A NEW RESONANT CONVERTER CIRCUIT FOR RELUCTANCE

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Abstract The purpose of this paper is to introduce a different type of converter circuit used to drive switched reluctance motors. It continues with detailed discussion on the resonant converter armed at minimizing or eliminating the transistors switching losses. Finally the drive has been tested on a disc-type reluctance motor for the performance and functionality.

Key Words Switched Reluctance Motor Drive, Converter Circuit, Resonant Converter

چکیده در این مقاله سعی بر معرفی و طراحی یک راه انداز جدید برای موتور رلوکتانس با هدف کم کردن تلفات کلیدزنی در ترانزیستورهای قدرت مدار راه انداز می باشد. این راه انداز براساس خاصیت تشدید که بین سیم پیچهای موتور و یک خازن سری با آنها که در مدار تعبیه گردیده باعث گذشتن جریان موتور از صفر می گردد. حال اگر کلیدزنی ترانزیستورها را زمانی انجام دهیم که جریان از صفر و یا نزدیک به صفر می گذرد تلفات در ترانزیستورهای قدرت بسیار کم می گردد.

INTRODUCTION

The essential features of the power switching circuit for each phase of reluctance motor comprises two parts:

1. A controlled switch to connect the voltage source to the coil windings to build up the current.
2. An alternative path for the current to flow when the switch is turned off, since the trapped energy in the phase winding can be used in the other strokes. In addition, this protects the switch from the high current produced by the energy trapped in the phase winding.

Figure 1 shows a simple form of switching circuit for a switched reluctance motor [1,2].

The general equation governing the flow of stator current can be written for Figure 1 as:

$$V = Ri + \frac{d\lambda}{dt} \tag{1}$$

Where, V is the voltage applied across the winding and λ is the flux linking the coil.

Considering a linear magnetic circuit and negligible resistance, Equation 1 can be rewritten as:

$$V = L\frac{di}{dt} + i\frac{dL}{d\theta}\frac{d\theta}{dt} \tag{2}$$

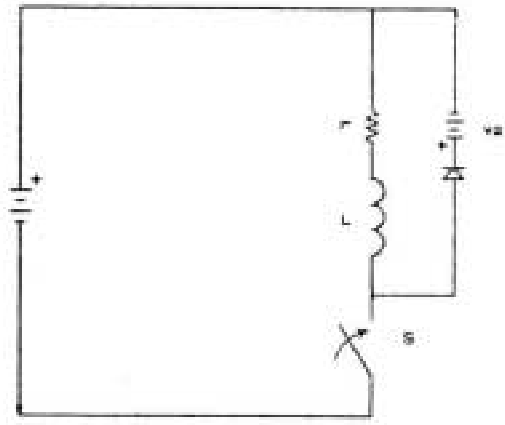


Figure 1. A simple switching circuit.

therefore, the rate of energy flow is given by:

$$vi = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + \frac{i^2}{2}\frac{dL}{d\theta}\omega \tag{3}$$

The above equation indicates that for a reluctance motor the input electrical power goes partly to increase the stored mangetic energy ($1/2Li^2$) and partly to provide mechanical output power ($i^2/2\ dL/d\theta\omega$).

REVIEW OF DRIVE CIRCUITS

Some of the proposed practical drive circuits for reluctance motor are: a two switch per pole circuit in which for each phase one transistor is used to control the amount of current through the winding, while the other transistor synchronizes the operation of that phase with the rotor position by the use of a sensor [2,3], and an N+1 transistors converter circuit for N-phase motor, in which only one transistor is common to all phases for the control of current [4].

In Bifilar winding converter configuration the number of switches and diodes per phase is reduced by introducing a Bifilar winding for each stator pole [5,6].

In the C-dump topologies, the energy stored in the winding is dumped on the capacitor and used again in the next stroke [7].

Finally, in regenerative single switch per phase converter the source voltage is connected to the phase winding by switching two transistors and when these transistors are off the energy stored in the phase winding is released to a capacitor and used in the next stroke [7,8].

RESONANT CONVERTER CIRCUIT

In order to eliminate the transistor switching losses a new resonant converter is proposed. In traditional drive circuits, there are energy losses due to on-off switching of the transistors used in the circuitry. These losses result from the switching action of the transistors. When a transistor is used as a switching device, especially for a high frequency switching, it will experience substantial losses. These losses are more evident when more than one power transistor is used for switching purposes. However, these losses could be eliminated by switching the transistor every time the collector current passes through zero. In order to accomplish zero collector current, a resonant circuit made of inductance and capacitance can be used to produce a resonating current in the drive circuit. By using resonant principle for the reluctance motor drive, a new circuit with lower switching losses is obtained. Figure 2 shows such a drive circuit in which the phase inductance of the reluctance motor and an external capacitor are used to produce the resonating current waveform.

The principle operation of this drive circuit can be explained as follows when the transistors S_1 and S_2 are on, the current flows into the motor phase windings which charges the capacitor C to some voltage V_{cf}. Subsequent to zero crossing of the phase current, the transistor S_1 is turned off, while the transistor S_2 is switched on. This results in discharging of capacitor C and flow of phase current in the opposite direction. The amount of current going into the phase winding of the motor can be controlled by controlling the switching periods of the transistors S_1 and S_2. In order to analyze this drive, a circuit representation for one phase of the motor is considered. This circuit configuration is shown in Figure 3.

When S_1 and S_3 switches are closed, the drive circuit can be simplified to a new circuit shown in Figure 4.

However, when switch S_2 is closed and S_1 is open, a different circuit is obtained as shown in Figure 5.

Writing KVL for circuits in Figures 4 and 5 results in the following differential equations:

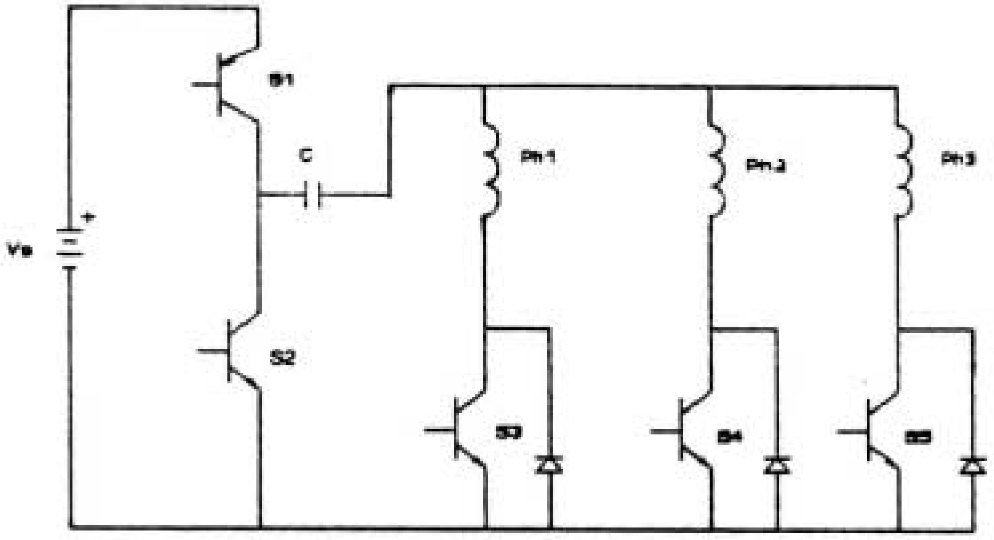


Figure 2. Resonant drive circuit.

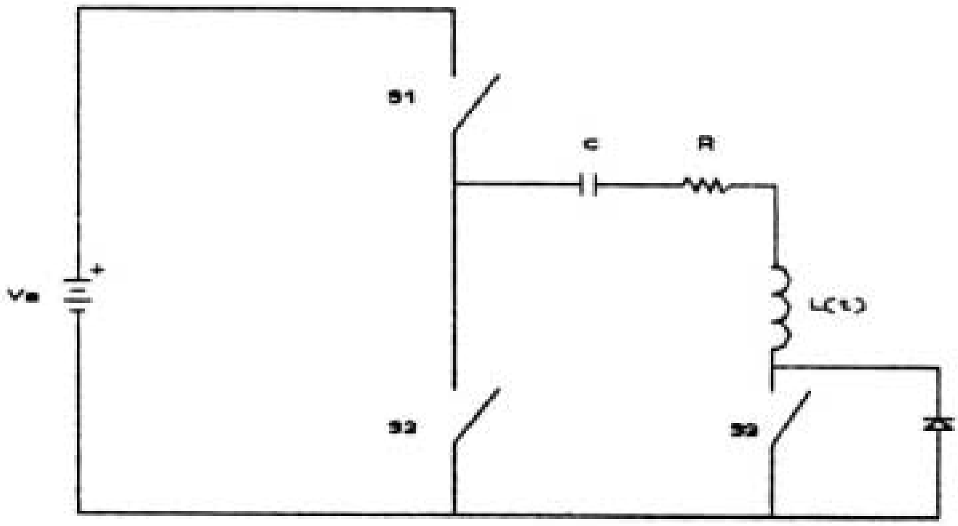


Figure 3. One phase representation of motor drive.

$$V_s = V_{c1} + L(t)\frac{di_1}{dt} + i_1\left(\frac{dL}{d\theta}\frac{d\theta}{dt} + R\right) \tag{4}$$

$$0 = V_{c2} + L(t)\frac{di_2}{dt} + i_2\left(\frac{dL}{d\theta}\frac{d\theta}{dt} + R\right) \tag{5}$$

then, the above equations can be rewritten as

$$V_s = V_{c1} + L(t)C\frac{dV_{c1}^2}{dt^2} + C\left(\omega_m\frac{dL}{d\theta} + R\right)\frac{dV_{c1}}{dt} \tag{6}$$

$$0 = V_{c2} + L(t)C\frac{dV_{c2}^2}{dt^2} + C\left(\omega_m\frac{dL}{d\theta} + R\right)\frac{dV_{c2}}{dt} \tag{7}$$

where V_{c1} or V_{c2} is the capacitor voltage, ω_m is the motor speed, and V_s is the source voltage.

When the resonance frequency is much higher than the motor frequency, $L(t)$ can be considered constant for one resonance frequency calculation and then Equations 6 and 7 can be written as

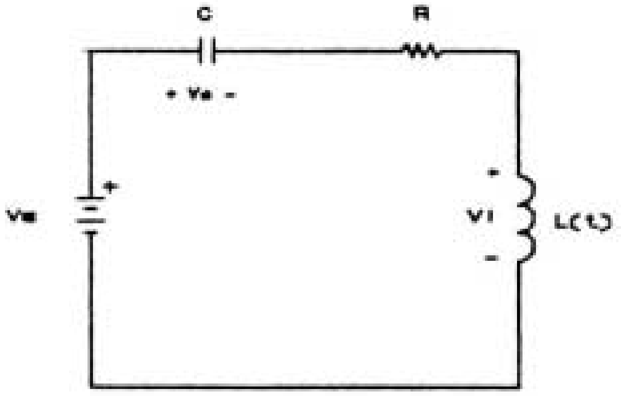


Figure 4. Simplified version of drive circuit.

$$\frac{dV_{c1}^2}{dt^2}+\left(\frac{\omega_m\frac{dL}{d\theta}+R}{L}\right)\frac{dV_{c1}}{dt}+\frac{V_{c1}}{CL}=\frac{V_s}{CL} \qquad (8)$$

$$\frac{dV_{c2}^2}{dt^2}+\left(\frac{\omega_m\frac{dL}{d\theta}+R}{L}\right)\frac{dV_{c2}}{dt}+\frac{V_{c2}}{CL}=0 \qquad (9)$$

The above differential equations have general solutions in the form of

$$V_c = V_{C_{ss}} + V_{C_{natural}} \qquad (10)$$

Where $V_{C_{ss}}$ Equations 8 and 9 are V_s and zero, respectively.

A plot of capacitor voltage and current versus time for a typical voltage of 20 volts is shown in Figure 6. As indicated in Figure 6, the capacitor voltage charges to almost one-half times the source voltage when transistor S_1 is on and then, discharges, when transistors S_1 and S_2 are turned off and on, respectively. The current waveform goes through the zero crossing every time the capacitor voltage reaches maximum or minimum level. Also, the magnitude of the current is larger in the second half of the resonance cycle. This is due to the charging of the capacitor voltage to almost one-half times the source voltage.

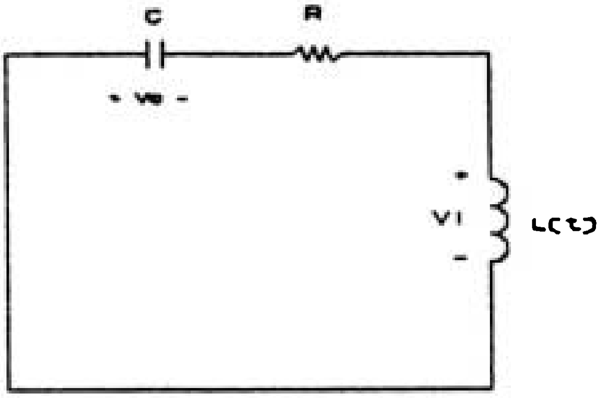


Figure 5. Circuit representation of drive circuit.

The minimum resonance capacitor value, C_{min}, is dictated by the minimum torque, T_{min}, produced by the motor. Since torque is proportional to square of current and also since, ourrent is directly related to the capacitor value, then, the minimum capacitor value can be found by

$$C_{min} \geq \frac{\sqrt{2T_{min}}}{\sqrt{\frac{dL}{d\theta}\frac{dV_c}{dt}}}. \qquad (11)$$

Therefore,

$$\frac{\sqrt{2T_{min}}}{\sqrt{\frac{dL}{d\theta}\frac{dV_c}{dt}}} \leq C \leq \frac{1}{36\,\omega_n^2 L_{avr}}. \qquad (12)$$

Figure 7 shows the complete resonant drive and open loop controller circuit used in the laboratory experiment.

In the above circuit, there are 4D-flip flops. Each flip-flop is set to trigger at the rising edge of the input pulses. Therefore, the resulting output frequency is cut in half and the procedure is repeated through the 4 flip - flops. The final resulting cutput frequency is 1/16 of the initial frequency, as shown in Figure 8.

The output from the flip flop circuit is first fed to the monostable multivibrator and then to the shift

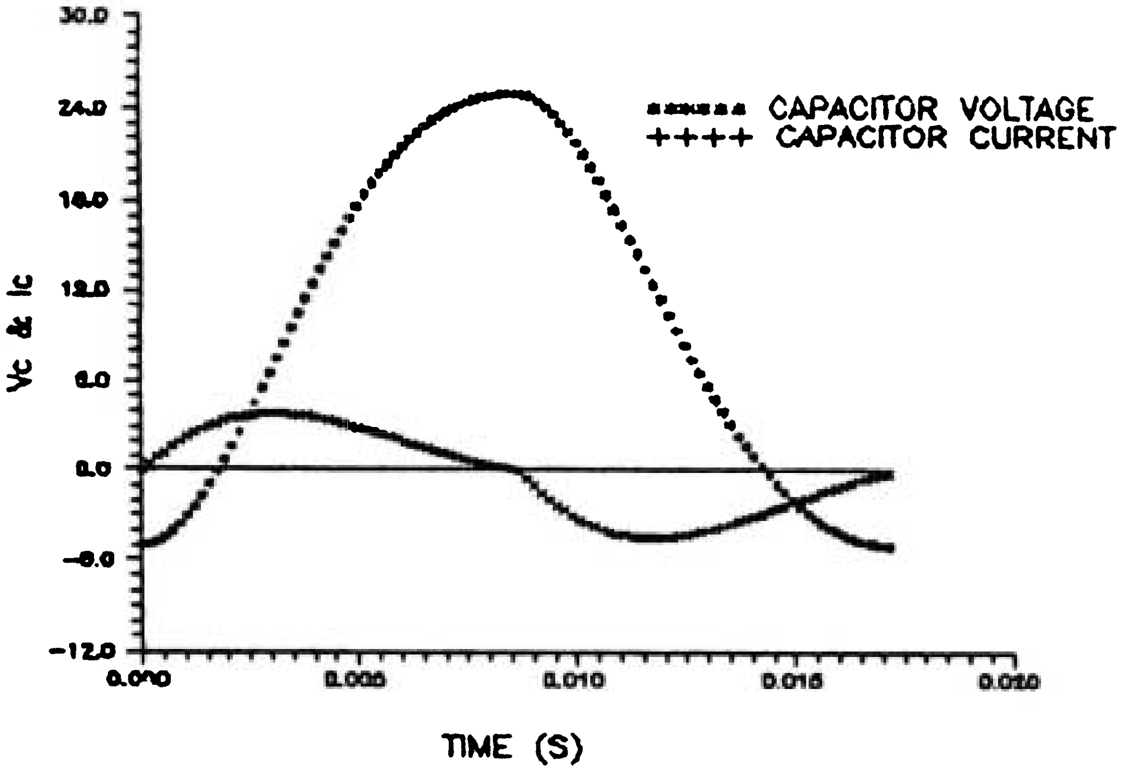


Figure 6. Capacitor voltage and current waveform.

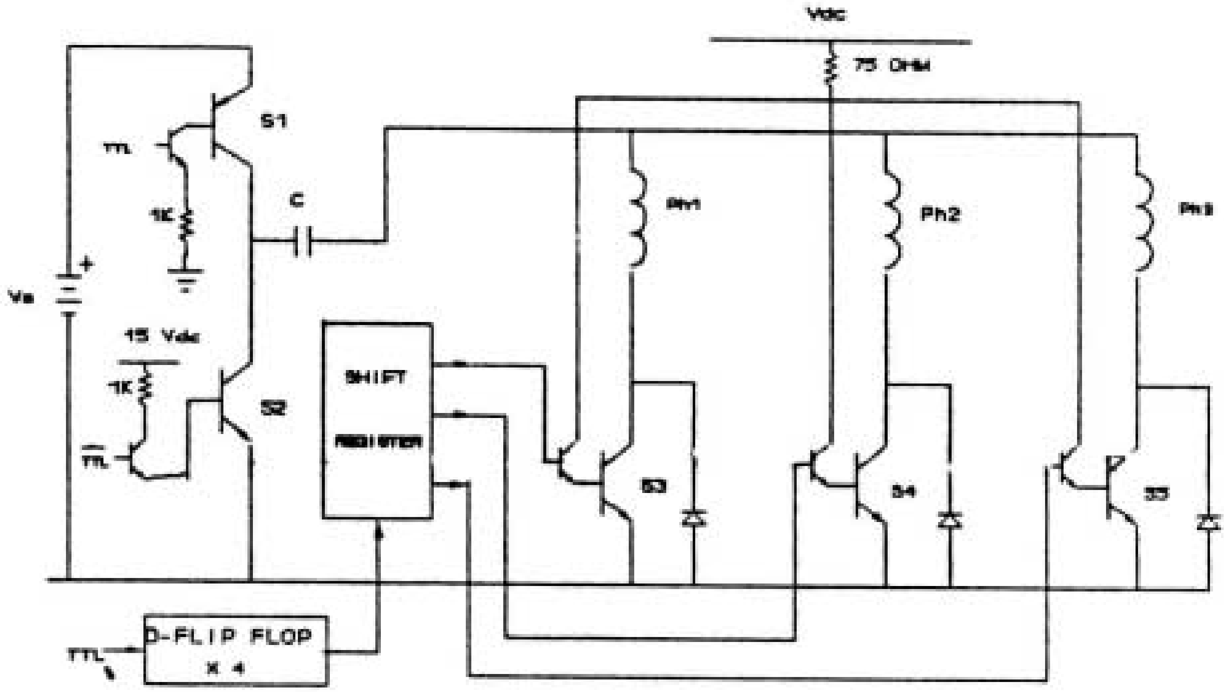


Figure 7. The complete drive circuit for the motor.

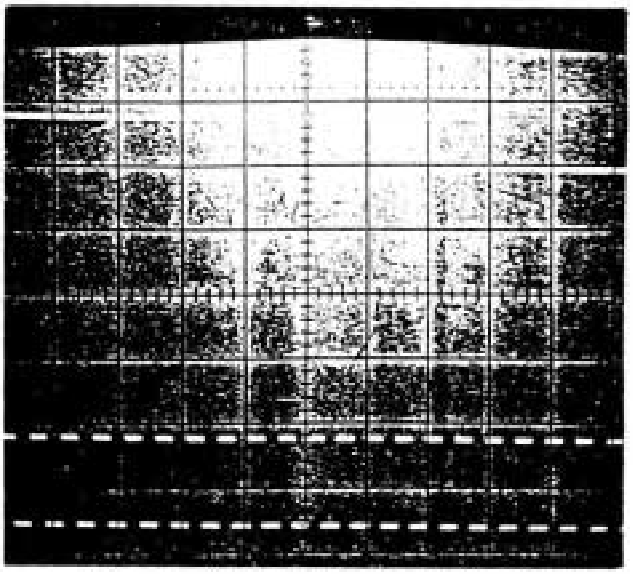


Figure 8. D-flip-flop Input and Output waveforms.

register. Since the output current produced by the shift register is very small and can not provide the sufficient base current to the power transistors (S_3, S_4, S_5), a current amplifier is used for each power transistor. In order to produce variable speed for the motor, the resonant drive circuit is operated in either continuous or discontinuous mode. Continuous mode is reached when the current has no discontinuity in its waveform. On the other hand, the discontinuous mode is achieved when the current experiences discontinuity in its waveform.

Figure 9 (a and b) show the capacitor voltage waveform in the continuous mode of operation for a source voltage of 20 VDC, and the corresponding input signal to the base of the power transistor S_1, respectively.

In Figure 9a, the voltage across the capacitor charges to almost one and half times the supply voltage when, the transistor S_1 is turned on, and then in discharges to -4 volts when the transistors S_1 and S_2 are turned off and on, respectively. The corresponding signal to the base of transistor S_1 is shown in Figure 9b.

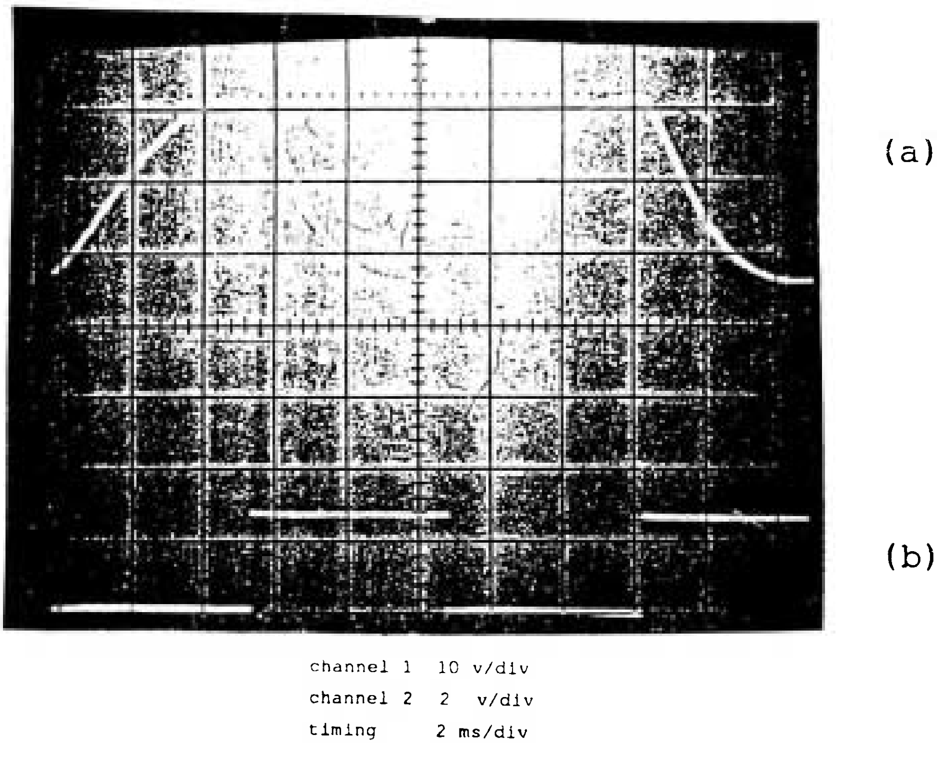


Figure 9. a) Capacitor voltage waveform, **b)** Control signal for power transistor.

The RMS value of the voltage waveform is measured to be 9.3 Volts. Figure 10 (a and b) show the capacitor current and the corresponding input signal to the base of the power transistor S_1, respectively.

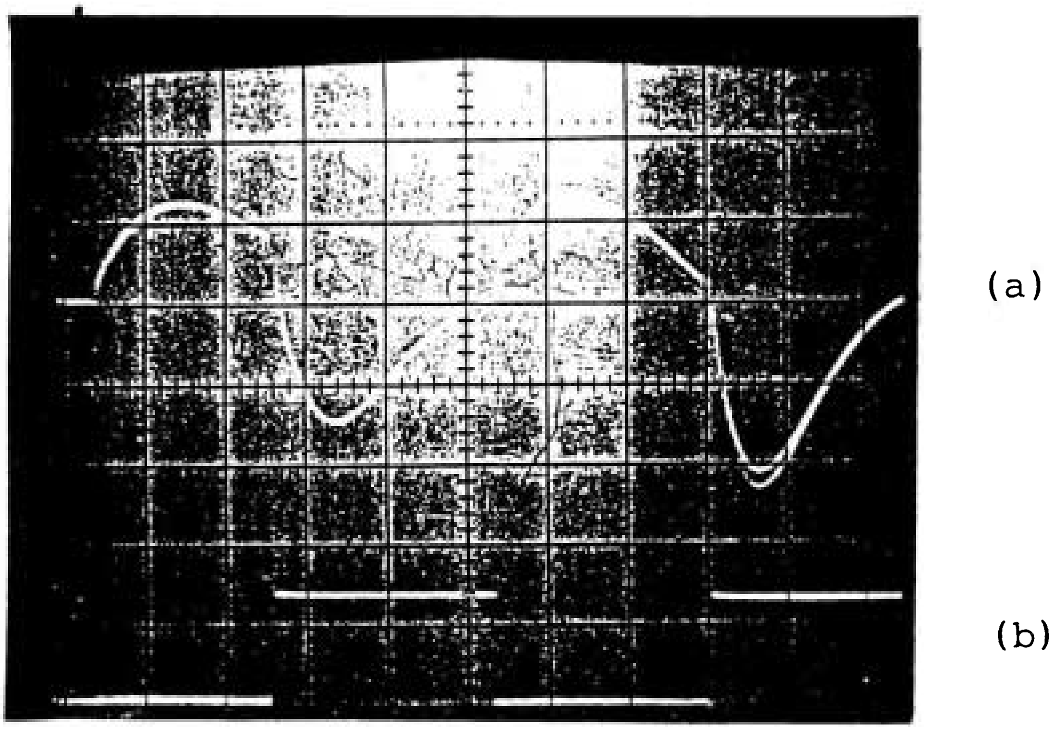
In Figure 10a, the current flows in the capacitor and passes through the zero crossing when, transistor S_1 is turned off and transistor S_2 is turned on. Figure 10b shows the corresponding signal to the base of transistor S_1. The RMS value of the current waveform is measured to be 2.85A. Figure 11 (a and b) show the voltage across and the current through the capacitor, respectively.

As shown above, the current waveform is the derivative of the voltage waveform. Finally, in the continuous mode, Figure 12 (a and b) show the source current waveform and the corresponding input signal to the power transistor S_1, respectively.

The current flows from the supply source when, transistor S_1 is turned on and it reaches zero when transistor S_1 is turned off. It stays at zero until S_1 is turned on again. The RMS value of this current waveform in measure to be 1.3.

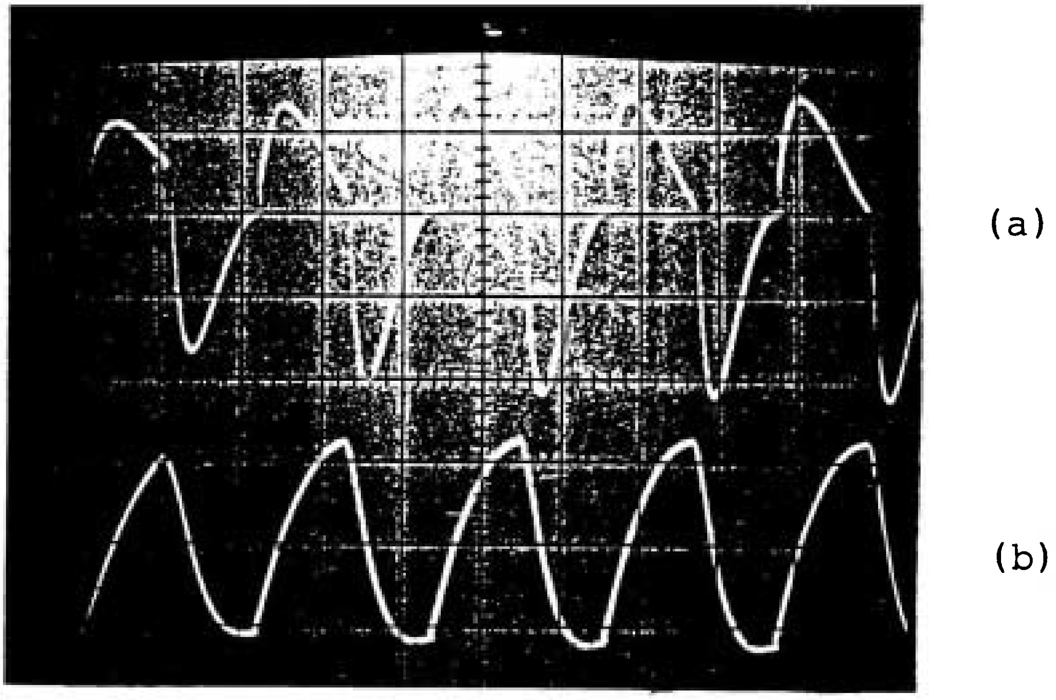
In the discontinuous mode, Figure 13 (a and b) show the capacitor voltage waveform for a source voltage of 20 VDC and the corresponding base signal to the power transistor S_1, respectively.

In Figure 13a, the capacitor voltage charges to the maximum voltage of twice the source voltage and stays at that level until transistors S_1 and S_2 are turned off and on, respectively. The corresponding signal to the base of transistor S_1 is shown in Figure 13b. Figure 14 (a and b) show the capacitor current and the



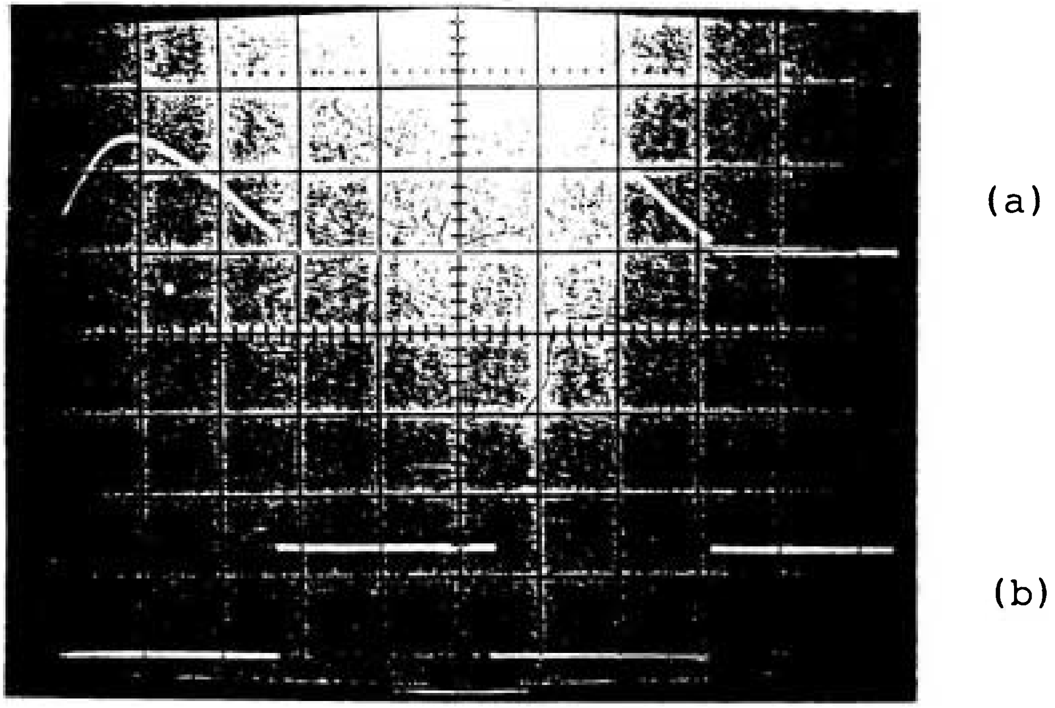
current amp 5 v/div
timing at 2 ms/div
channel 2 2 v/div

Figure 10. a) Capacitor current waveform, **b)** Input base signal to power transistor.



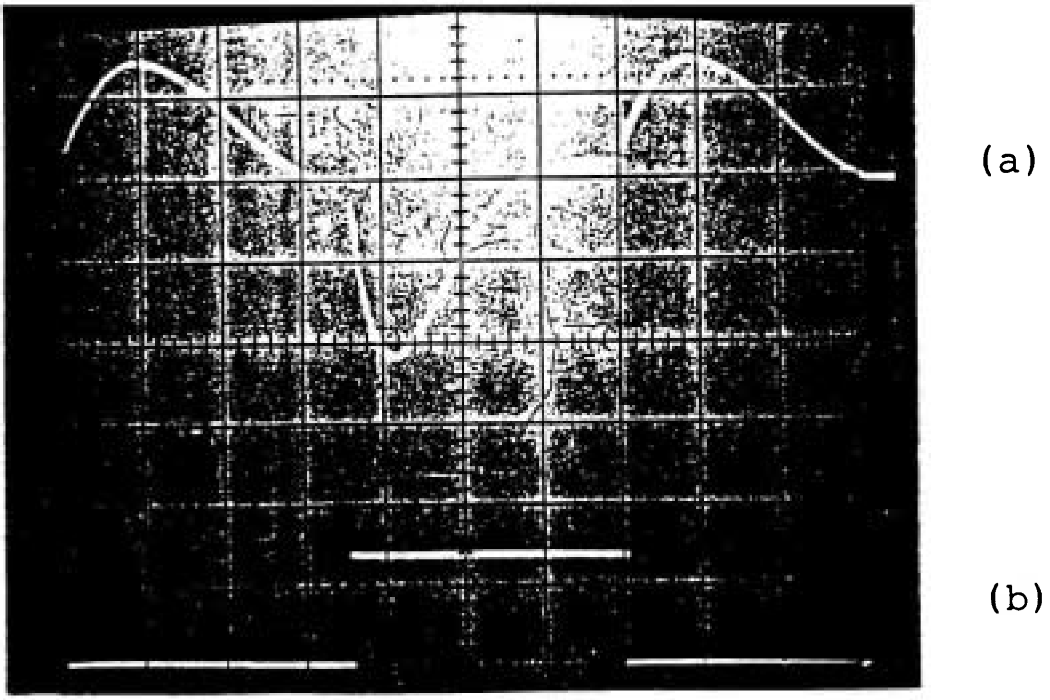
channel 2 10 v/div
current amp 5 v/div
timing at 5 ms/div

Figure 11. a) Capacitor current, b) Capacitor voltage.



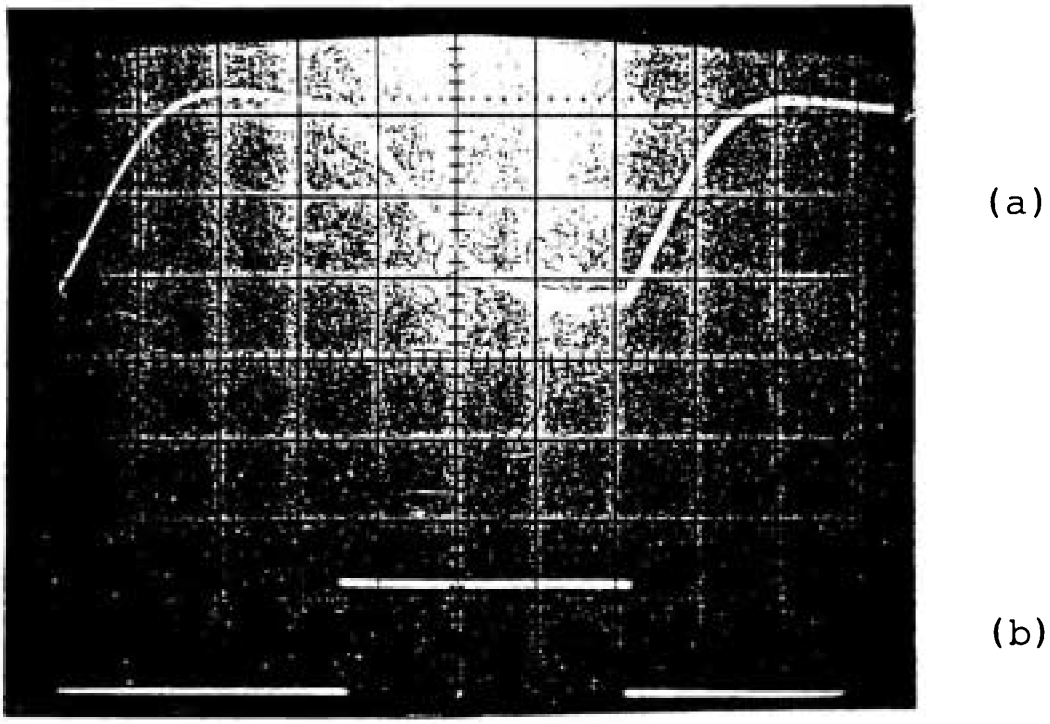
current amp 5 v/div
channel 2 2 v/div
timing 2 ms/div

Figure 12. a) Source current waveform, b) Base signal to power transistor.



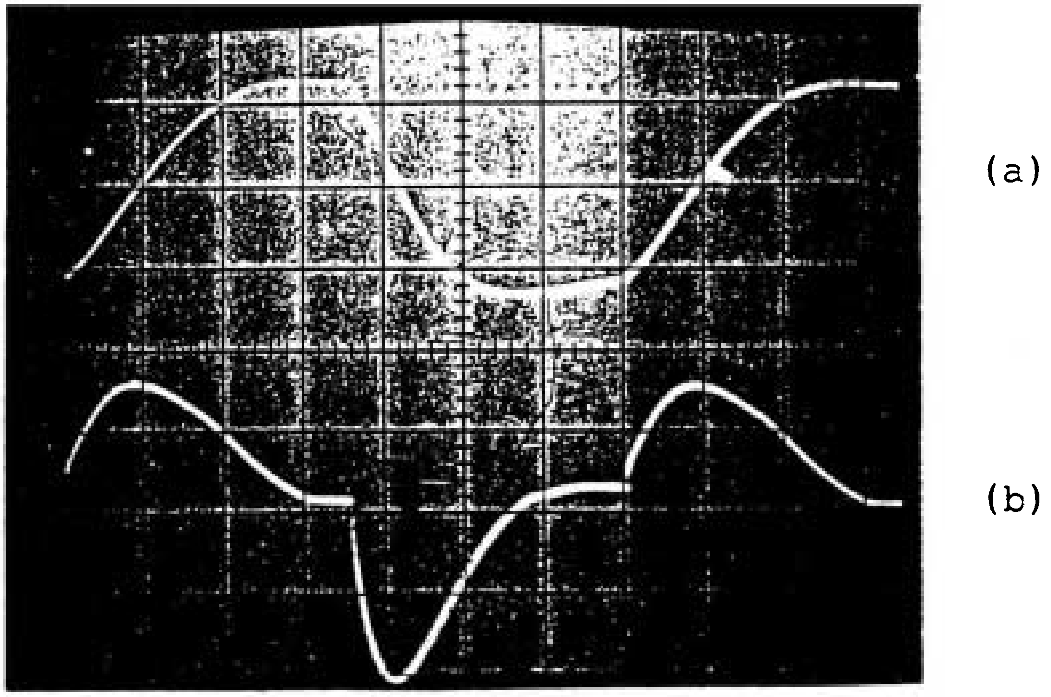
channel 1 10 v/div
channel 2 2 v/div
timing 2 ms/div

Figure 13. a) Capacitor voltage waveform, **b**) Base signal to the power transistor.



current amp 5 v/div
channel 2 2 v/div
timing at 2 ms/div

Figure 14. a) Capacitor current, **b)** Base signal to the power transistor.



channel 1 10 v/div
current amp 5 v/div
timing at 2 ms/div

Figure 15. a) Capacitor voltage, **b)** Capacitor current.

corresponding input signal to the base of transistor S_1, respectively.

In Figure 14a, the capacitor current reaches zero well before transisotr S_1 is turned off. It stays zero until transistor S_2 is turned on, then it starts flowing in the opposite direction of the current, when S_1 was on. Figure 14b is the corresponding base signal to the power transistor S_1. Figure 15 (a and b) show the capacitor voltage and current, respectively.

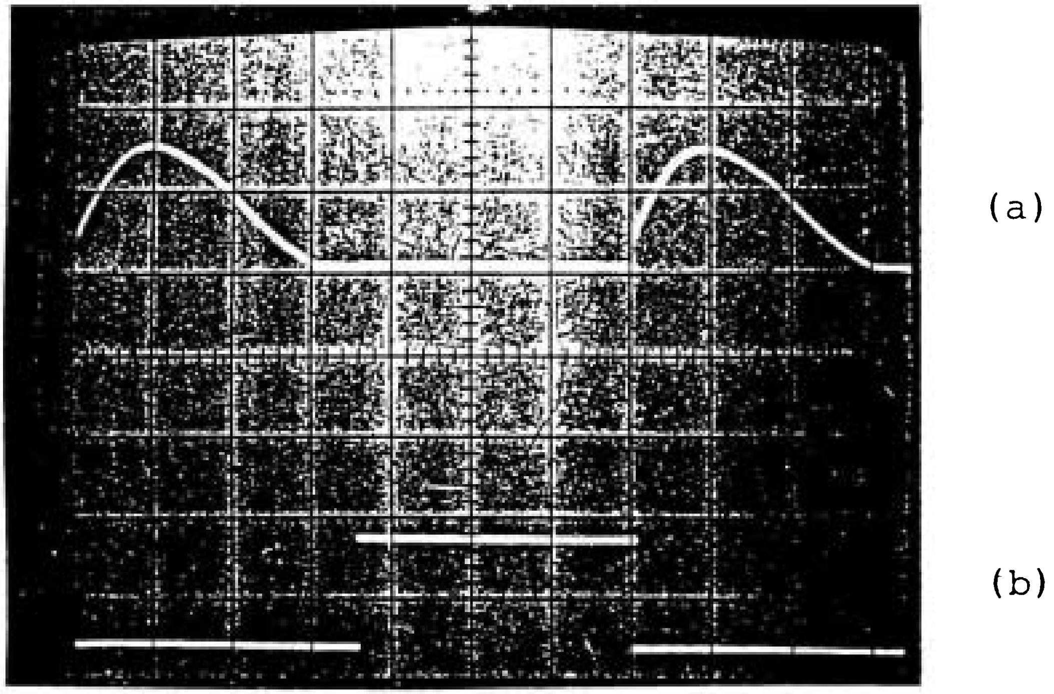
As shown above, the current waveform is the derivative of the voltage waveform; therefore, the current is zero when the capacitor voltage stays constant at the maximum or minimum voltage. The capacitor voltage and current measured to be 9.8 Vrms and 2.3A. Finally, in discontinuous mode of operation, Figure 16 (a and b) show the source current wave form and the input signal to the power transistor S_1, respectively.

The current flows from the supply and reaches zero even before transistor S_1 is turned off. It stays at zero until S_1 is turned on again. The RMS value of this current is measured to 1.27

CONCLUSIONS

The resonant converter has been built and tested to run a disc-type switched reluctance motor in low speeds. The resulting magnitude of current through the motor passes through zero, hence, power transistors used in the drive can be switched (on or off) at zero crossing of the current wave form which results in the reduction of the switching losses.

Comparing the resonant converter drive with regenerative-single-switch-per-pole and resonant C-dump, one can conclude the following: in the resonant converter the stored energy is used in the second half of the first storke while in the regenerative-single switch-per-pole or resonant C-dump the trapped



current amp 5 v/div
channel 2 2 v/div
timing at 2 ms/div

Figure 16. a) Source current waveform, **b)** Base signal to power transistor.

energy is directed to the capacitor to be used in the following strokes. Additionally, the resonant converter has lower component count when compared with the regenerative-single-switch-per-pole.

In order to produce 10A of continuous DC current in the regenerative-single-switch-per-pole converter circuit, the capacitor used varies between 1000 UF to 3000 UF and the maximum source voltage is 300 VDC, while the resonant converter circuit with a capacitor value of 450 UF and 20 VDC of source voltage produces 3 A_{RMS}. This comparison shows that the resonant converter can be practical.

The performance and functionality of the resonance converter have been satisfactory and in accordance with the expectation.

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