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A High Efficiency and High Power Chopper Circuit QRAS using Soft Switching under Test Evaluation at 8kW

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ABSTRACT

This paper is a record of the study on a high efficiency and high power chopper based on the new soft switching method QRAS (Quasi-resonant Regenerating Active Snubber) designed for a Fuel Cell Electric Vehicle (FCEV). This power chopper is basically proposed for 25kHz soft switching. To confirm the practicality and effectiveness of the converter, the fabrication of a prototype-model using IGBTs was completed. Additionally, a 8kW rating test, a light load test, a current discontinuous mode test and a stable operation resonance test was completed. The circuit geometry, the basic operation, and the 8kW one-tenth-prototype test results are reported with a 97.5% efficiency measurement.

Keywords: Boost chopper, DC-DC converter, Soft switching, QRAS, 2 switch, IGBT

1. Introduction

The recent progress of electric drives in the automobile industry has produced pure electric vehicles. Fuel cell technology makes it possible to implement a 100kW power range converter to a Fuel Cell Electric Vehicle (FCEV). In the recent middle and high power applications mentioned above, high power and high efficiency are major requirements of DC-DC converters to realize downsizing. In particular, in the case of a previous DC chopper circuit for high power applications, hard switching at low frequencies has been used because of the difficulty of high frequency operation. In other words, the size was large and the power dissipation was also large. Under this technological background, in order to overcome these problems, we have proposed a high-efficiency high-power DC chopper based on a new type of circuit - QRAS (Quasi-resonant Regenerating Active Snubber) which uses soft switching as shown in Fig.1. The proposed DC chopper circuit operates at the switching frequency of 25kHz. This paper describes the simulations by SPICE and experimental results of a newly proposed QRAS. The performance of the proposed new circuit was evaluated on an 8kW prototype model that was designed to operate from a 200V input and deliver up to 20 A at a 400V output.

2. A High Efficiency and High Power Chopper Circuit Requirements

The output voltage would depend on the power level and on the user's bus line demand. In the case of low and small power applications, the bus voltage would be about

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100V. On the other hand, in middle and high power applications our specifications can be 400V with a 100kW power range converter. An additional point to take into account is the fuel cell module used will determine the converters' topology. When the bus voltage is larger than the fuel cell voltage, a boost type converter is needed.

However, high voltage and high power applications mentioned above make high frequency switching and downsizing of the power converter difficult to be realized.

A practical model converter should have the following specifications:

Input voltage (fuel cell bus voltage) V_i=250~400[V]
Output voltage (bus voltage) V_O=400[V]
Switching frequency f_S=25k [Hz]
Output power P_O=80k [W]

3. Usual Chopper Circuit

3.1 Classifications of Chopper Circuits

Various types of chopper circuits have been used or proposed until now. A classification of this typical circuit is shown in Table 1.

Type 1 : Hard switching is shown in Type 1(a). Main switch S_1 cuts off the main current directly by eliminating the passive snubber from the conventional one. Main drawbacks are power dissipation and voltage overshoot. The switching power dissipation of this type is at a maximum in high frequency operations and the surge voltage depends on the wiring inductance. Type 1(b), the passive resonant snubber is added to the conventional one. The current stress on switch S_1 increases due to the resonant current of the snubber circuit superimposed on the load current when switch S_1 is turned on [2].

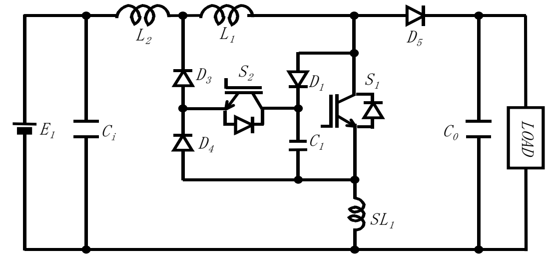


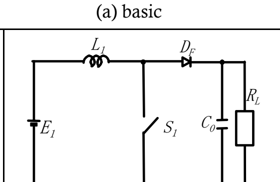
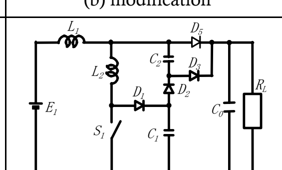
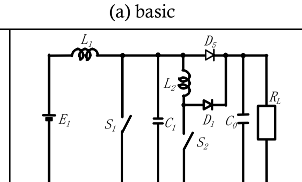
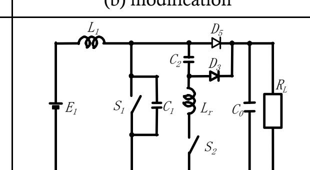
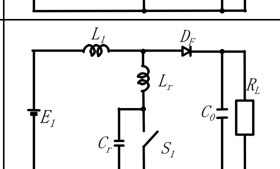
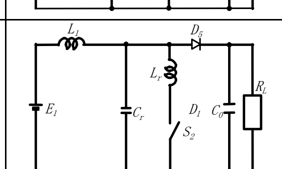
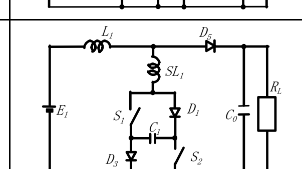
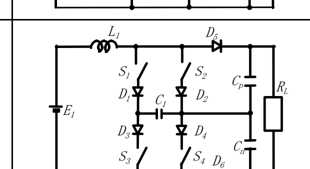
Fig. 1 New type of circuit for high power dc chopper QRAS

Type 2 : Type 2(a) and Type 2(b) are one-switch resonant schemes. In type 2(a), the circuit voltage doubles due to the utilization of the resonant phenomenon of capacitor C_r and reactor L_r which are added to the main circuit. Type 2(b), this type is regarded as being difficult to obtain high efficiency. Because the resonant current flow of constant amplitude is superimposed on load current through a switch device[3].

Type 3 : This type is 2 switch partial resonant scheme. A ZVT converter [4] is shown in Type 3(a). It is said that this type can obtain high efficiency without increasing the current stress of the main switch since the current flow of the auxiliary circuit does not pass through the main switch. Its drawback is the hard switching of the auxiliary switch. Type 3(b), the auxiliary switch circuit is modified to achieve the soft switching. But the overshoot voltage by parasitic oscillating phenomenon should be suppressed[5].

Type 4 : The previous C bridge switch type soft switching chopper [6] is depicted in Type 4(a). The main part is made of 2 switches and 1 capacitor. But it was

Table 1 Various Chopper Circuits

	(a) basic	(b) modification		(a) basic	(b) modification
1			3		
2			4		

proved to be necessary to adjust the turn on timing of switch S_1 and switch S_2 not to superimpose the capacitor charged voltage on the overshoot voltage of the output diode during its reverse recovery. Type 4(b), this is similar to the C bridge switch Type 4(a). But this is a soft-switched voltage-doubler rectifier. Its drawback is the component count. The soft switching reduces the losses of the switches, but as the number of diodes is multiplied by two, conduction losses are increased [7].

3.2 Conventional example of the prototype using Type 4(a)

Each type of circuit scheme listed in Table 1 has merits and demerits. The circuit topology should be determined depending on if one scheme or combined schemes is selectively chosen corresponding to its application's side specification and requirement. In the case of a 100kW power range converter using IGBT to the FCEV, Type 4(a) is most suitable regarding improving the efficiency of the hard switched converter, keeping the simplicity, the component number and availability of switching devices. It can operate as the promised and achieved snubber circuit without power stress and snubber loss. Fig. 2 shows a conventional example of the prototype. The voltage and current waveforms are shown in Fig. 3. This model seems to be ideal, but has risks which are listed below.

1) Since the main switch and a diode are connected in series, the power dissipation is large and there is ample scope for improvement in efficiency.
2) It was proved to be necessary to adjust the turn on timing of switch S_1 and switch S_2 so as not to superimpose the capacitor charged voltage on the overshoot voltage of the output diode during its reverse recovery. There is great risk of breakdown in the output diode.

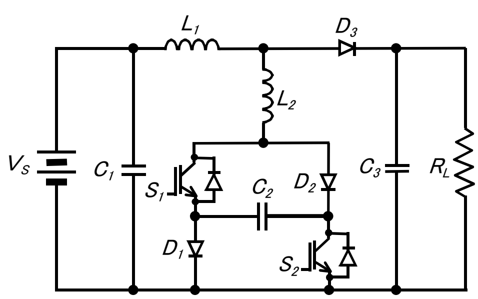


Fig. 2 The conventional example of prototype using Type 4(a) (C bridge switch)

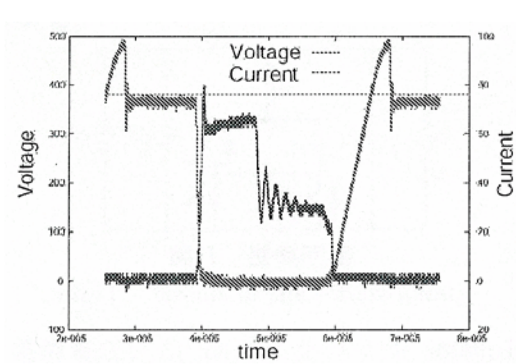


Fig. 3 Voltage and current waveforms of switch S_2

4. New Circuit of QRAS Type Soft Switching DC Chopper Circuit

4.1 Circuit topology

Fig. 1 depicts the new proposal QRAS (Quasi-resonant Regenerating Active Snubber) type soft switching DC chopper. The main part of proposal topology has a simple configuration of 2 switches (S_1 and S_2), 3 diodes (D_1,D_3 and D_4) and a capacitor C_1. This configuration retains the desirable properties of the low turn on switching loss and low turn off switching loss so called "soft switching". When switch S_1 is turned on, the rate of rise of switch S_1 current is limited to low by an additional inductor SL_1. Also when switch S_1 is turned off, the voltage across switch S_1 begins to increase from zero voltage by capacitor C_1. Thus it can operate as a loss less snubber whereby high power and high efficiency operation can be achieved. The QRAS is characterized by the following benefits as compared with the previous alternative.

1) The main switch consists of one series in the main circuit connection.
2) Since the storage charge in capacitor C_1 is regenerated back to the input power source and the output through each reactor L_2 and L_1, the overshoot voltage of the output diode D_5 is reduced.

4.2 Principle of operation

S_2 creates a reverse biased voltage across the diode D_4 that allows S_1 to turn on softly. The charge in C_1 is acquired at the end of the previous switching cycle,

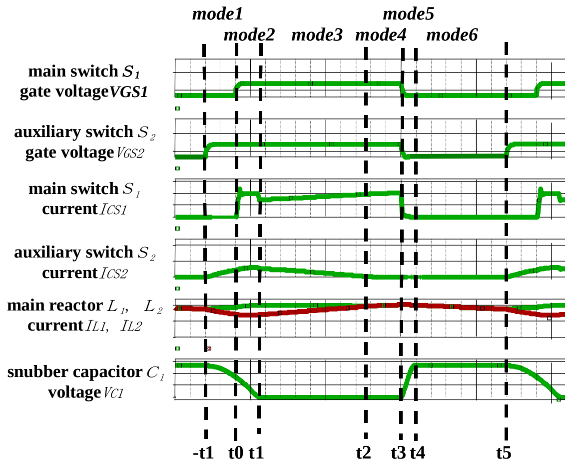


Fig. 4 The basic operating waveforms of QRAS

and any excess charge is returned to the supply through L_1 and L_2 in the early part of S_1 turning on. Fig.4 shows typical voltage and current operating waveforms of the proposed new circuit, calculated using SPICE. Each operating mode is illustrated in Fig.5 and operates as follows.

(a) mode 1 : Pre-turn-on

Auxiliary switch S_2 is turned on before turning on the main switch S_1 by a few micro-seconds for the soft turn-on of S_1.

(b) mode 2 : Turn-on

The main switch turns on softly and the charge in C_1 is transferred to the reactor L_1 and L_2.

(c) mode 3 : On state with regenerating

The magnetic energy in L_1 and L_2 transferred from C_1 is regenerated to the DC input source.

(d) mode 4 : On state

The reactor current is built up.

(e) mode 5 : Turn-off

The snubber capacitor C_1 is charged by the current flowing through D_1.

(f) mode 6 : Off-state

The switches are all in off-state.

5. 8kW One-tenth-model for Experiments

5.1 Prototype-model

A 8kW prototype-model using IGBTs was made and is shown in Fig. 6. The rating parameters of this prototype-model are as follows.

- Output ratings: V_0=400[V], P_{out}=8k[W]
- Duty: D=0.5,
- Switching frequency: fS=25k[Hz]
- Circuit parameters: C_1=0.33μ[F], L_1=L_2=100μ[H], SL_1=0.6μ[H]

5.2 Experimental evaluation and discussion

The principal circuit operation was verified by a rating

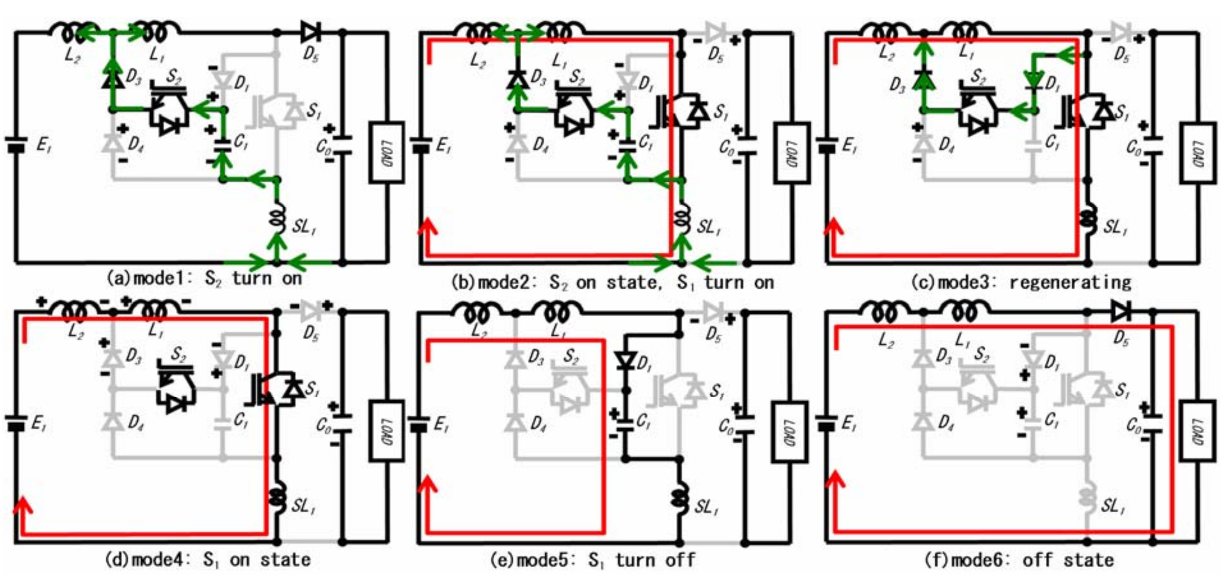


Fig. 5 The six operational modes of QRAS

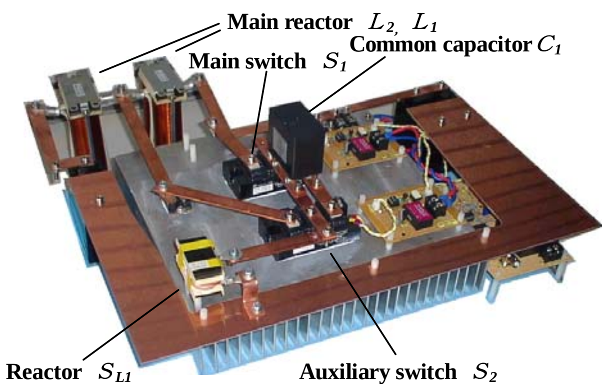


Fig. 6 Exterior of 8kW prototype model QRAS

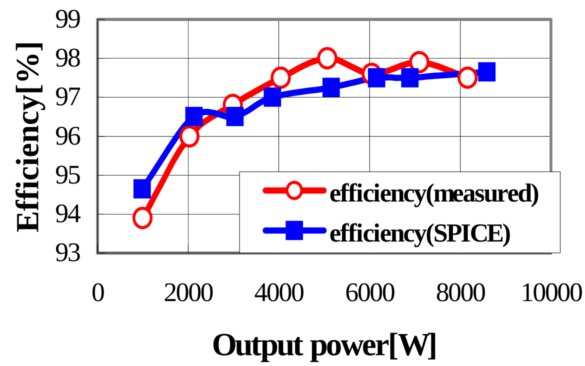


Fig. 8 The efficiency(measured) and efficiency(SPICE) vs. output power

test, light load test, current discontinuous mode test and test stable operational resonance. The soft switching by the proposed circuit is proved to be achieved. The experimental results from the prototype model tests are shown in Figures 7 to 10.

1) The evaluation of the circuitry operational verification

Fig. 7 shows the results of the measurement coincides with SPICE. The waveforms were measured by means of a WAVEPRO950 Lecroy digital oscilloscope. From these results, it is verified that the experimental results nearly corresponds to the simulation results. The normal operation of the prototype QRAS was confirmed.

2) The efficiency measurement

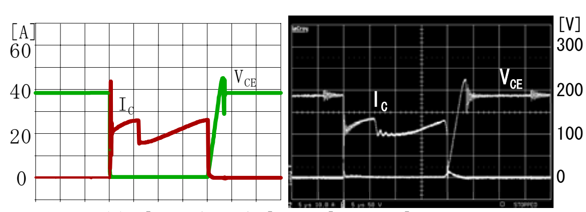
The prototype QRAS was tested and efficiency was measured every ΔP_{out}=1k[W] step until the rating condition of E_1=200[V], V_0=400[V], P_{out}=8k[W]. We measured 4 times under the same conditions allowing for reading error of the meters. Fig. 8 plots the average of the measurements mentioned above. Total efficiency was measured by means of VOAC7413 Iwatsu digital multi-meters, 2011 Yokogawa DC Ammeters and 2215 Yokogawa shunts. The efficiency measured shows the results that are nearly coincides with SPICE. The output power of 8kW with the efficiency of about 97.5% was obtained under the frequency of 25kHz and 50% duty ratio.

3) The discontinuous current mode test

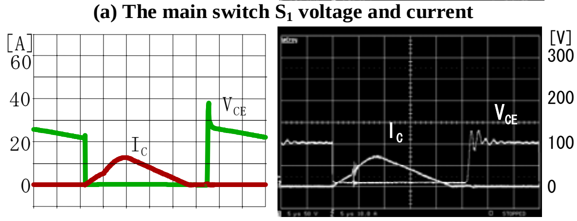
Next we tested the discontinuous mode condition under the specifications of the load resistance RL=480[Ω]. Fig. 9 shows the current discontinuous mode. The current of reactor L_1 decreases and touches zero. From this result, it was verified that the prototype QRAS operated normally.

4) Test of resonance stable operation

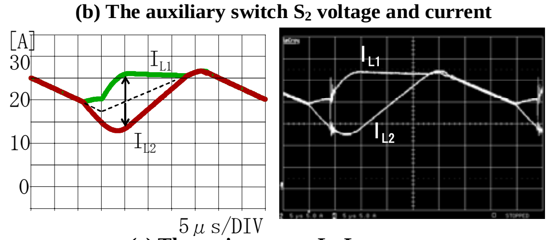
We define the stable operational resonance region as the duty control area where the prototype QRAS operates in the soft switching. We tested out of this region. Fig. 10 shows the typical waveforms in this mode when duty D=0.11. It is clear that the charge in C_1 is not discharged perfectly to zero. So the main switch S_1 and the auxiliary switch S_2 cannot be turned off from zero voltage. Thus



(a) The main switch S_1 voltage and current



(b) The auxiliary switch S_2 voltage and current



(c) The main reactor L_1,L_2 current

Fig. 7 The verification of the operational waveform (the comparison between SPICE and measurement)

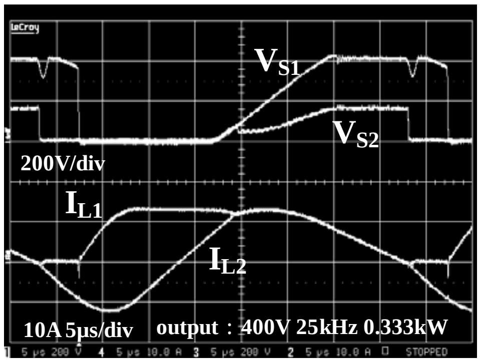


Fig. 9 The test result of the current discontinuous mode

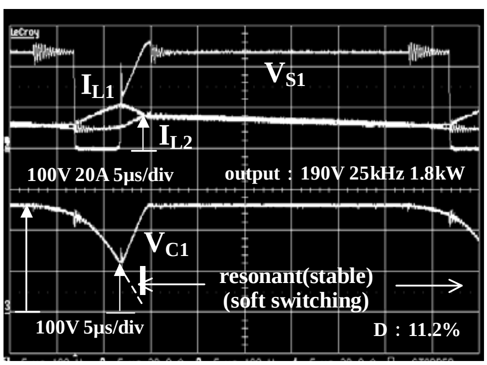


Fig. 10 The test result of the operation out of the resonance (stable)operational region

they are turned off by hard switching. However, we confirmed that duty D was able to reduce perfectly to zero in spite of the hard switching.

Considering the test evaluation mentioned above, it was proved that the proposed QRAS could operate with high performance in comparison to the conventional one.

6. Applying QRAS Scheme to The 6 Basic Converters

Fig. 11 shows the six basic converters based on the QRAS scheme. The operating principle of the QRAS scheme can be extended to other converter topologies. The five basic converters, except Fig. 11(b) boost type, can also be modified having main reactors divided into two, which are equivalent to one, one auxiliary switch, one capacitor and other 3 diodes. It is conceived that these modified circuits could operate by soft switching and by regenerating the snubber energy back to the DC power

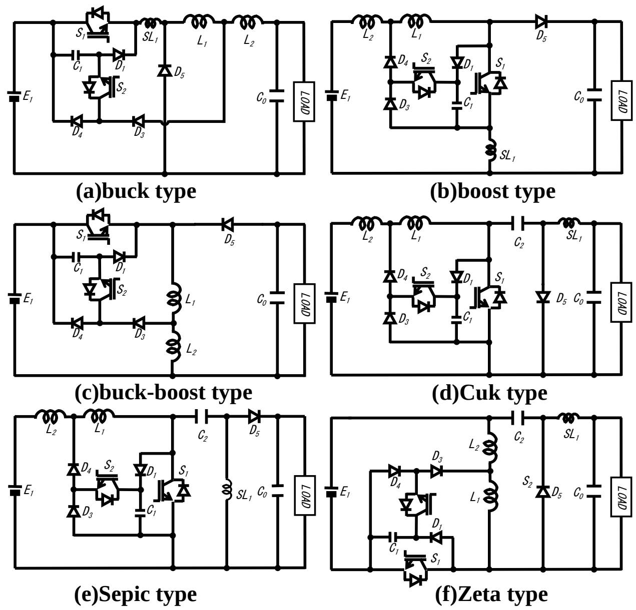


Fig. 11 The applications to the six basic converters based on QRAS scheme

source by transferring to the main reactors. The circuit operations of (a), (b), (d) in these schemes have been already confirmed by simulation.

7. Conclusion

A new DC chopper circuit(QRAS) is proposed and a prototype model has been fabricated. An output power of 8kW with the efficiency of about 97.5% was obtained under the frequency of 25kHz and 50% duty ratio. Using this proposed new circuit, a practical model of a high power DC chopper, for example 80kW 25kHz, can be realized.

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