7th WSEAS Int. Conf. on MATHEMATICAL METHODS and COMPUTATIONAL TECHNIQUES IN ELECTRICAL ENGINEERING, Sofia, 27-29/10/05 (pp56-62)

A Novel ZVS -ZCS Inverter With Auxiliary Resonant Snubber Using Pulse Current Feedback Transformer

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Abstract:- In order to enhance the performance of ARCPI (auxiliary resonant-commutated pole inverter), this paper proposes a novel ZVS-ZCS inverter with auxiliary resonant snubber using pulse current feedback transformer to solve the problem such as extra losses from auxiliary circuit, variable commutation duration, and poor reliability, which are common in existing ARCPIs. In this novel ARCPI, the application of commutation forcing voltage greater than half value of DC link voltage, fixed commutation duration, and protection for auxiliary switches furthest enhances the performance, and also extends its application. By the analysis, simulation, and experimentation, this new ARCPI is proved reasonable for use in high reliability application, especially in DFACTS.

Key-Words:-Auxiliary resonant commutated pole inverter (ARCPI), Zero-voltage switching (ZVS), Zero-current switching (ZCS), Distribution flexible ac transmission system (DFACTS)

1 Introduction

Today, a variety of soft switching techniques have been applied in power inverters to solve the problems resulting from hard-switching in high-frequency application [1]. Among those soft switching techniques, the performance of auxiliary resonant commutated pole inverter (ARCPI) has been found relatively outstanding [2]-[6]. ARCPI takes advantage of auxiliary switch to achieve ZVS or ZCS for main switch, and it maximally enhances switching frequency, efficiency, and reliability. Although ARCPI techniques have widely been used in SPWM inverters to achieve obvious advantages, but still few of major issue are unsolved, for example extra switching losses from auxiliary circuit [6], variable commutation duration or duty cycle loss and poor robustness. These problems seriously limit the performance of ARCPIs. A detail analysis about these limitations is described in following part of this section.

Fig.1 shows three kinds of ARCPIs, which all have achieved good performance in general applications, but in some application with severe current transients, the performance targets cannot be met. For example, the extra high resonant current of the topology shown in Fig.1a [4], resulting from high forcing voltage, can lead to severe current stresses in auxiliary switches, considerable power loss and severe thermal stress. The complex structure of the topology shown in Fig.1b [5], resulting from the advanced trigger control strategy, can lead to an unforeseen ZVS commutation failure and system oscillation [6]. As for as the topology shown in Fig.1c [6], one of major standing issues is the design of transformer, which is an over-designed transformer with larger leakage inductances. However in some high current and high voltage application such a transformer can be too inefficient and limit the application of this topology in high frequency range.

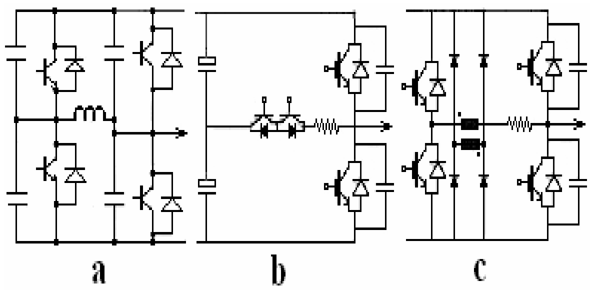


Fig.1 Configurations of some typical ARCPIs

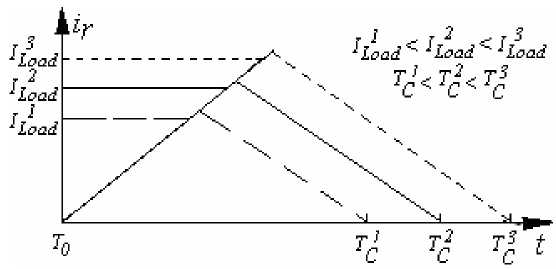


Fig.2 Variation of commutation duration VS. load current

Besides above-mentioned drawbacks, there is another drawback, which is common to all the ARCPIs, and that is the variation of commutation duration with load current as shown in Fig.2. It can be observed that, the commutation duration (Tc) is directly proportional to load current (I_{Load}). If an ARCPI is designed with fixed commutation duration of auxiliary switches, then at heavy load current, it can cause serious current stresses and extra switching losses to auxiliary switch. In order to ensure ZVS or ZCS operation of auxiliary switch and prevent auxiliary switch from getting damaged by the residual energy stored in *L*x, the extra control strategy adjusting commutation duration following load current is always adopted [5],[6]. The solution of variable commutation duration complicates trigger strategy, and also limits switching frequency, duty ratio and capacity of ARCPI. And in some extreme situation, this solution also is helpless.

Since the requirements for switching frequency, output capacity, efficiency and reliability of an ARCPI are becoming more stringent, hence the robustness of the snubber circuit is also becoming more important. Although the performance of existing ARCPIs is excellent in standard inverter applications like motor driver systems, but still it is not suitable for the applications with high transient currents and asymmetrical operations like APF, DVR [4].

Therefore based on the comprehension of advantages and disadvantages among existing topologies, this paper proposes an enhanced ARCPI as shown in Fig.3. It is named as ZVS-ZCS inverter with transformer-assisted commutation. This enhanced ARCPI caters the requirement of modern inverter technology and maximally enhances the performance of ARCPI. Furthermore, this ARCPI needn't keep track of load current to adjust commutation duration; therefore fixed commutation duration is adopted in this new ARCPI. The protection for auxiliary resonant circuit is considered by the structure of four auxiliary switches, and even in extreme over-current case, this special structure can well ensure the ZVS/ZCS commutation operation of the auxiliary switches. As a result, the stresses on auxiliary switch are much more reduced and there is very little risk of hard on/off commutation in auxiliary switches.

This paper is arranged in following order. In section 2, detail operation under normal and over load condition is discussed. Section 3 addresses the experimental results. Finally section 4 concludes in this paper.

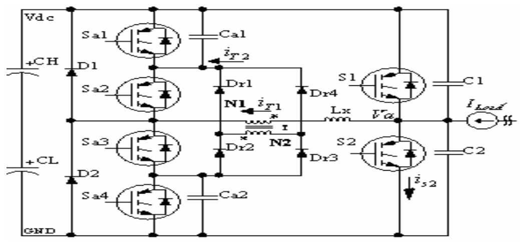


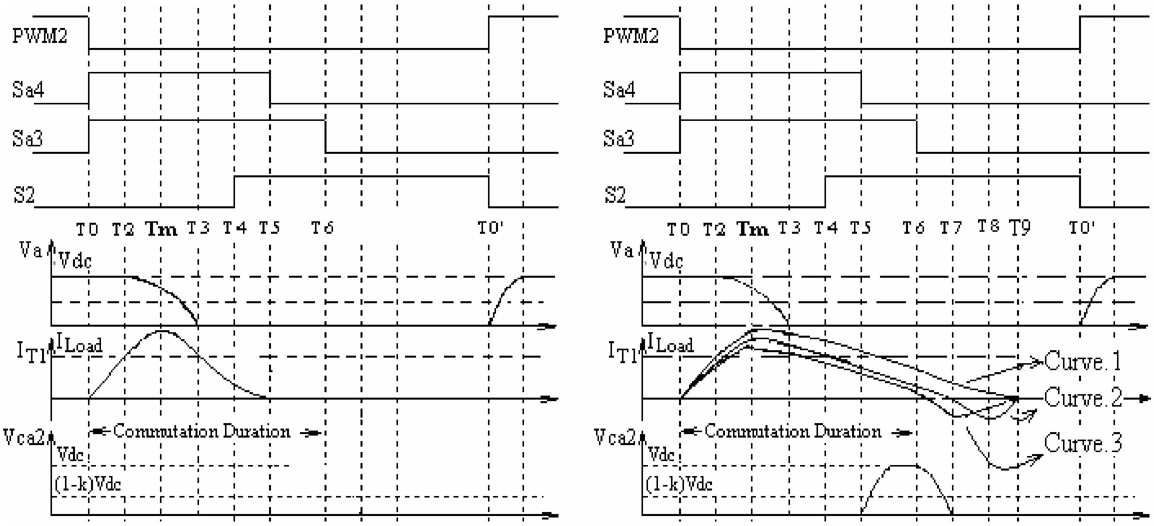
Fig.3 Configuration of the ZVS-ZCS inverter with transformer assisted commutation

2 Commutation Principle of The Novel ARCPI

In this section, commutation sequence for the proposed ARCPI is described. Two kinds of commutation processes, the commutation under normal load current and the commutation under abnormal load current, are supposed to occur. So the detail analysis of these two processes has been discussed separately. Since the case of fixed duration gating signals for auxiliary switches has been treated in this paper, the general switching sequence for all the auxiliary switches gate signals is same irrespective of commutation processes. Referring to Fig.3 and Fig.4, the general switching sequence is as follows. Considering, initially main switch S1 is in on state and all other switches including auxiliary switches are in off state. Now the target is to turn-off S1 under ZVS condition and turn-on S2 under ZVS/ZCS condition. To achieve this target, first S1 is turned off, Sa3 and Sa4 are turned on simultaneously; and then S2 is turned on if the voltage across S2 becomes zero in later part of the commutation. At the end of the of fixed commutation time for auxiliary circuit, first Sa4 is turned off at zero voltage and after a little delay, Sa3 is turned off at zero current. Likewise the general switching sequence for Sa1, Sa2 and S1 can be inferred analogously.

2.1 Commutation Principle under Normal Load Current

Referring to Fig.4 for the relevant commutation waveforms and Fig.5 for the commutation step diagrams, the commutation step of this enhanced ARCPI during half commutation cycle under normal load current is discussed in this section. Many of the commutation steps of this ARCPI are similar to those given in reference [6]. So the steps which are different from reference [6] will be described. Interested readers refer to [6] for the details.



a. Under normal load current b. Under abnormal load current

Fig.4 Predicted commutation wave during freewheeling diode of S1 to S2 under negative load current

Step0: $t < T_0$

Circuit is in steady state. Freewheeling diode of main switch S1 carries the load current.

Step1: $T_0 \le t < T_1$

At T_0, Sa3 and Sa4 are turned on simultaneously, leading to conduction of diodes Dr1 and Dr3 in bridge. If there is some initial charge on Ca1, it begins to discharge due to i_{T2} and voltage across it starts decreasing. This feature resets any residual voltage across Sa1 before start of next cycle and ZVS/ZCS turn on in the next cycle is always guaranteed. If the ARCPI is operating under normal load current then the voltages across Ca1 are always zero.

Step2~6: $T_1 \le t < T_6$

Under normal load current, the commutation steps during $T_1 \sim T_6$ is same as those presented in [6].

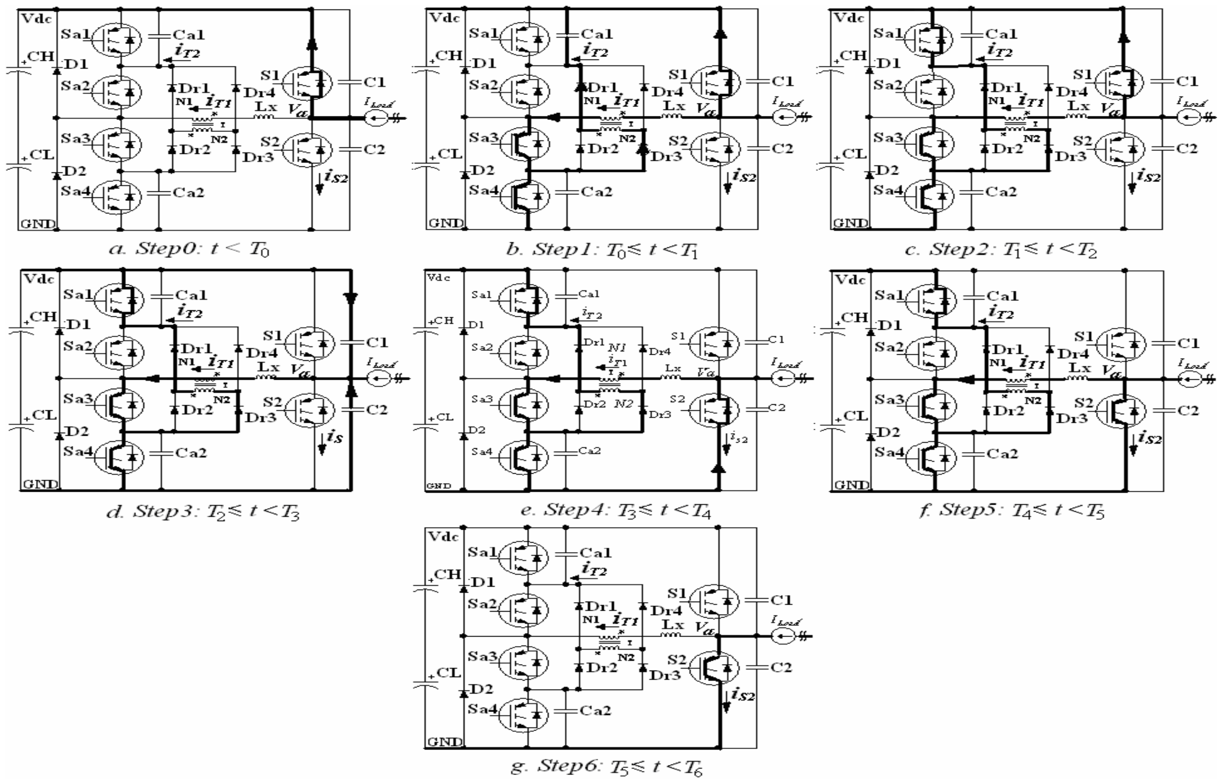


Fig.5 Commutation step diagrams of the ZVS-ZCS inverter with transformer assisted commutation during a switching cycle under normal load current.

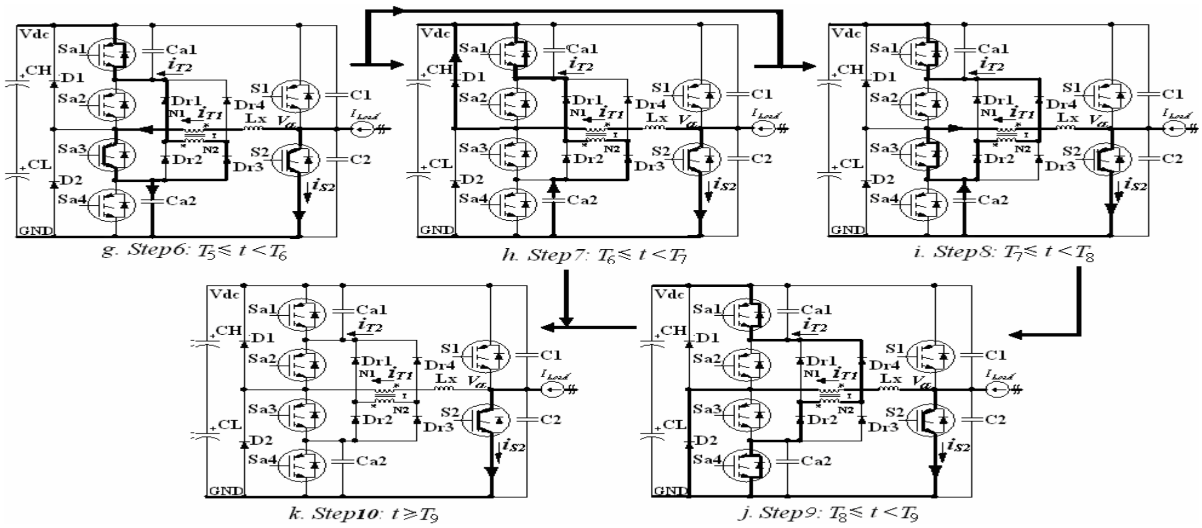


Fig.6 Commutation step diagrams of the ZVS-ZCS inverter with transformer-assisted commutation during a switching cycle under abnormal load current.

2.2 Commutation Principle under Abnormal Load Current

In an ARCPI running at high current level, i_{T1} (Fig.5f) doesn't reduce to zero at T_5 in contrast to normal load current commutation procedure. However auxiliary switches are turned off because of fixed commutation duration. Therefore the commutation sequence under normal operation and under abnormal operation is not same. The total number of steps involved during abnormal commutation varies according to the extent of over current, however the first five steps of the commutation remain same as those described for the situation of normal load current.

Referring to the procedure of commutation shown in Fig.6 and the predicted relevant commutation waveforms shown in Fig.4, three sequences of commutation are inferred due to the wide difference in load current. The first one is Step6 → Step7 →Step10 under extremely high load current, the second one is Step6 → Step7 → Step8 → Step9 → Step10 under medium high load current, and the last one is Step6 → Step8 → Step9 →Step10 under normal high load current. Details of all the sequences cannot be covered in limited available space. Therefore the detail analysis about the commutation sequence for medium high load current is discussed as following.

Step6: $T_5 \le t < T_6$

At T_5, i_{T1} still doesn't attenuate to zero value due to high resonant current. But because of the fixed commutation duration, Sa4 is turned off. Since Ca2 is in parallel to Sa4, this turn-off will always be ZVS under high load current. Now i_{T1} starts charging Ca2, and resonance between Lx and Ca2 initiates under the forcing voltage *k*Vdc+(1-*k*)Vca2.

Step7: $T_6 \le t < T_7$

At T_6, Ca2 has been charged by i_{T1} to the value of DC link voltage, however the current i_{T1} is still not reached to zero. At this point, D1 starts conducting and the current through Sa3 reduces to half the value of i_{T1}. Therefore, if Sa3 happens to be turned off due to fix commutation, in this mode (T_6), the peak current stresses during turn-off is also inside of its SOA due to half value of i_{T1} and it will take place under ZVS condition. Simultaneously, i_{T2} resulting from i_{T1} is discharging Ca2 by the ultra-fast rectifier. However in most cases the Sa3 turns off after this point under ZCS condition.

Step8: $T_7 \le t < T_8$

This step is likely to occur, if i_{T1} has attenuated to zero value and Ca2 still keeps at high voltage value. At T_7, current i_{T1} has decreased to zero, but the voltage of Ca2 hasn't been reduced to zero. Therefore Ca2 starts discharging by the freewheeling diode of Sa3 and the full-bridge rectifier. Resonance between Ca2 and Lx forced by voltage *k*Vdc-(1+*k*)Vca2 initiates, and i_{T1} starts building up in reversed direction. Simultaneously, the voltage across Ca2 starts decreasing.

Step9: $T_8 \le t < T_9$

At T_8, Ca2 has been discharged to zero voltage. But i_{T1} is not damped to zero, therefore it forces

D2 to conduct until its value reduces to zero and all the energy has resonated back to dc link.

Step10: $t \geq T_9$

At T_9, i_{T1} has been damped to zero, and Ca2 also has been discharged to zero, and the total commutation procedure under medium high load current is completed.

Referring to the above procedure, the other commutation of this new ARCPI can be inferred analogously.

By the analysis of commutation procedure, the introduction of fixed commutation duration has been proved feasible, even at high transient load current. To date, this enhanced ARCPI is most outstanding among all ARCPIs. And it is much more favorable in severe operating conditions.

3 Experimental Results

In order to check the feasibility of this ARCPI, a prototype half-bridge inverter of 10kw IGBT as show in Fig.7 has been built. In the prototype, the rated value of DC voltage is 370V, and DC link employs two 450V/10000uF capacitors to form the dc center tap; The main and auxiliary switches are SKM200GB128DN and SKM75GB128DN modules respectively and all the fast diodes are DSEI30-10A and the switching frequency of main switches reaches to 20kHz; The value of auxiliary resonant inductor is 5uH and the value of snubber capacitor C/Ca is 0.1uF/0.47uF; The ratio of auxilary transformer T is *k* (N1/N2), which is inside of 0.35~0.45; Six resistors (15Ω/20A) were connected in parallel as load; The driver of the main switch was interfaced with an extra zero-voltage detecting circuit, to ensures main IGBT ZVS turn-on.

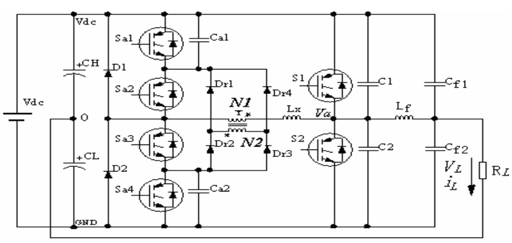
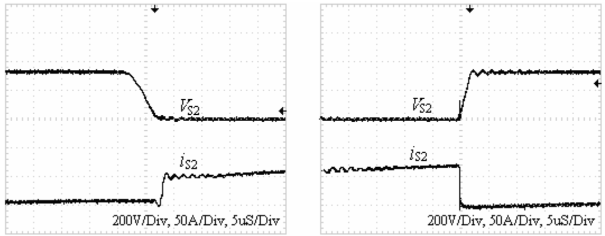


Fig.7 Configuration of the 10kW half-bridge IGBT ARCPI

Fig.9 gives the waveforms for main switch S2 turn-on and turn-off commutation under ZVS/ZCS operation for 50A load current. The values of dv/dt and di/dt during S2 turn-on are 70V/uS and 50A/uS respectively, and the values for dv/dt and di/dt during S2 turn off commutation are 175V/uS and 75A/uS respectively. All the values during switching transients are reasonable and inside the SOA of the IGBT.

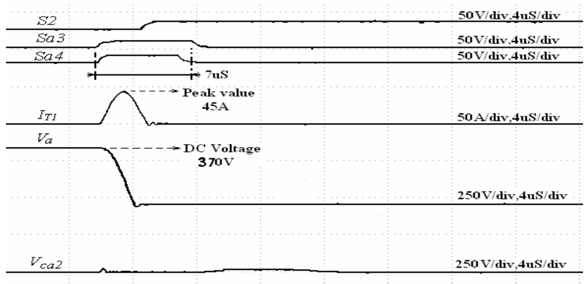


a b

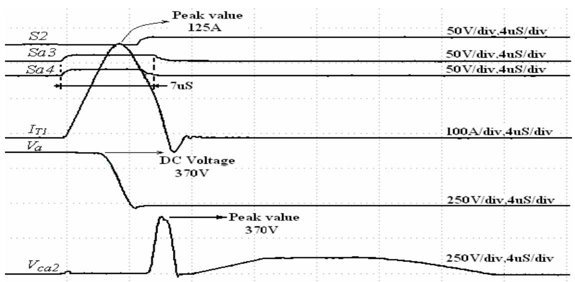
a. Turn-on of S2 b. Turn-off of S2

Fig.9 Experimental voltage and current waveforms

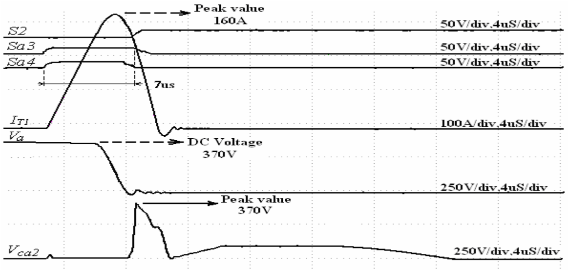
It can be observed in Fig.10 that all waveforms are obtained for fix commutation duration of the auxiliary switches Sa3/Sa4. So in any case the turn-on durations for the switches Sa4 and Sa3 are 5.5µS and 7µS respectively. Hence, the commutation duration from the start of the commutation cycle (turn-on of auxiliary switches Sa3/sa4) to the end (turn-off of auxiliary switches Sa3/sa4) is equal to7µs. These results indicate that the fixed commutation duration is feasible and the voltage Vca2 is never exceeds Vdc in any case. Besides, auxiliary Sa4 is always turned on and off at zero voltage; auxiliary switch Sa3 is turn on at zero voltage, and turned off at zero current under normal load current and at zero voltage under abnormal load current.



a. Under light load current about 27A



b. Under a normal high load current about 75A



c. Under extremely high load current about 100A

Fig.10 Experimental waveforms with variable load current

Fig.10a shows the commutation waveforms for normal current range. Because of small resonant current, there is no peak in Vca2. All the waveforms are in accordance with the simulated results. It means that the procedure of commutation under light load current is same as predicted.

Referring to the waveform shown in Fig.10b, there is an abnormal commutation under a little high load current 75A. Because of high resonant current in auxiliary circuit reaching to 125A, there is a peak in voltage across Ca2 almost touching the DC-link voltage value (370V). By comparing the commutation waveforms under abnormal load current and experimental waveforms given in Fig.12b, it can be inferred that the sequence of commutation is the same as sequence Step6 → Step8 → Step9 → Step10.

The waveform shown in Fig.10c represents the abnormal commutation under extremely high load current 100A. Referring to the waveform c, it can be seen that the peak value of Vca2 reaches to Vdc due to extremely high value of i_{T1} , simultaneously, the peak value of current i_{T1} reaches to 160A. Under extremely high load current 100A, the procedure of commutation is the same as sequence Step6 → Step 7→ Step10.

By comparison among predicated, simulated, and experimental waveforms, all key parameters and phenomenon are found consistent. With reasonable control logic, this topology can fulfill its task perfectly and achieves main switch and auxiliary switching at zero-voltage or zero-current, fixed commutation duration, and strong fault tolerance smoothly.

4 Conclusions

Based on above discussion, analysis and experimentation, the conclusions are inferred as following.

The voltage source (*1-k*)Vdc (>½Vdc) taking part in the commutation procedure that ensures zero-voltage switching of the main switch, and zero-voltage and zero-current switching of auxiliary switch without any extra detection and control circuit. So this novel ARCPI enhances reliability and efficiency.

Because of the special structure of four auxiliary switches, there is no need of extra protection for auxiliary switch and the fixed commutation duration can be adopted in it. And even if there is some fault at the resonant components, the stresses of auxiliary switches are in reasonable range. Therefore, the switching frequency is greatly enhanced and it also has strong fault tolerance.

By the simulation and experimentation, this new ARCPI is reasonable. The fixed commutation duration, zero-voltage switching for main switch and auxiliary circuit stress are validated.

By the experimentation, this new ARCPI is a prospective inverter to be used for high power, high efficiency, high switching frequency, and high reliability application, especially for DFACTS device.

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