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Frequency and pulse width modulation for zero-voltage -switching resonant pole inverter

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Abstract - The resonant pole inverter has the advantages of less component count and simple operation but the disadvantage is that the zero voltage switching can only be achieved for a very small load range. A new modulation technique is proposed to ensure the zero-voltage-switching to be maintained. Comparison of the proposed method to other modulation and inverter is presented. Theoretical and experimental results are shown.

I. INTRODUCTION

Inverter is an important circuit in Power Electronics and Drives System. Its application includes induction motor drives, AC power supplies and actuation system. For higher output power, typically greater 2kVA, three phase system will be more appropriate. The conventional hard switched inverter, as shown in Fig 1, suffers from switching losses. This type of inverter can usually switch at 12kHz as maximum. Higher switching frequency is possible but at the expense of higher loss. The recent development of IGBT and other switching devices such as MCT provides a possible higher switching frequencies, but it only limits to 20-30kHz. Output frequency of the inverter in many cases requires higher than 50Hz. For examples high speed drives and aerospace inverters which require 400Hz output frequency. A very high switching frequency is therefore necessary.

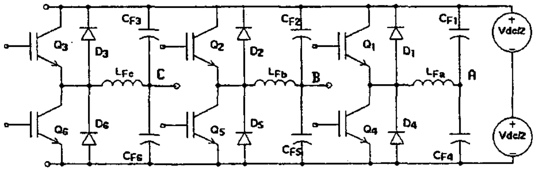

Fig. 1 Conventional hard-switched inverter

The conventional hard-switched inverters suffer from switching losses and hence cannot work at very high switching frequency. Recently some resonant topologies have been reported to overcome this problem. The resonant DC link inverter [1] requires high voltage rating transistors and the auxiliary resonant commutated pole inverter (ARCPI) [2] is an improved version of the resonant pole inverter (RPI)[3], however it has a high component count and the auxiliary transistors are only zero-current-switching rather than zero-voltage-switching transitions. Clamped Quasi-resonant inverters [4] is very similar to conventional resonant link inverter [1] and they both have problem of zero-voltage detection. The resonant snubber inverter [5] is using auxiliary device to assist resonance, its principle is similar to ARCPI [2] and also requires additional switching devices. Anyway the RPI although has a limited load range but also has a low component count and its operation is simple. The modulation strategy can either be natural or regular sampling and hence it is very easy to be implemented. The aim of this paper is to present a modulation method which can enable the RPI to maintain zero-voltage-switching for very wide load ranges.

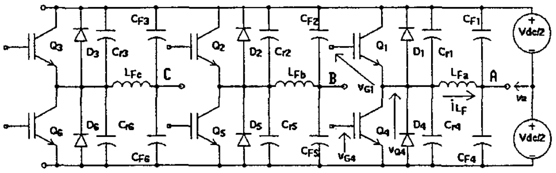

Fig.. 2 Schematic diagram of 3-phase Resonant Pole Inverter

II. PRINCIPLES OF OPERATION

Fig. 2 shows a typical circuit of RPI. It can be seen that this circuit is the same as that of a conventional hard-switched inverter except that resonant capacitors C_{r1} to C_{r6} are added in parallel with the transistors. The added capacitors are usually small and stray capacitors of the switching devices (Q_1-Q_6) form part of the capacitance. The operation of the RPI is explained here by using the inverter leg A (Q_1 and Q_4):

When Q_4 is turned off, C_{r4} is gradually charged to V_{dc} by current in L_{Fa}. Hence Q_4 is turned off under zero-voltage switching. When voltage across C_{r4} rises to V_{dc}, D_1 conducts. Q_1 is then turned on and hence Q_1 is turned on under zero-voltage switching. The duration between the turn-off of Q_4

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and the turn-on of Q_1 is called the dead-time T_{dead}. The principles of operation of zero-voltage-turn-on of Q_4 and turn-off of Q_1, and the zero-voltage-switchings of the other inverter legs are similar.

However, when instantaneous magnitude of i_{LF} is small or i_{LF} is still positive, there is insufficient current in L_F or the current flow direction is incorrect for charging the voltage of C_{r4} to V_{dc} before the next turn-on of Q_1, hence zero-voltage switching cannot be achieved in Q_1. The conventional regular or natural sampling sinusoidal modulation defines the pulse width as a function of modulating signal. Generally near the crest or trough of a sine wave, the pulse width of the gate signal to Q_4 or Q_1 is very small respectively. There is insufficient time for the current to build up in L_F so as to charge C_{r4} or C_{r1} respectively.

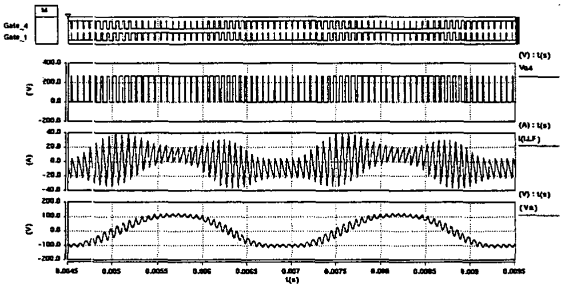

Fig. 3 Simulated waveforms of the resonant pole inverter using classical PWM techniques
(1^{st}: V_{G4}; 2^{nd} V_{G1}; 3^{rd}: V_{Q4}; 4^{th}: i_{LF}; 5^{th}: V_A)

Figure 3 shows a simulated results of the resonant pole inverter. Classical regular sampling sinusoidal modulation is used. The circuit parameters used were: C_r=22nF, L_F=75μH, C_F=4.7μF, V_{dc} = 270V, f_m=400Hz and M=0.85. Switching frequency=15kHz. Higher switching frequency cannot be used because it will seriously decrease the pulse width near the crest or trough of a sine wave.

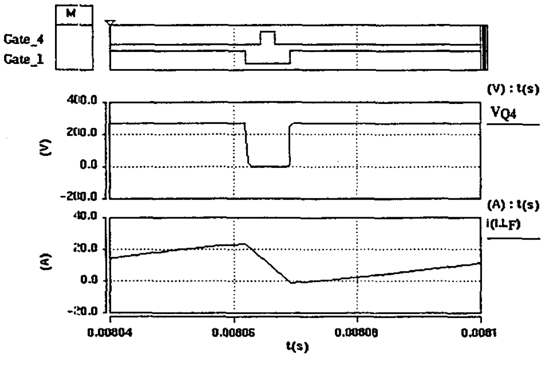

Fig. 4 Simulated waveforms of the transistor voltage Vsw near the crest
(1^{st}: V_{G4}; 2^{nd} V_{G1}; 3^{rd}: V_{Q4}; 4^{th}: i_{LF})

The inductor current i_{LF} is different from a sinusoidal waveform and is a characteristic of this inverter. The fcat that it cannot follow a sinusoidal waveform makes it unable to charge or discharge the resonant capacitor near the crest or trough of a sine wave. It can be seen that i_{LF} cannot switch to sufficient magnitude opposite polarity when the sinsoidal wave (output voltage Va) has already reached the creast or trough. The magnified waveform is shown in Fig. 4. It canbe seen that the rising current of i_{LF} has a sufficient magnitude to discharge the resonant capacitor to zero voltage before the next turn-on of the switching signal Gate_4 (Gate signal of Q_4). However when Q_4 is on, there is insufficient time for the current to change to sufficient magnitude in the opposite direction. Hence the resonant capacitor C_{r4} cannot charge to V_{dc} because Q_1 is turned on (Gate_1 is on).

III. ZERO-VOLTAGE SWITCHING MODULATION TECHNIQUE

The above problem can be improved by decreasing the carrier frequency hence the pulse width can be extended whereas the mark-space ratio can still be kept constant. This is important because regular sampling modulation can still be fulfilled. The modulation equation can be derived as follows. Let C_r be the capacitance of C_4 and L_F be the inductance of L_{Fa}. The mark-space ratio, *d*, can be given by regular symmetrical sampling modulation:

$$d=0.5(1+M\sin(2\pi f_m t)) \qquad (1)$$

where M is the modulation index and f_m is the modulating frequency. The inductor current i_{LF} can be given by:

$$2L_F\frac{di_{L_F}}{dt}=V_{dc}-V_{dc}d \qquad (2)$$

i_{LF} is to charge C_{r4} to V_{dc} before the lapse of T_{dead}, ie. Q_1 is turned on:

$$2C_r\frac{dV_{Cr}}{dt}=i_{L_F} \qquad (3)$$

Eqn (2) and (3) give

$$f_c=4(1-d)df_s \qquad (4)$$

where

$$f_s = \frac{T_{dead}}{16 L_F C_r} \tag{5}$$

f_s is the maximum value of the carrier frequency f_c. f_c is proportional to *(1-d)d.* It can also be seen that f_c is maximum when *d* is 0.5 and approaches to 0 when *d* =0 or 1. In practice, f_c must be limited to a minimum value.

IV. SIMULATION OF THE INVERTER

The above variable frequency regular sampling symmetrical modulation has been programmed to simulate the RPI using simulation package SABER. The parameters used were: C_r=22nF, L_F=75µH, C_F=4.7µF, V_{dc} = 270V, f_m=400Hz and M=0.85. Range of f_c = 12.5kHz - 40kHz. It can be seen that the carrier frequency varies as the mark-space ratio is varied. At crest or trough of the modulating (sine wave) signal, the carrier frequency is low. i_{LF} is characterized by a sinusoidal wave shape. The magnified waveforms are shown in Fig. 6.

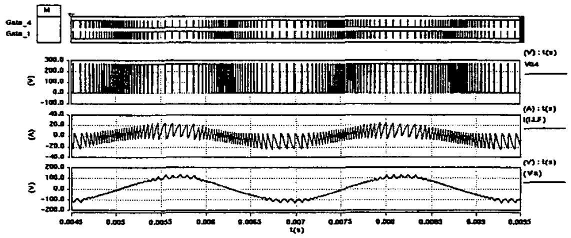

Fig. 5 Simulated waveforms of the resonant pole inverter using zero-voltage switching modulation technique
(1^{st}: V_{G4}; 2^{nd} V_{G1}; 3^{rd}: V_{Q4}; 4^{th}: i_{LF}; 5^{th}: V_A)

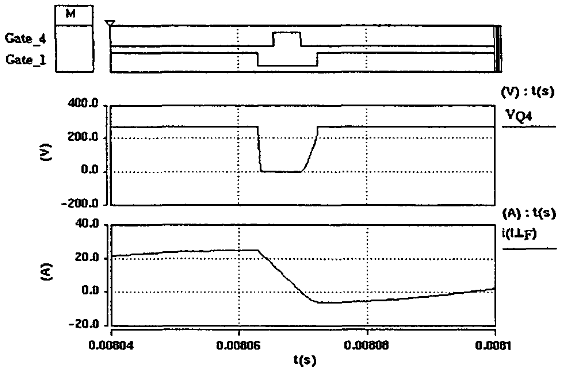

Fig. 6 Simulated waveforms of the resonant pole inverter using zero-Voltage switching modulation technique
(1^{st}: V_{G4}; 2^{nd} V_{G1}; 3^{rd}: V_{Q4}; 4^{th}: i_{LF})

It can be seen that the pulse width of Gate_4 is extended because of the carrier frequency is also modulated. I_{LF} is now switched to sufficient magnitude in the opposite polarity. The transistor Q4 is now switched under zero-voltage switching.

V. EXPERIMENTAL RESULTS

A prototype RPI has been built and tested. Same component values as Section IV were used. The modulation signal is programmed by a DSP TMS320C31. The transistors used were third generation 600V, 50A IGBT. Three half-bridge modules are used. The on-state voltage is low. A small thermal subsystem is sufficient.

Sandwiched DC bus bar are used to minimise the stray inductance and increase the decouple filtering effect..

Fig. 7 and 8 shows the experimental results at 1.8kW. Fig. 7 shows the waveforms of the i_{LF} and V_{Q4}. It can be seen that V_{Q4} decreased to zero before gate signal V_{G4} was applied. It is confirmed that zero-voltage-switching has been achieved. Fig. 8 shows the experimental waveforms of the inductor current and the output phase voltage V_A at output frequency of 400Hz. The Total Harmonic Distortion measured was 8.8% which met the international standards MIL-704E and BSI 3G 100: Part 3. The output voltage has an observable distortion near the crest and trough. This is because the instantaneous switching frequency is modulated to 15kHz. The instantaneous switching frequency near the zero-crossing is 40kHz, hence the ripple voltage is small. Nevertheless, the overall THD of the waveform is still low. It should be noted that the small filter size (L_F, C_F) is used. Its THD can be improved further if it is needed.

The measured efficiency is 95%. Usually for medium or high power system, the efficiency is higher than 92%. The

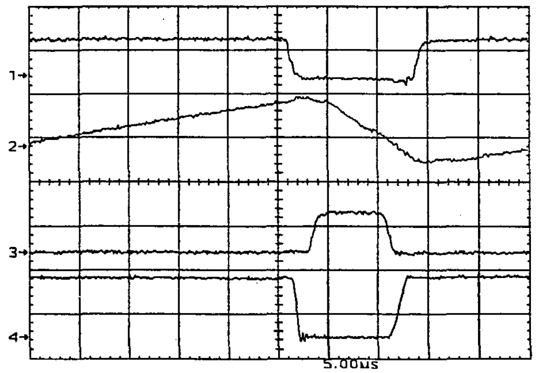

Fig. 7 Experimental waveforms of the inverter
(1^{st}: V_{G1}: 20V/div; 2^{nd}: i_{LFa}: 20A/div; 3^{rd}: V_{G4} 20V/div; 4^{th}: V_{Q4} 200V/div; 5µs/div)

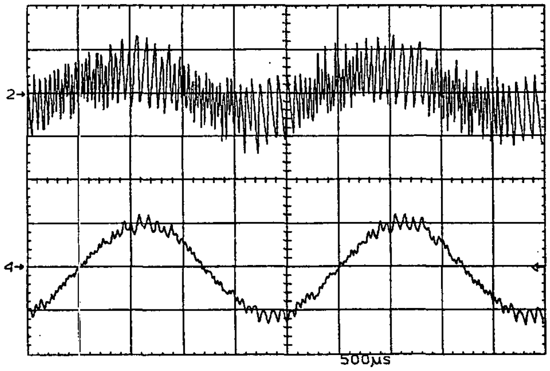

Fig. 8 Experimental waveforms of the inductor current and output voltage
(upper: i_{LF_a} 20A/div; lower: output phase voltage V_A 100V/div; 500µs/div)

prototype inverter, because of small component count and using zero-voltage switching, have achieved above average efficiency.

VI. COMPARISON WITH OTHER INVERTERS

Soft-switching is one of the future technologies of the power electronics development. Because the switching devices can now switched at much high frequency, it is common concept to increase the switching frequency to as high as possible. Using the conventional modulation applied to RPI causes problem in the non-zero voltage switching. It therefore generate switching noise and lost. The switching frequency cannot be very high, typical 12.5kHz, but still suffer from switching loss during the crest or trough of the modulating signal. The problem becomes serious when the output frequency (modulating frequency is high) such as 400Hz. High output frequency is very common in industrial application such as aerospace power inverters and high speed drives. Low switching frequency causes problems of output voltage distortion.

Auxiliary resonant commutated pole inverter (ARCPI) [2] is a very common inverter and is popular for its zero-voltage switching for a wide load range. This converter has a very high components and hence it is usually used in the very high power application. Its reliability is rather poor. The proposed RPI is therefore is better than the ARCPI especially when it is operated in medium power level, typically less than 10kVA.

VII. HARMONICS CONSIDERATION

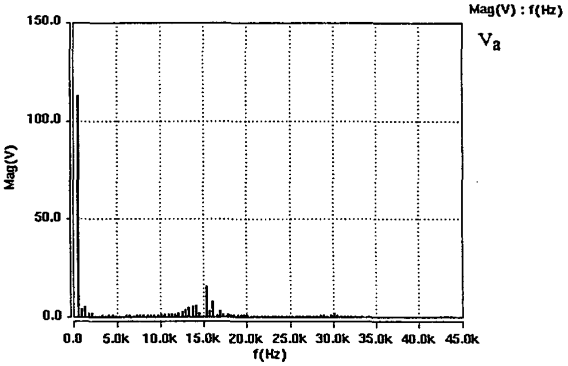

Fig. 9 Harmonic spectrum of the output voltage of RPI using conventional modulation method

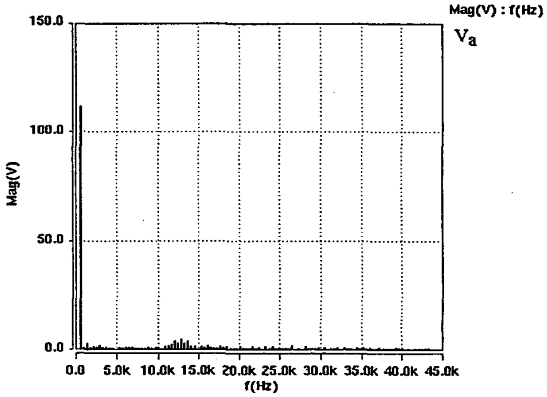

Fig. 10 Harmonic spectrum of output phase voltage the RPI using zero-voltage switching modulation method

The output harmonics are important factor of consideration because it may produce distortion in the output voltage and torque ripple when it is driving a machine. The spectrum of the RPI using conventional modulation techniques has been simulation and is shown in Fig. 9. It can be seen that the distortion is high and the THD is 20% which does not meet many international standards.

The spectrum of the output voltage of the RPI using the proposed zero-voltage switching modulation method is shown in Fig 10. It can be seen that the harmonic distortion is very small. The THD is 9% which meets many international standards. The proposed modulation method using frequency modulation hence the switching frequencies are distributed between 12.5kHz and 40kHz. This components can be easily be filtered by L_F and C_F.

VII. CONCLUSIONS

A novel variable frequency modulation scheme is proposed for the Resonant Pole Inverter. The proposed method enables that the inverter has zero-voltage switching for a wide load range. The harmonic distortion is low and the circuit is simple. The frequency and pulse width modulation method proposed is also very simple and easily to be implemented in an inverter. The reliability of the circuit is high because of the small component count. Theoretical, simulation and experiment has demonstrated the operation of the circuit and verified the feasibility of the circuit. It is therefore suitable for many industrial applications and even for aerospace actuation.

ACKNOWLEDGEMENT

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