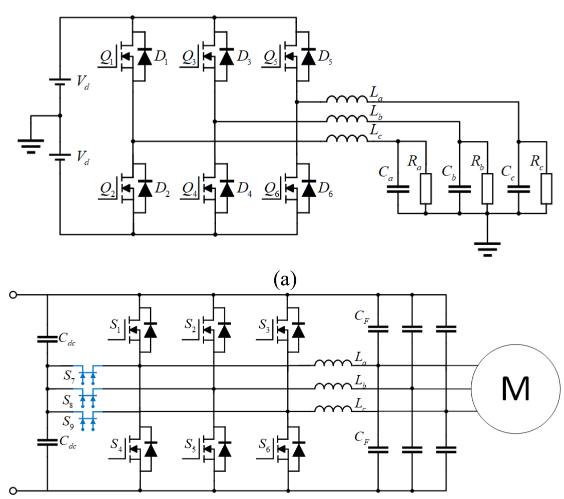


(a) (b)

Fig. 1. Two types of SSIs based on LC link. (a) LC link on the DC side. (b) LC link on the AC side.

The DC-side LC link inverters are gradually replaced by active circuit designs, while the AC-side LC link inverters are still suitable for photovoltaic inverters and grid-connected inverters [31], [41], [47]-[49]. In [28], a ZVS inverter based on a three-phase LC filter was introduced, as shown in Fig. 2(a), controlled by current mode method. This design necessitates grounding the neutral point of the three-phase LC filter, thereby requiring the implementation of split bus capacitors. [47] proposed a T-type rectifier/inverter based on bidirectional GaN devices, as shown in Fig. 2(b). In [48], the T-type inverter was extended to a $L_1C_1 - L_2C_2$ circuit, as demonstrated in Fig. 2(c). Notably, [49] utilizing an LCL link configuration circumvented the need for split bus capacitors, as represented in Fig. 2(d).

Generally, several circuits in Fig. 2 use a lot of inductors and capacitors, which meant a large overall size for the inverters. SSIs-PD are more appropriate for grid-connected inverters and photovoltaic inverters. As a mode of transport,



(a)

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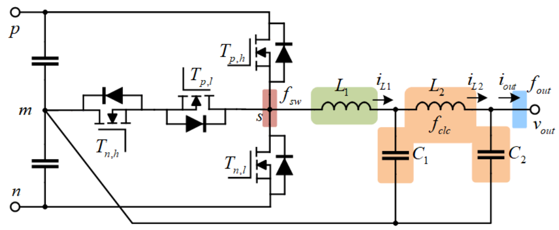

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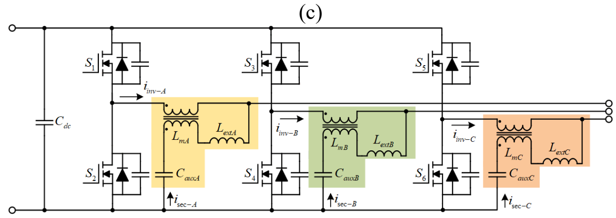


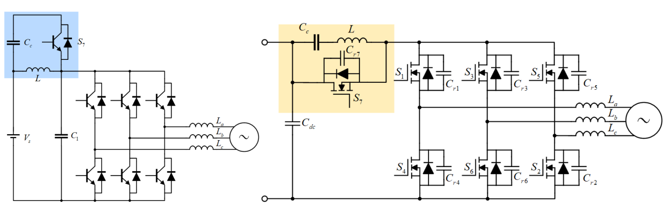
(d)

Fig. 2. Four SSIs based on passive devices. (a) LC filter for AC output. (b) T-type inverter with LC on the AC side. (c) L_1C_1- L_2C_2 for AC output. (d) LCL link configuration.

EVs have stringent requirements regarding volume and weight. Consequently, this type of SSIs is unsuitable for EVs.

B. Active Clamping Resonant DC Link Inverters

The concept of active-clamping resonant DC link was proposed in [7]. Based on diodes and resonant inductors, passive clamping circuits brought 2 to 3 times voltage stresses. In contrast, active clamping circuits brought 1.2-1.4 times voltage stresses by adding an auxiliary switch and clamping capacitor. Fig. 3(a) illustrates ACRDCLIs [7], [10].



(a) (b)

Fig. 3. Two types of ACRDCLIs. (a) The earliest ACRDCLI. (b) The minimum voltage active clamping inverter.

In [9], ACRDCLI was enhanced through an additional bidirectional switch, evolving it into an active quasi-resonant DC link inverter. The selection of resonant inductors in ACRDCLIs is limited due to the need to mitigate losses. In contrast, the resonant inductor in the active quasi-resonant DC link inverter only operates during the auxiliary period, which leads to losses reduction and provides more flexibility for component selection. [26] proposed a minimum voltage active clamping inverter, shown in Fig. 3(b). This design merely adjusts the position of the clamping capacitor, but almost eliminates additional voltage stresses. Similar to [47]-[48], active clamping circuits have also been adapted for T-type inverters [50], as illustrated in Fig. 4.

The voltage and current stresses of the active clamp circuits are acceptable, and the auxiliary components required are simple, thus the increased volume is small. However, the auxiliary switch continues to operate under high current conditions, requiring higher performance specifications compared to main switches.

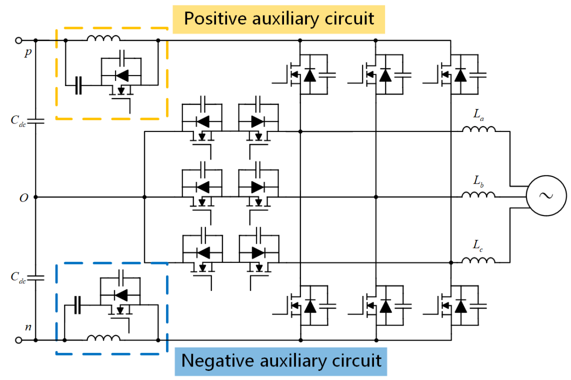


Fig. 4. An ACRDCLI in T-type.

C. Quasi-resonant DC Link Inverters

Unlike the auxiliary circuits of ACRDCLIs working continuously, the auxiliary circuits of QRDCLIs operate for a short time during each switching period. The proposed inverter in [9] is a combination of ACRDCLI and QRDCLI. [11] proposed a QRDCLI with minimal additional voltage stresses. However, the implementation of this inverter is challenging, owing to the incorporation of four auxiliary switches that costs a lot and the increased overall size. In contrast, the circuit structure and control are simple in [12], with only two auxiliary switches. Nevertheless, the circuit offers a limited soft switching range, which hinders its applicability for motor drives. As demonstrated in Fig. 5, [13] and [42] proposed an improved circuit suitable for motor drives. The losses of the inverter are reduced under low modulation ratio region by flexible zero-voltage duration control. Besides, it helps to reduce voltage overshoot and common-mode voltage on the motor side.

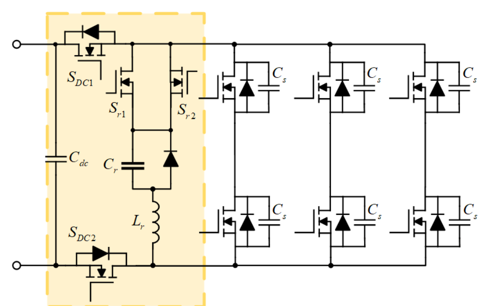


Fig. 5. An QRDCLI, friendly to motor.

A range of QRDCLIs have been explored in various studies [15], [51]-[57]. The structure in Fig. 6(a) is simple, but its soft switching range is relatively small. Based on Fig. 6(a), the circuit in Fig. 6(b) incorporates a connection to the neutral point of a split capacitor. It offers the benefit of a reduced rate of voltage change (dv/dt) at the expense of elevated current stresses. In Fig. 6(c), the auxiliary circuit employs a minimal number of devices, which simplifies control and enhances flexibility. However, the voltage stresses of the auxiliary diode and switch are inconsistent. The structure shown in Fig. 6(d) is complex due to the assembly of auxiliary components. Additionally, [57] proposed a three-phase, four-wire, and three-level hybrid inverter with a simple auxiliary circuit, but rarely used in EVs.

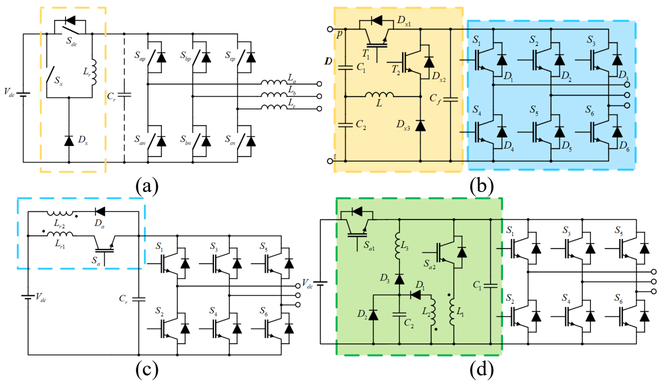


Fig. 6. Four QRDCLIs. (a) Auxiliary circuit with simple structure. (b) With a split bus capacitor. (c) Utilizing coupling inductance, with minimal components. (d) Utilizing coupling inductance, complex structure.

One of significant advantages of QRDCLIs is that the auxiliary circuit operates for a brief period within each switching period, then leads to minimal losses. Furthermore, it is friendly to EVs as there are several QRDCLIs equipped with simple structures and control methods. However, the drawback is that the soft switching range of QRDCLIs is limited, so it is necessary to research on control methods to broaden soft switching range effectively.

D. *Resonant Snubber Inverters*

Initially, to achieve soft switching, McMurray proposed the concept of resonant snubbers combining auxiliary switches, inductors and capacitors [58]. Fig. 7(a) illustrates the SSI based on the resonant snubbers proposed in [37], [59], [60]. This circuit was also converted into a full-bridge inverter [61], as illustrated in Fig. 7(b). This paper delved into the overvoltage mechanism and presented a strategy to suppress the overvoltage. The auxiliary circuit consists of three auxiliary switches and three resonant inductors, as depicted in Fig. 7(c). [62] introduced a SSI based on active quasi-resonant snubbers on the DC side. This circuit involves three auxiliary switches, along with several other components, rending it less advantageous than some of the circuits previously described.

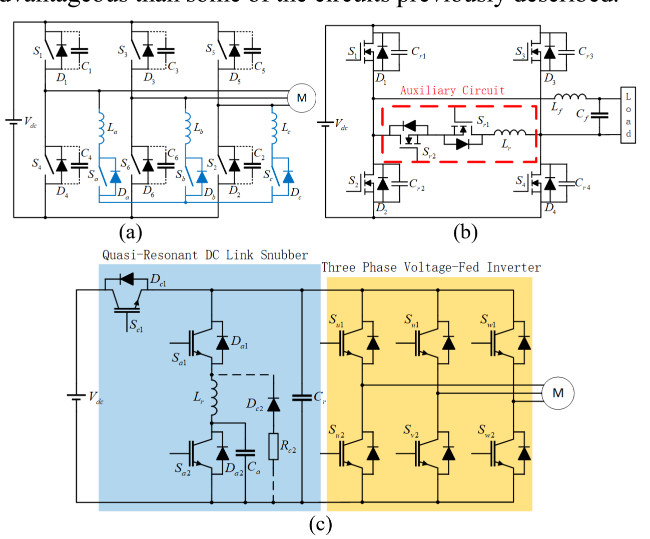


Fig. 7. Three RSIs. (a) An inverter with resonant snubbers on the AC side. (b) A full-bridge inverter with snubber circuit. (c) An active quasi-resonant DC snubbers inverter.

[30] and [45] investigated the resonant snubber circuit shown in Fig. 8. In the design, each main switch is connected in series with an inductor and in parallel with an auxiliary switch, a capacitor, and a diode. This configuration ensures that the switches experience minimal additional current stresses. A similar circuit was introduced in [36]. All main switches achieve ZCS during turn-on and ZVS during turn-off, while the auxiliary switches accomplish ZCS due to the series inductors. The auxiliary circuit is connected to the neutral point of split bus capacitors to reduce the voltage stresses.

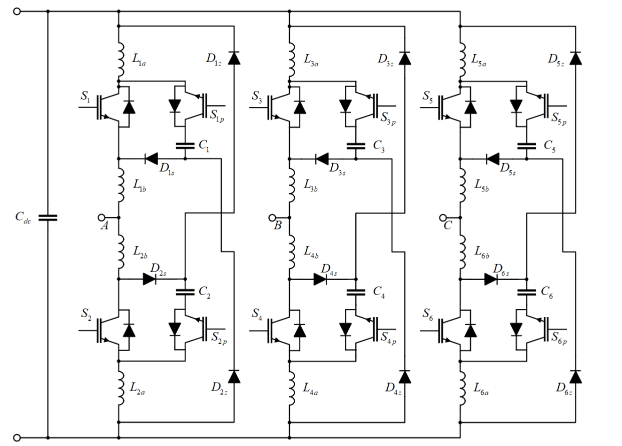
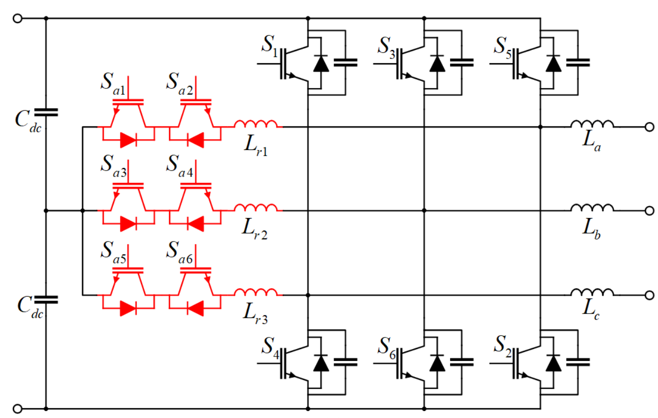


Fig. 8. Inverter based on resonant snubber, with series inductors, parallel capacitors and auxiliary switches.

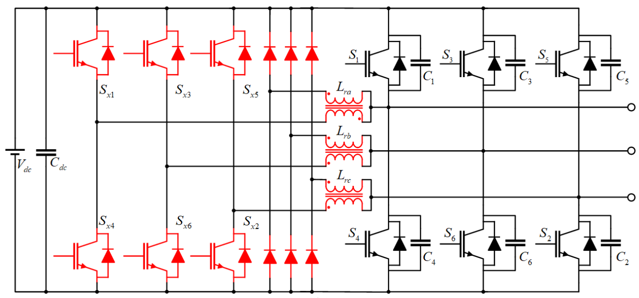
RSIs facilitate soft transitions for both turning on and off. Nonetheless, while parallel capacitors serve as voltage buffers, the practicality of integrating capacitors must be carefully considered.

E. *Auxiliary Resonant Commutated Pole Inverters*

Based on the inverter in Fig. 1(b), [63] introduced an auxiliary diode resonant pole inverter, which was subsequently evolved into an auxiliary resonant pole inverter incorporating auxiliary switches [64]-[65]. [64] proposed an ARCPI, as shown in Fig. 9(a), which utilizes bidirectional switches, resonant inductors, and a split bus capacitor. The performance and control methods of ARCPI were explored in [48], [66]. Moreover, [23]-[24], [44], [67]-[68] investigated enhancements to the circuit and control methods in Fig. 9(b).



(a)



(b)

Fig. 9. Two ARCP inverters. (a) Resonant poles with bidirectional switches. (b) Resonant poles with coupling inductors.

For EVs, [69] proposed an ARCPI devoid of capacitors, relying instead on high-frequency transformers. The equivalent single-phase circuit is shown in Fig. 10(a). Its auxiliary circuit is complex, so the losses might exceed the losses reduced by soft switching under some conditions, potentially reducing efficiency compared to hard switching. [34] and [70] discussed an improved ARCPI and its control method, confirming the efficiency benefit of soft switching. Moreover, a modified inverter was proposed in [71], shown in Fig. 10(b). [72]-[73] proposed a new ARCPI, shown in Fig. 10(c), which increased the efficiency by 0.8% with a 1 kW load [73].

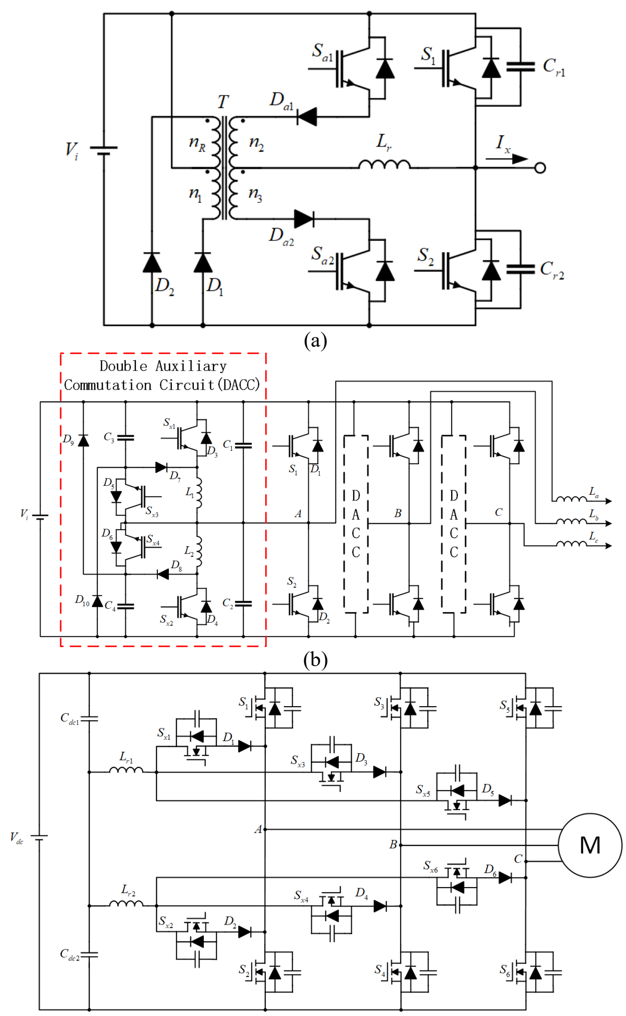


Fig. 10. ARCPIs for EVs. (a) Non-capacitive ARCPI. (b) An inverter with double auxiliary commutation circuits. (c) A new ARCPI with an inductor reduced.

ARCPIs configure the auxiliary resonant commutated pole for each phase leg. The auxiliary circuits employ many components in three-phase inverters, contributing to their complexity. Moreover, it is important to note that the additional losses are non-negligible, even exceeding the reductions gain form soft switching. Consequently, this could negate any potential efficiency advantage.

F. ZVT-PWM/ZCT-PWM Inverters

With a three-phase diode rectifier configured in the auxiliary circuit, as shown in Fig. 11(a), the inverter achieves ZVT-PWM and also recycles the energy from the auxiliary circuit to the DC power supply [16], [20]-[21]. Fig. 11(b) shows another inverter with ZCT-PWM technology, which has been effectively verified on a 50 kW three-phase inverter [74]-[75]. [76] analyzed a ZCT-PWM inverter with an auxiliary circuit on the DC side. [77] studied two types of ZVT DC link inverters for brushless DC motors.

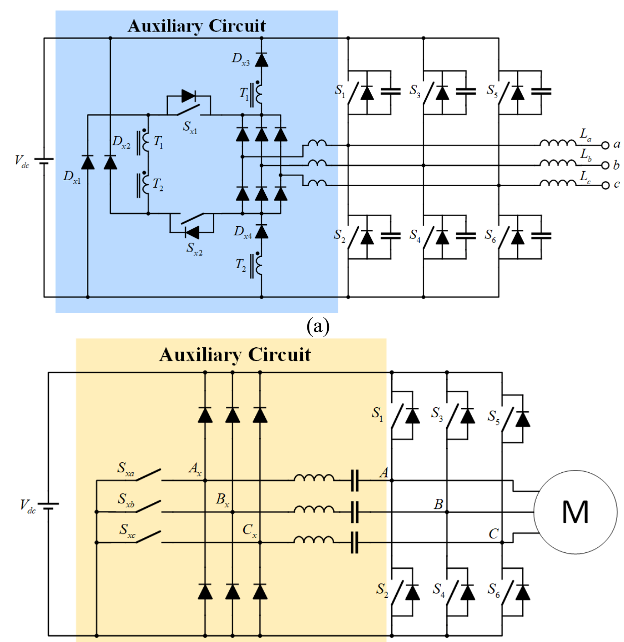


Fig. 11. (a) An ZVT-PWM inverter. (b) An ZCT-PWM inverter.

The initial generations of SSIs implemented control methods such as discrete pulse modulation (DPM), current-regulated delta modulator (CRΔM), which resulted in complex harmonics. Since the 1990s, soft switching PWM technology has developed. Subsequently, many earlier SSIs have transitioned to employ PWM techniques due to their enhanced reliability and friendliness. For instance, ACRDCLI which utilizes a bidirectional switch in [9], adopted ZVT-PWM in [78]. Presently, PWM strategies have become the broadly adopted for switching power supplies.

G. Applications of SSIs

Among the above six types of SSIs, a typical circuit is selected from each type. The experimental results of their prototypes are integrated in Table I, with relevant literatures listed. Apparently, the switching frequency can reach 100 kHz when the switches are SiC MOSFETs and the inverters are connected to power grid. For inductive load or motor driving, the switching frequency is usually 10-20 kHz. The recent research shows that the efficiency of SSIs is over 99%.

For motor driving, SSIs-PD attach several inductors and capacitors on the AC side, making it unsuitable for motor driving. Table II summarizes the research progress of the other five types of SSIs, when they operate as motor drives.

In [79], the total losses of the proposed SSI and conventional HSIs were estimated by theoretical loss breakdown. [42] discussed two topologies of SSIs. The simulation efficiency of the first inverter is verified to be consistent with the experimental results. Then, the efficiency of the improved inverter is calculated through simulation. One RSI in [30] is verified by a 3 kW prototype, and the losses of the RSI are estimated by the loss model of IGBT and inductor. Therefore, the total losses of the RSI and the HSI are calculated with the rated power of 100 kW and the switching frequency of 9 kHz. [68] evaluated the performance of SSI for high temperature hybrid EVs driving. The efficiency under different motor conditions and temperatures is obtained. A proposed ZVT PWM inverter in [78] is verified under the load of a 1.1 kW AC motor.

As the total losses in Table II shown, the results of [79] and [30] indicate the efficiency advantage of SSIs.

TABLE I
APPLICATIONS OF SOFT SWITCHING INVERTERS

		Number of auxiliary components [a]	Type of switches	Type of load	Maximum output power/kVA	Switching frequency/kHz	Control complexity
Inverters based on passive devices	[31]	3L+3C+3L	SiC MOSFETs	Power grid	12.5	300	Medium
ACRDCLI	[33]	1S+1L+1C	SiC MOSFETs	Power grid	5	100	Complex
QRDCLI	[54]	1S+1D+1L	MOSFETs	Load with 0.8 Power factor	0.25	20	Medium
RSI	[45]	6S+12D+6L+6C	IGBTs	RL and IM [b]	3	1~3	Complex
ARCPI	[73]	6S+2L	MOSFETs	RL	1	20	Complex
ZVT-PWM inverters	[75]	3S+6D+3L+3C	IGBTs	Motor	47	10	Complex

[a] S: Switch; D: Diode; L: Inductor; C: Capacitor.
[b] RL: Three-Phase Resistor and Inductor; IM: Induction Motor.

TABLE II
SOFT SWITCHING INVERTERS FOR MOTOR DRIVING

		Number of auxiliary components [a]	Type of switches	Maximum output power	Switching frequency/kHz	DC voltage/V	Peak efficiency	Total loss of SSI/W	Total Loss of HSI/W
ACRDCLI	[79]	1S+1L+1C	IGBTs	200 kVA	12	530	--	3738	4109
QRDCLI	[42]	4S+1D+1L+1C	MOSFETs + IGBTs	3.2 kW	12.5	530	95%	--	--
RSI	[30]	6S+12D+6L+6C	IGBT	3 kW	3	100	98.52%	1526	2930
ARCPI	[68]	6S+6D+6L	MOSFETs + IGBTs	18.3 kVA	10	325	98.9%	--	--
ZVT-PWM Inverter	[78]	3S+1D+1L	IGBTs	1.1 kW	3.3	510	--	--	--

[a] S: Switch; D: Diode; L: Inductor; C: Capacitor.

III. CONTROL METHODS

As soft switching PWM technology mentioned, this section introduces several modulation strategies for SSIs.

Firstly, it is necessary to distinguish switching types. Generally, there are two current commuting types. Taking MOSFETs as an example, Fig. 12(a) shows type 1, where the current is converted from MOSFET to diode. Fig. 12(b) shows type 2, where the current commutation occurs from the diode back to the MOSFET [80]. For type 1, the MOSFET S1 is turned off under hard switching condition, while the diode D4 realizes ZVS turn-on; for type 2, S1 is turned on hardly, while D4 realizes ZVS turn-off. For MOSFETs, particularly SiC MOSFETs, the turn-on losses associated with type 2 typically surpass the turn-off losses related to type 1. In addition, type 2 encompasses the reverse recovery process of the diode, which gives rise to EMI. Therefore, soft switching technology is primarily directed towards mitigating the impact of type 2, as

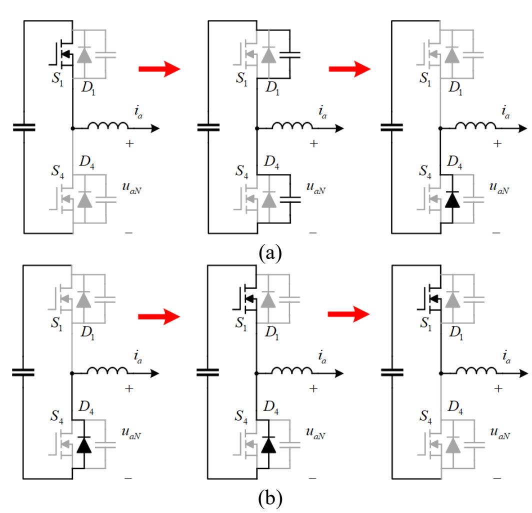


Fig. 12. Two types of current commutation. (a) Type 1, MOSFET to diode. (b) Type 2, diode to MOSFET.

there are some SSIs effectively mitigating the influence of type 1 by parallel capacitors.

For ACRDCLIs, in order to reduce the operation times of auxiliary circuit, their soft switching modulation strategies are mainly for type 2, and type 1 is mitigated by parallel buffer capacitors. Consequently, the typical control method of ACRDCLIs is EAPWM or modified SVPWM, making the auxiliary circuit operate only once per switching period. Attributed to the characteristics of quasi-resonance, the auxiliary circuit in QRDCLIs could operate twice, helping to realize ZVS/ZCS for both type 1 and type 2. For most RSIs and ARCPIs, there is auxiliary commutation branch for each phase-leg, so they can also make effort on both type 1 and type 2. Therefore, the control method for these SSIs are primarily conventional control method (typically SVPWM) or modified SVPWM. SSIs-PD with LC link on the AC side employ the current mode control.

A. EAPWM

For conventional symmetric continuous PWM (CPWM) scheme, each main switch is turned on and off once, and the auxiliary circuit needs to operate three times per switching period. To reduce the frequency of operations and coordinate the current waveform of the resonant inductor, EAPWM was proposed in [80]. The control scheme for EAPWM is shown as Fig. 13. The three-phase modulation waves u_{mabc} are attained by adding three-phase voltage u_{abc} and the injected harmonic voltage u_{zs} . u_{abc} are usually determined by the output of closed-loop control, and u_{zs} depends on the specific PWM methods. u_{zs} is 0 when edge-aligned sinusoidal PWM used. The PWM signals contain driving signals for both main switches and auxiliary switch (es), generated by carrier waves comparison, delay and logic processing. It is critical that the carrier wave must be sawtooth wave whose edge direction (rising or falling) is determined by the polarity of output current. Consequently, the soft switching time of three-phase legs is aligned at the initial moment of each switching cycle. Additionally, the auxiliary circuit only is activated only once.

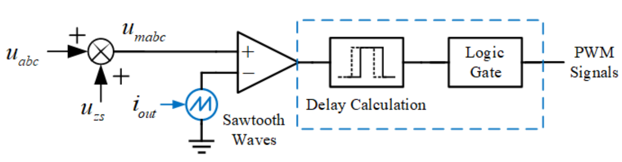


Fig. 13. The control scheme for EAPWM.

Fig. 14 shows two EAPWM schemes. Edge-aligned CPWM is based on the conventional CPWM through the evolution of edge processing. Edge-aligned discontinuous PWM (DPWM) is a combination of DPWM and edge alignment, further decreasing both switching losses and the number of operations.

In [54], the sawtooth wave with fixed direction and frequency is used as the carrier wave, so there is an edge of PWM signals for three phase-legs aligned. Then, the switching times of the auxiliary switch in one switching period is four. This method is appropriate for QRDCLIs, but not suitable for ACRDCLIs.

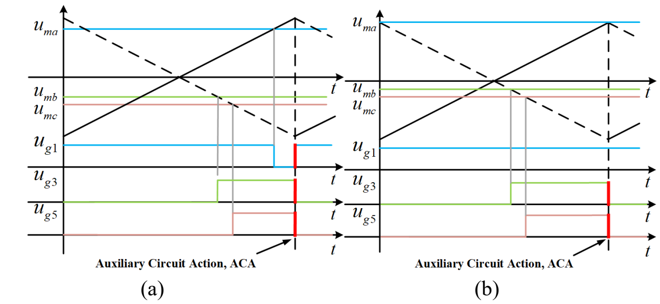


Fig. 14. Two EAPWM schemes. (a) Eege-aligned CPWM. (b) Edge-aligned DPWM.

B. SVPWM

Fig. 15 presents the control scheme for modified SVPWM. The synthesis mode of the reference voltage vector u_{ref} in SVPWM is usually reconstructed for SSIs, in order to reduce switching losses, simplify soft switching conditions, expand soft switching range, etc. Then, the duty cycles of several new fundamental vectors are calculated. Subsequently, the PWM signals of main switches are generated. The PWM signal (s) of auxiliary switch (es) is (are) determined by the PWM signals of main switches and the working principle of specific SSIs.

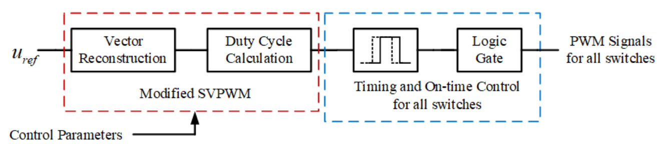


Fig. 15. The control scheme for modified SVPWM.

[25] proposed a ZVS-SVM (Space Vector Modulation) method by vector reconstruction of u_{ref} , as Fig. 16 shown. u_{ref} is composed of two basic effective vectors and basic zero vectors. In conventional vector synthesis mode, there are into 7 segments per switching period. In ZVS-SVM vector synthesis mode, there are only 3 segments, corresponding to 3 basic vectors. The zero vector is decided by the output current for each switching period. It can be derived that ZVS-SVM is equivalent to the edge-aligned DPWM scheme. To realize soft switching over a power factor angle φ range from 0 to 90°, a generalized SVPWM was proposed in [33]. When $\varphi \in [0,30°]$, ZVS-SVM is adopted; when $\varphi \in \left(30^{\circ},90^{\circ}\right)$, as Fig. 17 shown, u_{ref} is reconstructed by the vector synthesis mode, where k_2 is the duty cycle of the second basic vector $\vec{V}_{2nd}$.

[27] proposed a modified SVPWM suitable for most quasi-resonant circuits. When u_{ref} is located in Sec. 1, Fig. 18 presents its vector synthesis mode, which lets the auxiliary circuit operate twice in every switching period. The first transition is $\vec{V}_1$ to $\vec{V}_0$, and the second is $\vec{V}_2$ to $\vec{V}_7$. Therefore, when the upper switch is turned on in type 2, it realizes soft

switching during the second transition. Similarly, soft switching occurs for the lower switch in type 2 during the first transition.

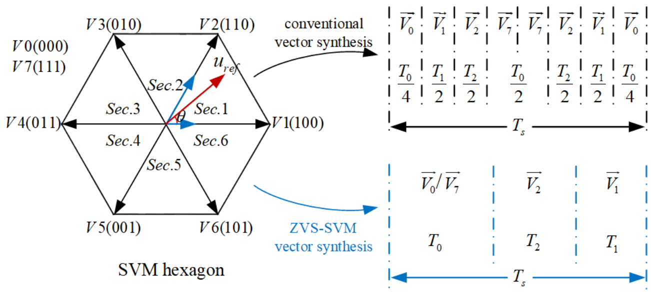


Fig. 16. A modified SVPWM method: ZVS-SVM for an ACRDCLI.

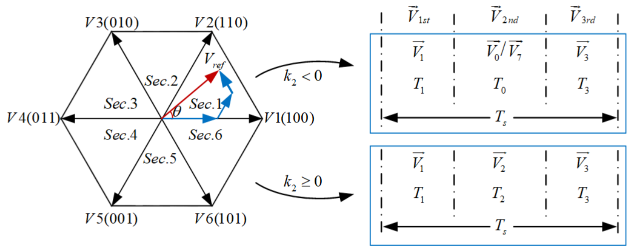


Fig. 17. Generalized SVM when $\varphi \in (30^{\circ}, 90^{\circ})$ for an ACRDCLI.

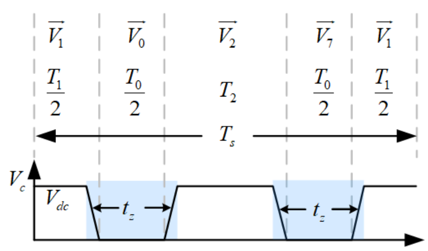


Fig. 18. A modified SVPWM method: ZVS-SVM for a QRDCLI.

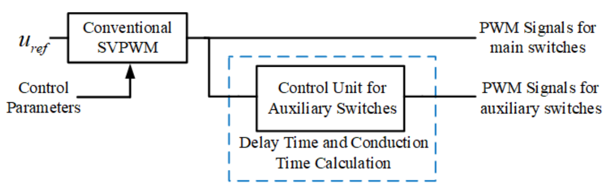


Fig. 19. The control scheme for SSIs based on conventional SVPWM.

For RSIs and ARCPIs, conventional control method (typically SVPWM, shown in Fig. 19) are used. To driving the auxiliary switches, there are control unit generating their PWM signals, whose delay time and duty cycle are calculated by the working principle of specific SSIs.

C. Current Mode

The current mode control method is mainly applied to SSIs based on AC LC link [28], [31], [46]-[49]. Fig. 20 illustrates the control scheme for current mode control method. i_{out} represents the output current of the inverter. It is crucial to design the positive boundary and negative boundary of i_{out}, that is I_{p+} and I_{p-}. When i_{out} reaches to I_{p+} or I_{p-}, the flip-flop will be triggered to make the drive signals invert in the corresponding phase channel.

[28] proposed three current mode methods, one shown in Fig. 21(a). For soft switching, the inverter's output current is required to reverse zero during each cycle. Meanwhile, the average value of the current aims to be sinusoidal current. Guided by this concept, the switching frequency conversion range is extensive, especially near the current zero crossing. [31] put forth an improved current mode control method to limit the maximum switching frequency. The mechanism of this method is shown in Fig. 21(b). Discontinuous conduction mode (DCM) is employed in the current phase angle range of 0-30°, critical conduction mode (CRM) is effective from 30-60°, and the switches are clamped between 60-90°. So the switching frequency is significantly reduced from more than 3 MHz to about 300 kHz.

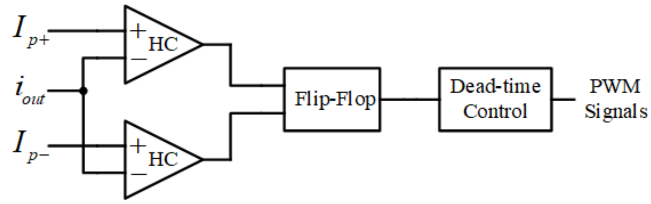


Fig. 20. The control scheme for current mode control method.

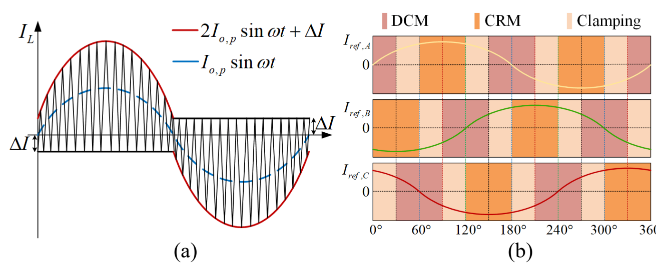


Fig. 21. A current mode control method. (a) Current waveform illustrating the principle. (b) An improved method to limit switching frequency.

IV. Comparison of HSI, ACRDCLI and ARCPI

From the review presented above, HSI and SSIs are simulated to compare their performance. For SSIs, an ACRDCLI and an ARCPI are chosen as representatives of soft switching technologies on the DC and AC side. The ACRDCLI has simple topology, while ARCPI represents SSIs using simple control method. Fig. 22 displays the selected improved ACRDCLI, where an auxiliary switch is added to provide a charging path. This addition ensures the facilitation of soft switching conditions across a wide load range. The selected ARCPI is shown in Fig. 9(b).

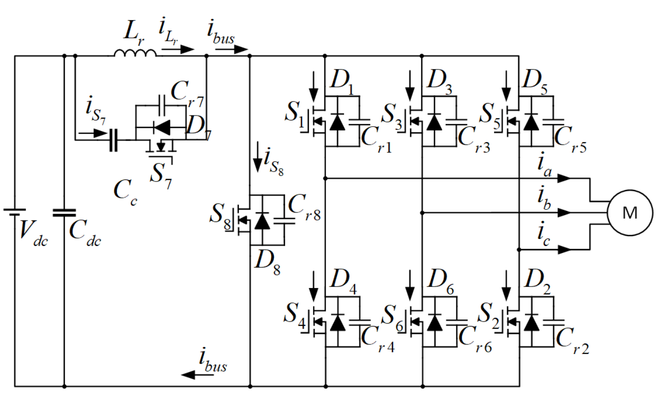


Fig. 22. The selected improved ACRDCLI for simulation.

A. Simulation Specification

The software for simulation is PLECS, and the semiconductors are SiC MOSFETs (CAB760M12HM3). The load is a permanent magnet synchronous motor (PMSM) whose parameters are shown in Table III. Some unified simulation parameters are shown in Table IV. The parameters of the two SSIs are shown in Table V.

TABLE III
THE PARAMETERS OF MOTOR

Parameters	Values
Rated voltage/V	424
Rated current/A	440
Rated power/kW	250
Poles	6
Rated speed/rpm	1364
Peak speed/rpm	3500
Rated torque/(N·m)	1750
Peak torque/(N·m)	2800

TABLE IV
SIMULATION PARAMETERS

Parameters	Values
DC Voltage/V	600
Bus capacitor/μF	1000
Switching frequency/kHz	30
Dead time/μs	1

TABLE V
THE PARAMETERS OF INVERTERS

	ACRDCL	ARCP
Resonant inductor/μH	1	0.36
The ratio of inductor	/	1:2.8
Parallel capacitor/nF	3.3	90
Clamping capacitor/μF	200	/

B. Comparison between HSI and ACRDCLI

ACRDCLI is controlled by EADPWM, and HSI uses conventional symmetric SVPWM. The motor performance controlled by HSI and ACRDCLI under the rated working conditions is simulated, shown in Table VI. The torque ripple and total harmonic distortion (THD) of the output current of SSI are higher than that of HSI, but the 5^{th} and 7^{th} harmonic amplitudes of the output current in SSI are lower than HSI. According to the values in the table, SSI has little effect on motor performance.

TABLE VI
COMPARISON OF MOTOR PERFORMANCE

	HSI	SSI
Torque ripple at 1750/(N·m)	4 N·m (0.23%)	16 N·m (0.91%)
THD of output current	0.539%	0.572%
5^{th} harmonic amplitude/A	1.6	1.52
7^{th} harmonic amplitude/A	1.2	0.9

The losses of the inverters are calculated by simulation, and the results are recorded in Fig. 23. It is apparent that the total turn-on loss of SSI is greatly reduced, but the losses of auxiliary passive devices are also introduced. The control methods used by the two inverters are different. So loss of the diodes is also different, and Pd_on of SSI is greater than HSI. In general, the total loss of SSI is significantly lower than that of HSI. It means the use of soft switching technology can reduce the switching loss of inverter and improve the efficiency of inverter.

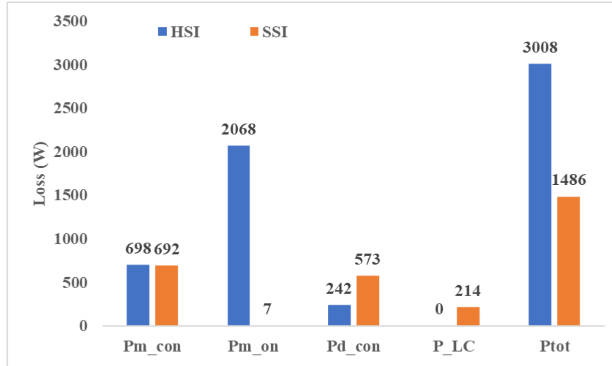


Fig. 23. Loss breakdown comparison of HSI and SSI. Pm_con, Pm_on are total conduction loss and turn-on loss of all MOSFETs; Pd_con is total conduction loss of all anti-parallel diodes; P_LC is total loss of the auxiliary passive devices in SSI; Ptot is total loss of the inverter.

C. Comparison between ACRDCLI and ARCPI

1) Stresses

The performances of ACRDCLI and ARCPI are simulated under the rated conditions of motor. The current stresses are recorded in Table VII. The peak output current is 556 A. The voltage stresses in ACRDCLI remain within 1.1 times of the rated voltage, and the switches in ARCPI experience no supplementary voltage stresses.

TABLE VII
CURRENT STRESSES OF ACRDCLI AND ARCPI

	ACRDCL			ARCP		
	i_{s1}	i_{s7}	i_{s8}	i_{s1}	i_{sx1}	i_{dx1}
Maximum current/A	653	582	635	716	617	220
Minimum current/A	-563	-734	-174	-334	-221	--
Current stress	1.17	1.32	1.14	1.29	1.11	0.40

2) Harmonics

The Fast Fourier Transform (FFT) is applied to the output current waveforms, and the results are shown in Fig. 24. The fundamental frequency of the output current is 136 Hz. Both inverters have few harmonics. However, for ARCPI, the output currents are more symmetrical and contains fewer harmonics. For switches in the two inverters, the frequencies of harmonics are 30 kHz, 60 kHz, and 90 kHz, mainly from the switching actions. In contrast, the harmonics of switches in ACRDCLI are higher than that in ARCPI, because the auxiliary circuit of ARCPI works quickly in each switching cycle.

3) Comprehensive Assessment

In addition to analyzing stress levels and harmonic frequencies, several other aspects of the system's performance are evaluated:

1) The inverter's ability to facilitate soft switching, both when the motor functions as a motor and a generator.

2) The inverter's capability to maintain soft switching under varying load conditions, ranging from light to heavy loads.

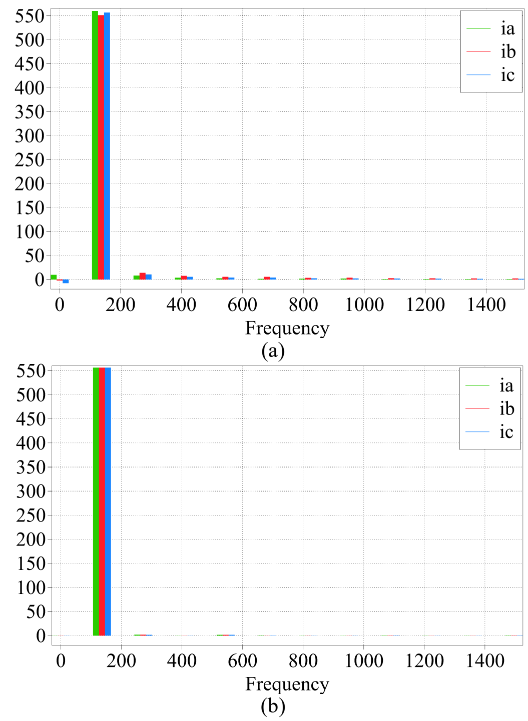


Fig. 24. FFT results of the output current. (a) ACRDCL inverter. (b) ARCP inverter.

3) The inverter's resilience to inaccuracies in the device parameters within its circuitry, particularly its capacity to sustain soft switching in such conditions.

4) The volumetric advantages of the inverter.

5) The efficiency advantage of the inverter.

The performances of the two inverters are synthesized in Table VIII. For circuit topology, ACRDCLI utilizes fewer auxiliary components compared to ARCPI. So the cost of the ACRDCL inverter is lower than ARCPI, and its volume is smaller. The voltage stresses of the two inverters are minimal, and there are current stresses (about 1.2 to 1.5 times). With regard to harmonics, the load current harmonic levels in both inverters are modest. Nonetheless, the harmonics of ACRDCLI are higher than that of ARCPI. Voltage utilization for both is remarkably high, near 100%. Additionally, both inverters can function as an inverter or a rectifier. It is challenging for the ACRDCLI to meet soft switching conditions under extreme loads. In contrast, the current stresses in ARCPI are significantly influenced by the resonant inductor, and the parameter sensitivity of ARCPI is high. In terms of efficiency, ACRDCLI has fewer auxiliary devices, while the auxiliary circuit of ARCPI operates shortly. Therefore, both of them have efficiency improvement compared to traditional HSIs.

TABLE VIII
COMPARISON OF ACRDCLI AND ARCPI

	ACRDCL	ARCP
Devices number	less	more
Voltage stress	1.1	1
Current stress	1.4	1.3
Harmonic	more	middle
Voltage utilization ratio	high	high
Motor/Generator	√	√
Light/Heavy load	★★★	★★★★
Parameter sensitivity	★★★★★	★★
Volume	★★★★	★★
Efficiency	★★★★	★★★★

In general, SSIs reduces the switching losses, restrain switching oscillations, and augmenting the performance of high-power and high-frequency inverters. When designing the motor controller for EVs, it is critical to evaluate numerous factors, including the controller's power density, cost, and operating conditions. Overall, the soft switching technology on the DC side is more advantageous.

V. Challenges and Prospects

Soft switching technology offers a promising approach to the evolving demand for high power and high frequency in EVs motor controller development. However, there are several challenges before its practical application.

First, there is a specific requirement for the switches used. Switches with superior power density and switching frequencies are essential. For instance, replacing IGBTs with SiC MOSFETs would be a suitable upgrade. Nonetheless, the high cost associated with SiC MOSFETs necessitates a reduction in the costs of switches for broader applicability. Additionally, the high current demands of switches pose a significant issue. To circumvent the complexities and increased size that come with using parallel switches, it is imperative to enhance the rated and peak current handling capabilities of single switches.

Secondly, designing passive components that accommodate auxiliary currents presents another layer of challenge. The resonant inductors in the auxiliary circuits operate at frequencies as high as the switching frequency, thus subjecting them to significant current stresses. Given the need to maintain a high power density within the controller, it is crucial to minimize the inductors' physical size as much as possible. Consequently, the design of inductors must account for their ability to handle both high frequencies and high currents. To mitigate the skin effect, inductors are often constructed with multiple strands of wire wound into coils. Moreover, it is essential to minimize the parasitic parameters of passive devices within the inverter, such as the equivalent series resistance (ESR) of capacitors and inductors, as well as the equivalent series inductance (ESL) of capacitors. If not addressed, the losses associated with these passive devices can be substantial, potentially undermining efforts to reduce switching device losses and rendering such improvements inconsequential.

Thirdly, the controller's structural design demands special attention. The integration of an auxiliary circuit complicates device layout. Stray inductances are present in every connection of a power circuit which exacerbate switching oscillations, leading to severe EMI. To mitigate this, careful attention must be given to the device layout, ensuring that the auxiliary circuit and the main switches are positioned as closely as possible, with the switches located near the capacitor. In addition, it is imperative for the main switches' connection to utilize a laminated bus bar design. This approach is crucial to minimize stray inductances that otherwise arise from the use of conventional bus bars. Such refinements are essential in maintaining the integrity and performance of the power circuit.

Furthermore, there is a necessity for concurrent updates to the control chip. The programming that governs motor control within a SSI is intricate, encompassing fault detection, communication, and an array of additional functionalities. Consequently, existing control chips, such as the TMS320F28335, struggle to support switching frequencies beyond 50 kHz. For controllers that operate at high frequencies, particularly those managing high-speed motors, the adoption of faster control chips is essential to ensure efficient and reliable performance.

VI. Conclusion

This paper begins by examining the developmental trends of EVs, highlighting several challenges emerging when motor controllers are pushed towards higher power and frequency. Soft switching technology is an effective strategy to address these issues.

For EVs motor controllers specifically, soft switching technology on the DC side is typically favored for its compactness and cost-efficiency, exemplified by devices such as the ACRDCL and QRDCL inverters. The paper also presents an overview of the modulation techniques for SSIs that have been introduced in recent years.

Additionally, HSI, ACRDCLI and ARCPI are simulated to compare their performance for motor driving. The outcomes indicate that soft switching technology improve the efficiency of inverter. And, ACRDCLI offers benefits in terms of lower costs and reduced size, while ARCPI presents advantages like diminished harmonics, lessened component stresses, and simplicity in control.

The paper concludes by exploring potential issues and prospects for the refinement of soft switching technology in the context of EVs motor controllers.

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