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PWM ZCS DC Motor Drive And DC Power Supply

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***Abstract*— Following the extension and increase in capacity of power electronic elements, many convertors with special applications have been designed. Convertors such as rectifiers, AC and DC power supplies, AC and DC drivers and so on. At present, optimization of these convertors, decreasing loss and bringing down the electromagnetic interference are desired. In this paper, a DC to DC convertor for controlling the speed of DC motor is designed and one prototype is presented in which switching losses is close to zero and it has a very low electromagnetic interference. In this convertor, the switches turn on and turn off approximately with zero current.**

The speed of motor is controlled by PWM. This plan includes advantages of PWM and resonant convertors.The disadvantages, such as ; high switching losses and changing switching frequency for controlling output were removed. As switching frequency has a direct relation with switching losses, when losses decreased, it is possible to increase the frequency, then volume and weight of passive filter elements can be decreased. Besides, by decreasing the losses , the need of heatsink , which is the heavy and voluminous elements of convertors, can be removed.

***Keywords*— ZCS,PWM,Switching losses,DC motor drive,DC power supply**

I. Introduction

In the 1970's, conventional PWM power convertors were operated in a switched mode operation. Power switches have to cut off the load current within the turn-on and turn-off times under the hard switching conditions. Hard switching refers to the stressful switching behavior of the power electronic devices. The switching trajectory of a hard-switched power device is shown in Fig.1. During the turn-on and turn-off processes, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stress. Dissipative passive snubbers are usually added to the power circuits so that the dv/dt and di/dt of the power devices could be reduced, and the switching loss and stress be diverted to the passive snubber circuits. However, the switching loss is proportional to the switching frequency, thus limiting the maximum switching frequency of the power convertors. Typical convertor switching frequency was limited to a few tens of kilo-Hertz (typically 20kHz to 50kHz) in early 1980's. The stray inductive and capacitive components in the power circuits and power devices still cause considerable transient effects, which in turn give rise to electromagnetic interference (EMI) problems. The transient ringing effects are major causes of EMI.[1],[2]

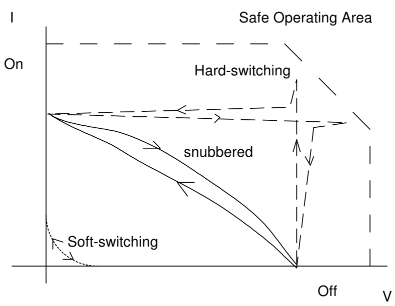

Fig. 1 Switching Diagram(hard switching and soft switching)

In the 1980's, lots of research efforts were diverted towards the use of resonant convertors. The concept was to incorporate resonant tanks in the convertors to create oscillatory (usually sinusoidal) voltage and/or current waveforms so that zero voltage switching (ZVS) or zero current switching (ZCS) conditions can be created for the power switches. The reduction of switching loss and the continual improvement of power switches allow the switching frequency of the resonant converters to reach hundreds of kilo-Hertz (typically 100kHz to 500kHz). Consequently, magnetic sizes can be reduced and the power density of the convertors increased.[1],[2] Various forms of resonant convertors have been proposed and developed. However, most of the resonant convertors suffer several problems. When compared with the conventional PWM converters, the resonant current and voltage of resonant converters have high peak values, leading to higher conduction loss and higher voltage and current ratings requirements for the power devices. Also, many resonant converters require frequency modulation (FM) for output regulation. Variable switching frequency operation makes the filter design and control more complicated.[3],[4]

You can see a sample of resonant step down dc-dc converter in figure (2) and its waveforms in figure (3).
The output filter inductor L_f is sufficiently large so that its current is approximately constant. Prior to turning the switch on, the output current I_o freewheels through the freewheeling diode D_f. The resonant capacitor voltage V_{Cr} equals zero. At t_0, the switch is turned on with ZCS. A quasi-sinusoidal current I_S flows through L_r and C_r, the output filter, and the load. S is then softly commutated at t_2 with ZCS again. During and after the gate pulse, the resonant capacitor voltage V_{Cr} rises and then decays at a rate depending on the output current. Output voltage regulation is achieved by controlling the switching frequency. Operation and characteristics of the converter depend mainly on the design of the resonant circuit L_r - C_r.

A plan is proposed in this paper where normal convertors are equipped with auxiliary circuits and switches current at the time of switching is zero as a result of which switching loss is very little and there is no need to change switching frequency any more.[5],[6]
In part 2 and 2-A, the new plan will be introduced and the way it works will be studied through mathematical formulas. In part 2-B, simulation results will be compared with prototype output sample taken with oscilloscope.

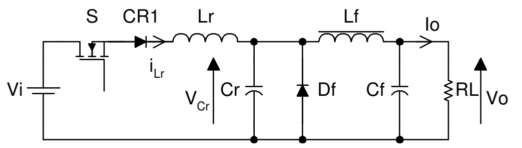

Fig. 2 Resonant step down DC to DC converter

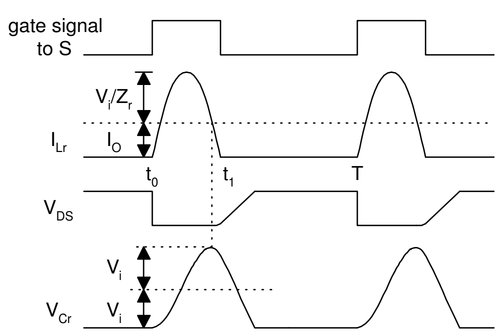

Fig. 3 Waveforms of resonant Dc to Dc step down converter(fig2)

II. New plan

So far, limited plans from combination of PWM convertors and resonant convertors have been proposed. Most of these plans include many elements and many auxiliary switches and their analysis is involved with complicated and difficult computations.

A. *Circuit model and mathematical analysis*

A simple circuit has been introduced which used the resonant auxiliary circuits only when needed in a way that every time the switch is turning on or off, the resonant auxiliary circuit is activated and provides a switching in zero current. The proposed plan in this paper is shown in figure (4).

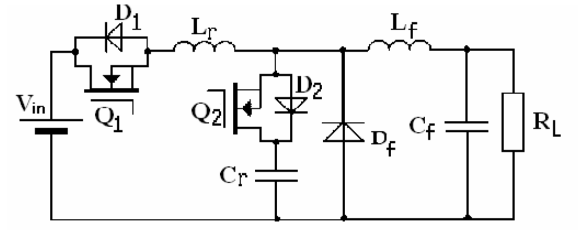

Fig. 4 The plan presented of combining PWM and resonant convertors

For analyzing circuit, a cycle is divided in 6 intervals. You can see these intervals in figure (5).

First interval (t_0-t_1): it's the time when main switch and auxiliary switch are off and because of existence of large capacitor in parallel with load , freewheeling diode is transmitting current to load and turn the main switch on by applying pulse to the gate. because of freewheeling diode has been short circuited , all the input voltage falls on inductor(L_r) and the linear current increases as much as to reach to load current (I_O). At this time freewheeling diode turns off.

$$i_L = \frac{V_{in}}{L} t \tag{1}$$

$$t_1 = \frac{I_0 L}{V_{in}} \tag{2}$$

Second interval (t_1-t_2): in this interval, crossing current from inductor (L_r) increases and is divided to two parts. One is I_O which provides the load current and the other is used for charging the capacitor (C_r). When I_{Lr} reaches its peak, C_r will have been charged up to the voltage V_{in}. The C_r and L_r start resonancing, yet due to existence of D_r diode, the current will not be backward. The capacitor is charged up to $2V_{in}$ when the value of I_{Lr} current returns to I_O.

$$i_L = I_m \sin \omega_0 t + I_0 \tag{3}$$

$$I_m = V_{in} \sqrt{\frac{C_r}{L_r}} \tag{4}$$

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}} \tag{5}$$

$$v_{cr} = V_{in}(1 - \cos \omega_0 t) \tag{6}$$

The main switch current peak occurs at the time $t = \pi / 2\sqrt{L_r C_r}$ and its amount is $I_p = I_m + I_0$.

$$t_2 = \pi\sqrt{L_r C_r} \quad (7)$$

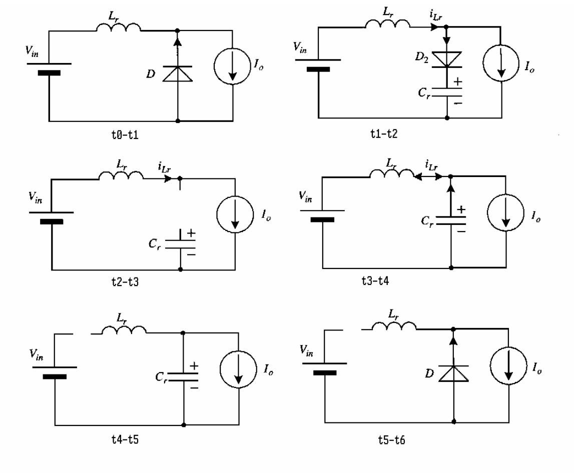

Fig. 5 six intervals of a cycle

Third interval(t_2-t_3): D_r diode has been turned off and the capacitor holds voltage $2V_{in}$. The duty cycle is still continuing and the main switch is providing the load current (I_0).

Fourth interval(t_3-t_4): at the beginning of this phase the time of only one resonant C_r and L_r from duty cycle, is remained. At this time, in order to bring down the main switch current to zero, the auxiliary switch is activated. At this time, the main switch current starts going down and at the time of t'_3, current changes direction due to existence of anti-parallel diode and the current reaches zero again at t_4. In this circuit, due to the existence of anti-parallel diode with switch, some amount of energy return to the source.

$$i_{Lr} = I_0 - I_m \sin \omega_0 t \quad (8)$$

$$v_c = 2V_{in} \cos \omega_0 t \quad (9)$$

$$t'_3 = \sqrt{L_r C_r} \sin^{-1}(1/x) \quad (10)$$

That $x = I_m/I_0 = (V_{ins}/I_0)\sqrt{C_r/L_r}$

Fifth phase: At the beginning of this phase, the switch current is zero and the switch must be turned off. The voltage of Capacitor C_r, that reached to V'_c in previous phase having started going down due to the activation of auxiliary switch , is discharged and reaches zero.

$$v_c = V'_c - \frac{I_0}{C} t \quad (11)$$

$$v_c(t_5) = 0, t_5 = V'_c C / I_o \quad (12)$$

Sixth phase: in this step, after the capacitor voltage is zero, the auxiliary switch whose current is zero, turns off and the freewheeling diode starts conducting. After t_6, with respect to duty cycle, second cycle can be started. as you see, the output voltage can be controlled with PWM .the switching losses is close to zero due to zero current switching. With respect to the mathematical formulas, if the circuit waveforms are drawn, we will get to figure (6)

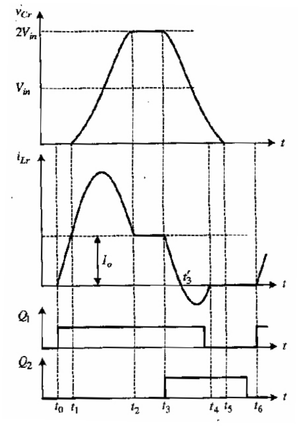

Fig. 6 waveforms drawn with respect to math. Formulas

B. Simulation and taking sample from prototype circuit

For a more complete study and comparison of waveforms, we will do the stimulation first and then study and compare the waves which have been sampled by oscilloscope.

In figure (7), the changes of resonance capacitor voltages and auxiliary switch pulses to time are seen ,which are like figure (6), as expected.

In figure (8), the changes of main switch current to the time and main switch pulses are seen which are like figure (6) as expected.

For more study of the circuit and waveforms, we have made a 2 kw prototype sample which you can see in the figure (9) and have taken sample of using oscilloscope.

The samples are seen in figures (10)-(13)

As it be seen the prototype samples are approximately like to simulation with software.

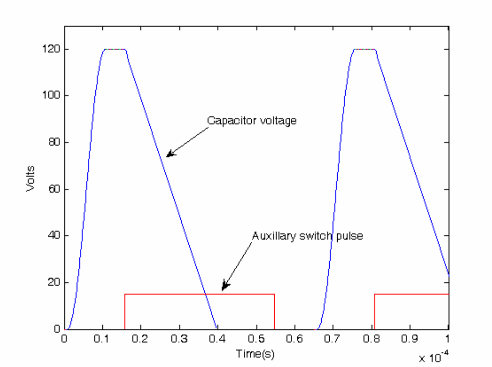

Fig. 7 simulation of resonant capacitor voltage

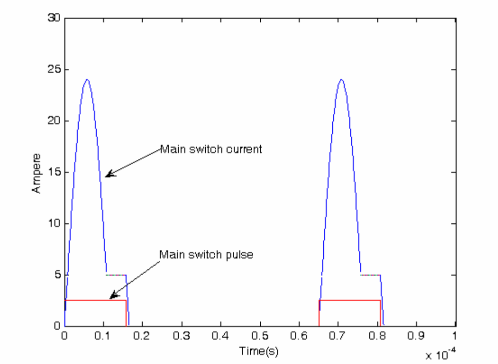

Fig. 8 simulation of main swith current

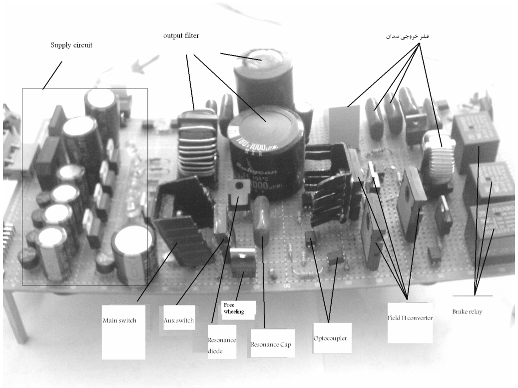

Fig. 9 2 KW prototype

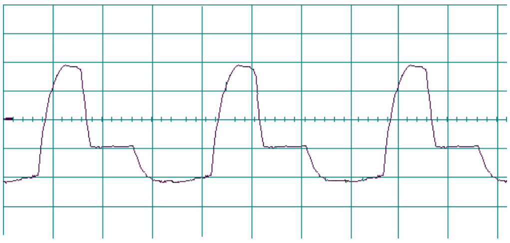

Fig. 10 main swith current (sampled with CT & oscilloscope)

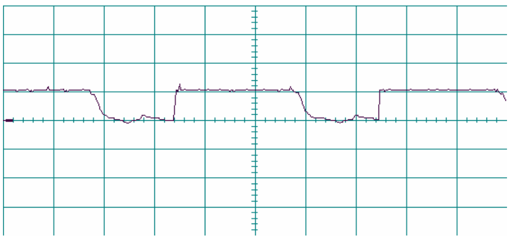

Fig. 11 main swith gate pulse (sampled with oscilloscope)

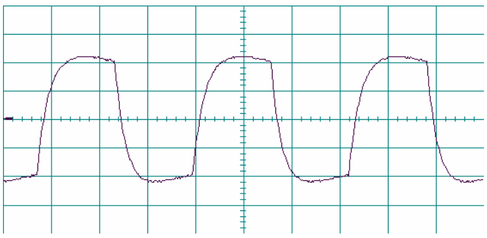

Fig. 12 resonant capacitor voltage (sampled with oscilloscope)

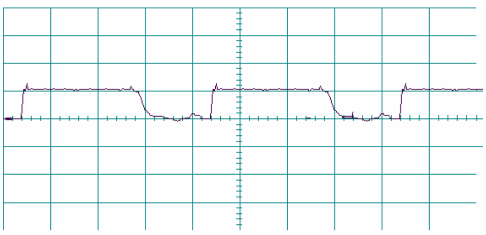

Fig. 13 auxiliary swith gate pulse (sampled with oscilloscope)

III. Conclusions

Due to quick changes in voltage and current in switching convertors, in switching interval, these convertors have a very high loss. What is more, these convertors incorporate electromagnetic interferences. One of the way of reduction in loss and electromagnetic interferences is designing appropriate auxiliary circuits.

Using ZCS circuits will reduce the switching losses and EMI and increases the density of converter. However, using traditional ZCS circuits have their own problems. the resonant current and voltage of resonant converters have high peak values, leading to higher conduction loss and higher voltage and current ratings requirements for the power devices. Also, many resonant converters require frequency modulation (FM) for output regulation. Variable switching frequency operation makes the filter design and control more complicated.

Using the novel method of controlling ZCS switching through PWM method causes great and noteworthy improvement in regulation of output voltages with load changes, leading to more simple filters and so there will be no more need frequency changes which creates lots of problems.

Also, IGBT switch on drive which needs heat sink and fan in a typical scenario is now working in room temperature. Nevertheless, as you can see in the wave forms, the main switch current have peaks more than load current which result in conductive losses and we will have to use a switch with a higher capability, yet since the switching loss in medium frequencies and rated load is more times higher than conductive loss, this plan is acceptable.

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