

Efficiency and Noise Evaluation of AC Link Soft-switching Inverter

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ABSTRACT

Soft switching inverter technology was examined as a means of increasing the efficiency and reducing the noise of the inverters used to drive motors in hybrid electric vehicles and fuel cell vehicles. From the various soft switching circuit topologies available, AC link inverters were selected as the research focus, because they can be used in high-power applications and require few additional circuit components. Specifically, the single inductor auxiliary resonant AC link inverter was worked out to further reduce the number of inductors. Comparisons with hard switching inverters showed a 0.5% improvement in efficiency. In addition, conduction noise was reduced at almost all frequency bands and radiation noise was reduced at all frequency bands, and demonstrated maximum reductions of 10 dB and 20 dB respectively.

1. Introduction

The demand for reductions in automotive fuel consumption and emissions continues in light of the issue of global warming. Honda has consistently beaten the competition in these areas, with our introduction of the electric vehicle EV PLUS in 1997, with the hybrid vehicles Insight and Civic Hybrid, which combine a gasoline engine and electric motor and were introduced in 1999 and 2001, respectively, and with the FCX, a fuel cell vehicle which rolled out at the end of 2002. The electric motors in these vehicles provide part or all of the driving force. Motor output power is controlled in an inverter, which converts electricity from DC to AC using semiconductor switching devices such as insulated gate bipolar transistors (IGBT). Conversion in the inverter is accomplished by cycling the switching devices between the on and off conditions (switching), but during the transition, the elements are exposed to large currents and

voltages; this causes large losses. Other undesirable results of the simultaneous, rapid changes in currents and voltage are surge voltages and electromagnetic noise.

Soft-switching inverter technology is expected to allow reductions in both the losses which occur during switching in semiconductor switching devices (switching losses) and electromagnetic noise. This paper shows the circuit operation of an AC link soft-switching inverter, a new soft-switching inverter topology proposed here, and the results of efficiency and noise compared with those parameters in a hard-switching inverter.

2. Conventional Technology

Inverters are devices which convert DC input into 3-phase AC by continual switching with semiconductor switching devices according to magnetic pole position

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(Fig. 1). They are placed between batteries or other DC sources and their loads, the motors. The output power can be controlled by pulse width modulation (PWM) which varies the ratio of on time to off time. The waveforms for voltage V_{ce} , current I_c , and loss, expressed by $V_{ce} \times I_c$, in the semiconductor switching devices in the circuit in Fig. 1, are shown in Fig. 2. This conventional method of switching is called 'hard-switching', in contrast with 'soft-switching'.

Two kinds of losses occur in semiconductor switching devices during switching, conduction loss and switching losses.

Conduction loss is calculated from the product of 2V saturation voltage across the two leads of the switching device, and current, during on condition in which current runs through the semiconductor switching device. Another term for it is 'ON loss'. This loss depends on the materials and structure of the semiconductor switching device and has been reduced with advances in semiconductor technology.

Switching losses occur during the transient conditions while the semiconductor switching device is being changed from on condition to off condition (turn-off), and from off condition to on condition (turn-on).

Both conduction loss and switching losses must be reduced in order to minimize losses in semiconductor switching devices. Reduction of conduction loss is a matter

of advances in semiconductor technology. In contrast, switching losses can be decreased by two methods: By reducing the incidence of switching between conductive and off conditions by reducing the switching frequency, and by shortening the time necessary for changing between conditions, so that there is less time of overlap between current and voltage. However, decreasing the switching frequency raises the issue of motor noise when it enters audio frequencies. Also, shortening the switching time increases the rate of change of the current (dI/dt) flowing through the semiconductor switching device; this causes a surge voltage due to wiring inductance, which, in turn, causes a high rate of change of the voltage applied across the semiconductor switching device (dV/dt). This raises the issues of increased conduction noise and radiation noise. If the surge voltage is particularly large and exceeds the withstand voltage, the semiconductor switching device can be destroyed. When semiconductor switching devices with high withstand voltages are used in order to guard against this, the conduction loss is actually augmented, the opposite of the desired solution. A snubber circuit can be used to absorb the surge voltage, but there are losses associated with the consumption of the energy absorbed by the snubber circuit. Thus, there are limits to the reductions attainable in hard-switching.

3. Soft-Switching Technology

3.1. Concepts

Soft-switching technologies have been proposed as a solution for the issues attendant upon reducing the losses in hard-switching. Resonant switches (see Fig. 3) in which inductors (L) and condensers (C) are connected to the semiconductor switching devices moderate the speed of changes of current and voltage at the semiconductor switching devices, for the purpose of switching between the conductive and off conditions while the actual current or voltage is at low or even zero values. As shown in Fig. 4, the current and voltage at the semiconductor switching devices under resonant switches change at lower rates than during hard-switching. This enables reductions in switching losses, since overlap of voltage and current has been reduced. During turn-on, switching is performed while current from the added inductor is flowing into the free wheeling diode connected to the semiconductor switching device. The current and voltage at the semiconductor switching device

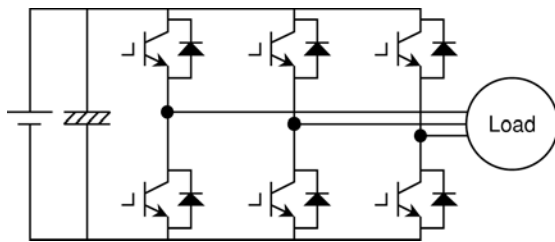


Fig. 1 Inverter circuit

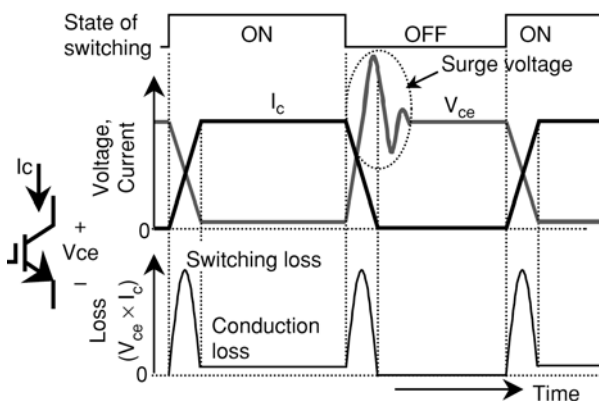


Fig. 2 Voltage, current and loss under hard-switching condition

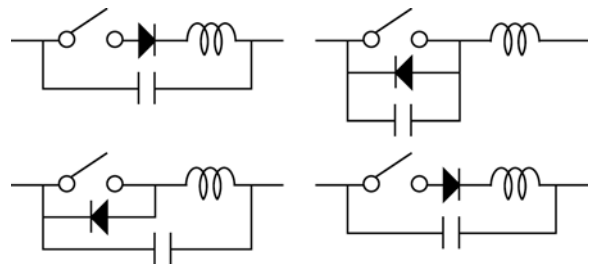


Fig. 3 Resonant switches

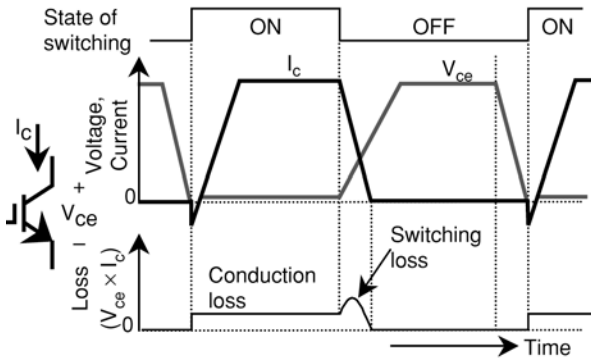


Fig. 4 Voltage, current and loss under soft-switching condition

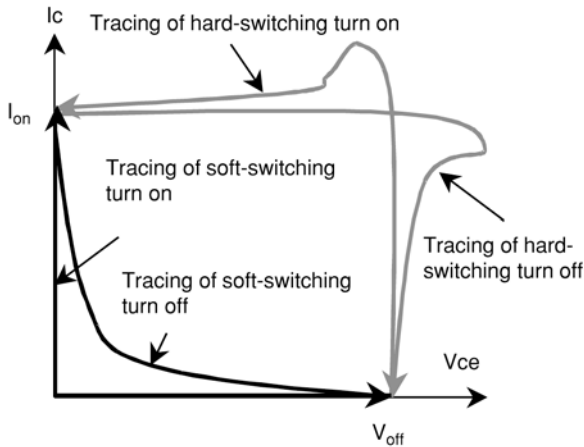


Fig. 5 Lissajous waveform of I_c and V_{ce}

reach zero together, allowing the loss to be eliminated. During turn-off, losses are lessened by the reduction in voltage and current overlap, as the changes in voltage are moderated by the condenser at both ends of the switch. As shown in Fig. 5, the Lissajous waveforms of current and voltage during turn-on and turn-off have come closer to the axes than during hard-switching. It is not possible to completely eliminate losses during turn-off, but it is clear that they are much smaller than during hard-switching.

3.2. Circuit Topology

There are many circuit topologies for reducing losses^{(1) (2)} besides the soft-switching method shown in Fig. 4. One performs switching when the current has been brought to zero at both turn-on and turn-off; another does so when the voltage across not only the semiconductor switching device but also the entire inverter has been brought to zero. Representative examples will be described in this section.

The resonant DC link inverter shown in Fig. 6(a) uses the method of an LC resonant circuit inserted between the power

supply and the inverter. The resonant circuit changes the input voltage to the inverter to a sinusoidal shape using the resonant circuit, and switching is done when the voltage across the inverter reaches zero. Switching losses are reduced; however, this circuit is still vulnerable to some issues. The voltage in the resonant circuit depends on the load current and cannot be assumed always to reach zero, and the resonance can increase the voltage to several times that of the power supply. At present, improved versions of this circuit have been proposed. The auxiliary resonant tank (ART) inverter shown in Fig. 6(b) is one of these. The auxiliary resonant circuit is inserted in the DC side of the inverter, and does not produce voltages exceeding that of the power supply. It can reduce the voltage to zero at switching time. A 100 kW class version of this circuit is already being used in the field, as the inverter for the motor drive circuit of an electric bus in the United States⁽³⁾. There are many DC link inverters besides the above, including those with a clamp switch inserted between the power supply and the inverter to isolate the inverter and power supply during switching^{(1) (2)}, but they are considered better for low-power applications because clamp switches have conduction losses.

In the auxiliary resonant commutated pole (ARCP) inverter, shown in Fig. 6(c), the auxiliary resonant circuits are inserted between the DC and the AC side, in contrast to the DC link inverter described above. Turn-off in this circuit is performed at zero voltage, maintained by condensers on both sides of the semiconductor switching device; during turn-on, current is passed from auxiliary resonant circuits to free wheeling diodes, allowing switching at zero voltage and zero current. The waveforms of voltage and current from this semiconductor switching device are those presented in Fig. 4. Since there are no components between the power supply and the inverter in this circuit, in contrast to the DC link circuit, it is suited to handling high power applications, and it allows separate PWM control of each phase. However, a condenser is necessary to maintain the neutral DC voltage point, and under high power applications, a very large condenser is needed.

The resonant snubber inverter⁽⁴⁾ (RSI), shown in Fig. 6(d), has an auxiliary resonant circuit on the AC side. This type does not need the condenser to hold the neutral point required by the previous circuit, and since it has no components on the DC side, it suffers no losses there. It is considered to be suited for high power applications. As in the ARCP inverter, switching is through zero voltage at turn-off, due to condensers, and at turn-on, auxiliary resonant circuits containing free wheeling diodes enable switching through zero current and voltage. However, this circuit does not have the ARCP circuit's capacity for isolated switching of each phase. At least two phases must be switched simultaneously, complicating PWM output during three phase control.

The circuits shown in Figs. 6(a)-(d) all fit into the classification of zero-voltage switching, as they all feature zero voltage potential at both ends of the switching device during switching. In contrast, the zero current transition (ZCT) inverter^{(5) (6)} shown in Fig. 6(e) fits into the classification of zero-current switching. Since no current flows through the semiconductor switching devices during switching in this circuit, switching losses are completely eliminated during both turn-on and turn-off.

Figure 6(f) shows the newest version, soft-switching circuit with the zero current and zero voltage transition (ZCZVT) inverter. This circuit allows switch current and voltage of zero at both turn-on and turn-off⁽⁷⁾.

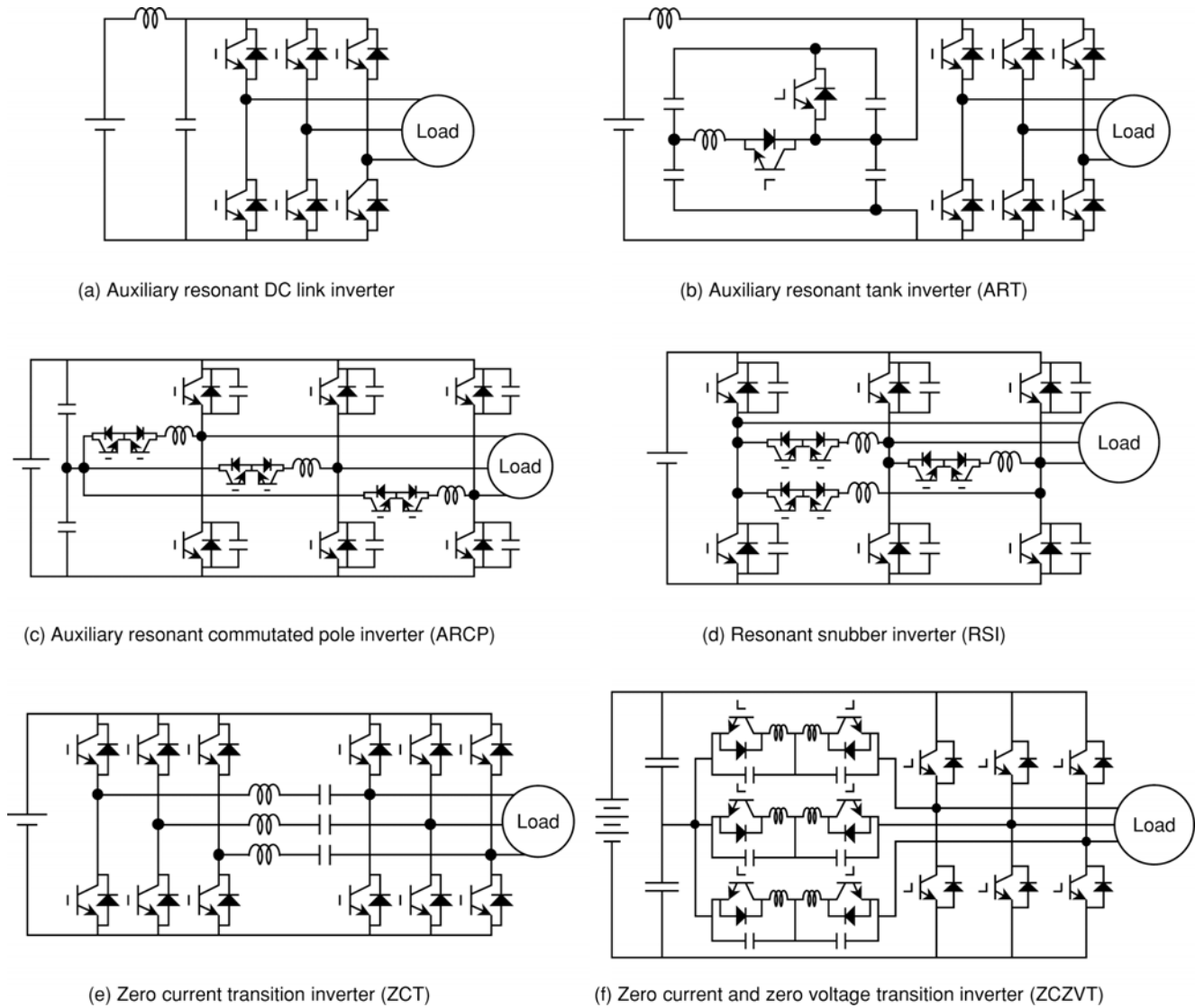


Fig. 6 Soft-switching inverter circuits

4. Single Inductor Auxiliary Resonant AC Link Inverter

The single inductor auxiliary resonant AC link inverter proposed in this paper is pictured in Fig. 7. This circuit is superior to the RSI in both suitability for high power applications and its small number of auxiliary resonant circuit components. It has just a single inductor. It has the smallest number of components of any AC link inverter.

4.1. Principle of Operation

The operation of the single inductor auxiliary resonant AC link inverter will be described using a single-phase circuit. Figure 8 provides the circuit diagram, the designations of the elements, and symbols. The explanation will begin with the circuit as shown in Fig. 10(a), where S_2 and S_3 are on and current is being supplied to the load. Those switches are turned off, transforming the condition to that shown in Fig. 10(e), with continuity through D_1 and D_4 ; subsequently, the circuit is returned to the condition of

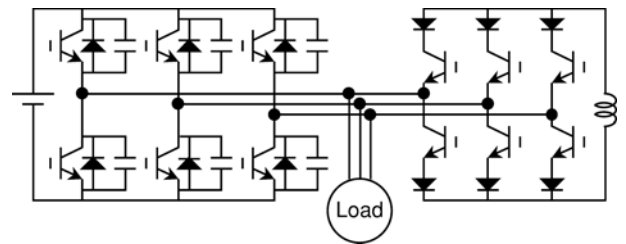


Fig. 7 Single inductor auxiliary resonant AC link inverter

Fig. 10(a), completing the cycle. Since the load current flowing through the inductor is nearly constant, it functions as a current source. The on/off signals of the switches and the waveforms at each part are shown in Fig. 9.

Mode 1. Stationary mode 1

In Fig. 10(a), S_2 and S_3 are on and the currents are flowing as indicated at the power supply, S_2 , the load, and S_3 .

Mode 2. Inductor charging mode 1

As shown in Fig. 10(b), before turning S_2 and S_3 off, auxiliary resonant switches S_{r1} and S_{r4} are turned on and current flow is initiated through resonance inductor L_r . Since the inductance of L_r is set lower than that of the load, the current (I_{Lr}) through L_r increases quickly. S_{r1} and S_{r4} are turned on while the current is zero, so this corresponds to zero-current switching.

Mode 3. Resonant mode 1

Once I_{Lr} reaches a value sufficient to enable charge and discharge of the condenser, S_2 and S_3 are turned off. C_{r2} and C_{r3} are charged by the resonant current, as shown in Fig. 10(c), their voltage rises, and C_{r1} and C_{r4} are discharged, lowering their voltage. Then, S_2 and S_3 are turned off while

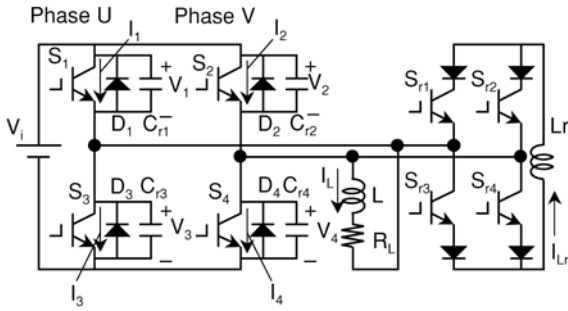


Fig. 8 Single inductor auxiliary resonant AC link inverter two phase circuit

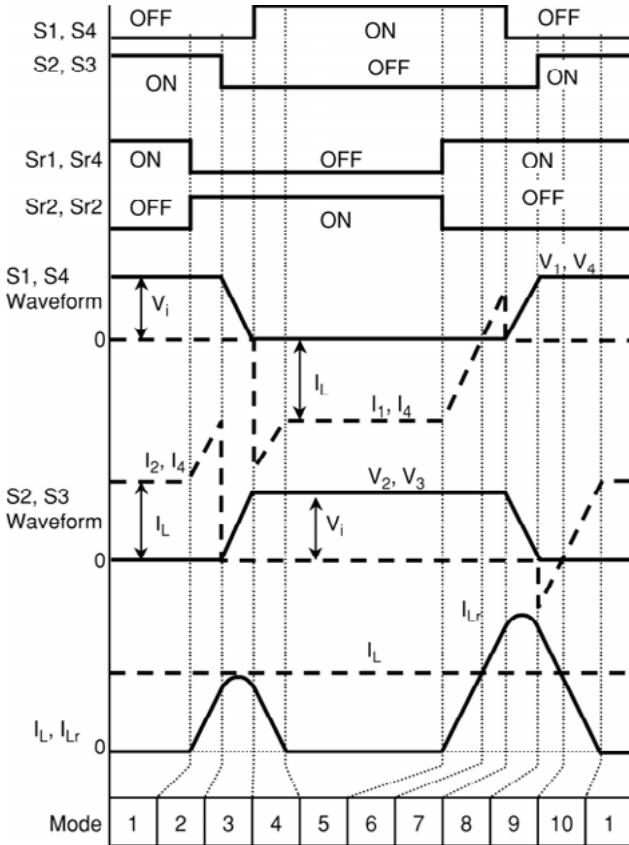


Fig. 9 Single inductor auxiliary resonant AC link inverter waveforms

the voltage is kept at zero; thus, this corresponds to zero-voltage switching.

Mode 4. Inductor discharging mode 1

When the voltages across C_{r1} and C_{r4} reach zero, diodes D_1 and D_4 become conductive, as shown in Fig. 10(d). When semiconductor switching devices S_1 and S_4 are turned on under this condition, the current passing through them is zero and the forward drop voltage is equal to those across D_1 and D_4 (≈ 0); thus, switching is accomplished at zero current and zero voltage. Since the power supply voltage V_i is applied to L_r in the opposite sense, I_{Lr} falls steadily, and when it reaches zero, the flow of current is stopped by the reverse-current blocking diodes connected to S_{r1} and S_{r2} in series. This establishes stationary mode 2. Also, switches S_{r1} and S_{r4} are turned off after I_{Lr} has reached zero, so that zero-current switching is performed.

Mode 5. Stationary mode 2

Under this condition, the load current runs through the diodes D_1 and D_4 , as shown in Fig. 10(e), and S_1 and S_4 are on.

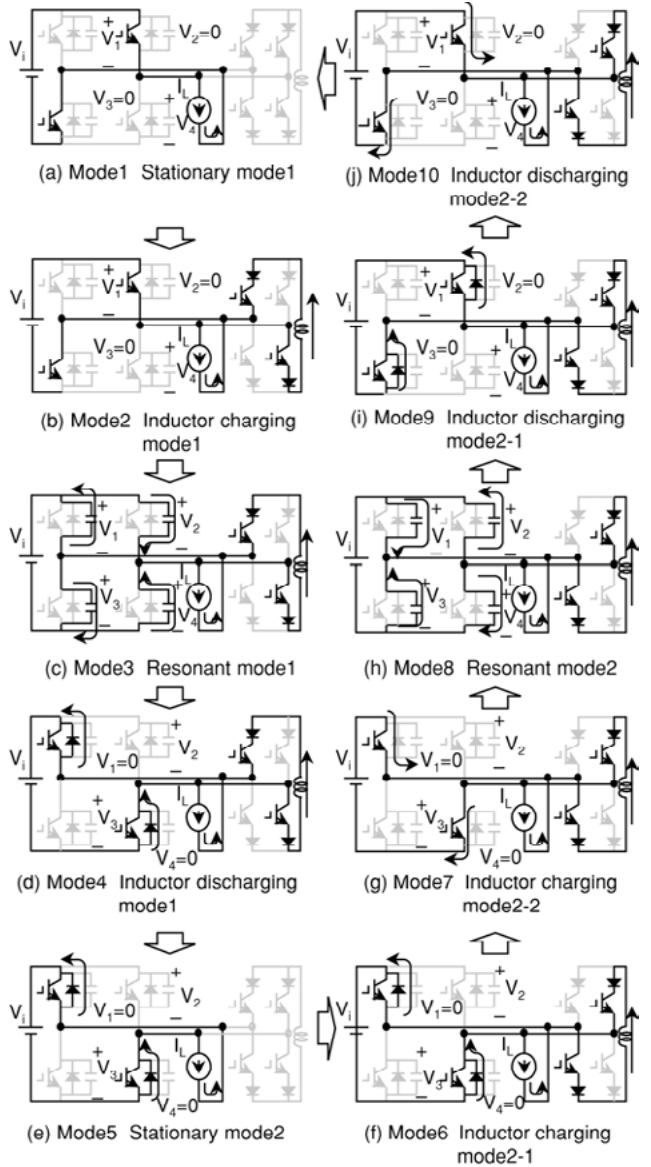


Fig. 10 Single inductor auxiliary resonant AC link inverter switching modes

Mode 6. Inductor charging mode 2-1

When the auxiliary switches S_{r2} and S_{r3} are turned on, the collector potential of S_{r3} is V_i and the emitter potential of S_{r2} is zero, so the current I_{Lr} begins to run in the resonance inductor L_r , as shown in Fig. 10(f). As with S_{r1} and S_{r4} in Mode 2, S_{r2} and S_{r3} can be switched at zero current.

Mode 7. Inductor charging mode 2-2

I_{Lr} increases, and when it exceeds the load current, the current through diodes D_1 and D_4 shown in Fig. 10(g) fall to zero, and a resonance current begins to flow in S_1 and S_4 . When I_{Lr} reaches the value sufficient for charge and discharge of the resonance capacitors, S_1 and S_4 are turned off and the next mode is reached.

Mode 8. Resonant mode 2

When S_1 and S_4 are turned off, capacitors C_{r1} and C_{r4} are charged, as shown in Fig. 10(h), increasing their voltages; meanwhile, the capacitors C_{r2} and C_{r3} , connected across S_2 and S_3 , are discharged, reducing their voltages. Since S_1 and S_4 are switched while their voltages are held at zero by the capacitors across them, this corresponds to zero-voltage switching.

Mode 9. Inductor discharging mode 2-1

As shown in Fig. 10(i), the voltage across C_{r2} and C_{r3} falls, and when it reaches zero, D_2 and D_3 become conductive. S_2 and S_3 can be turned on at this time under conditions of zero current and zero voltage. The resonance inductor is exposed to the reverse of the supply voltage V_i , so the current I_{Lr} begins to decrease.

Mode 10. Inductor discharging mode 2-2

When the currents entering D_2 and D_3 fall to zero due to the decrease of I_{Lr} , current begins to flow through the semiconductor switching devices S_2 and S_3 , as shown in Fig. 10(j). Once I_{Lr} drops to zero, it is blocked by the reverse-current blocking diodes and stops flowing, and the circuit reverts to Mode 1. S_{r2} and S_{r3} can be switched on after I_{Lr} is zero, under zero-current conditions.

The above shows the process of soft-switching. From Mode 2, when the load current and resonant current flow in the same direction, through Mode 3, if the current from charging and discharging the capacitor is flowing into the load, switching at zero voltage can be performed without activity in the auxiliary resonant circuit. In the following, this control method will be called 'soft-switching with non-resonant operation'.

4.2. Explanation of 3-Phase Operation

In contrast to the ARCP circuit shown in Fig. 6(c), the DC link inverters and some other circuits which allow isolated switching of each phase, soft-switching inverters with auxiliary resonant circuits on the load side such as the RSI shown in Fig. 6(d) and the single inductor auxiliary resonant AC link inverter shown in Fig. 7, cannot supply current to auxiliary resonant circuits unless at least two phases are switched simultaneously. This was shown in Fig. 10. Soft-switching is not possible if only a single phase is switched; the process is then equivalent to hard-switching. Also, when switching is done while all three phases are conductive on either the high side or the low side, it is impossible to supply current to the auxiliary resonant circuit. This places limits on how the conductive and off conditions can be changed. It is easier to consider the method of switching under AC link PWM control if the vector diagram in Fig. 11 is used.

Consider the condition for each phase as 1 when the high side is on and the low side is off, and 0 when the low side is

on and the high side is off; the phases are expressed in the order U, V, W from left to right. Then, the complete conduction pattern is as shown by the vectors in Fig. 11. The limitations on the conduction pattern of the AC link inverter are that (1) soft-switching cannot be done when the output conditions are 111 or 000, and (2) because soft-switching requires switching on the high and low sides on at least 2 phases, it is not possible to move directly from one phase on the vector space to a neighboring phase. For example, when the motor is set to the rotor position between vector 100 and vector 110 in Fig. 11, this can be obtained under hard-switching by voltage commands of $100 \rightarrow 110 \rightarrow 000$. With the AC link inverter, the following conduction pattern is followed: Since it is not possible to reset to a neighboring phase after outputting 100, first, the vector opposite in sense to the desired vector, 001, is output; then, vector 110 is output. As shown in Fig. 12, the same result as with the vector 000 in hard-switching is obtained in soft-switching by outputting 110 and 001 for the same time to cancel each other out.

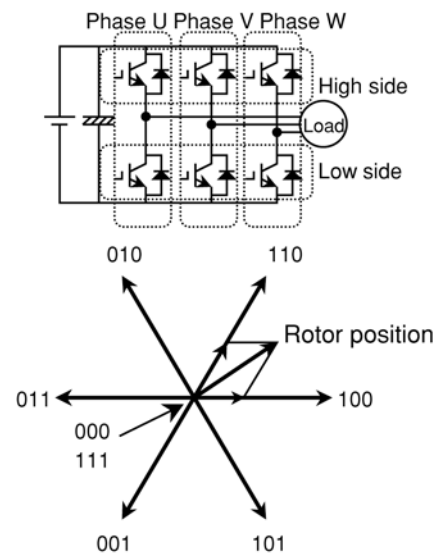


Fig. 11 Command voltage vector diagram

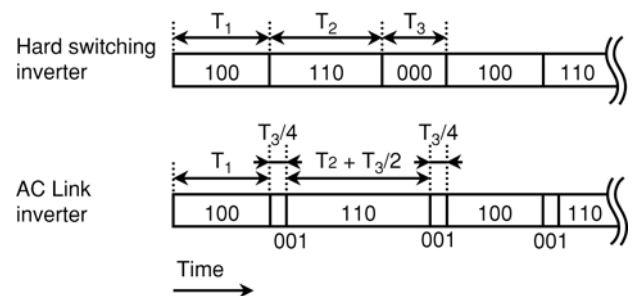


Fig. 12 Comparison of command voltage control

4.3. Experimental Results

4.3.1. Waveforms in each operation

Figure 13 shows the current waveform at the load for the three phases output by the single inductor auxiliary resonant AC link inverter. It is possible to obtain a sine wave of output current using the conduction pattern shown in the lower part of Fig. 12. Also, Fig. 14 shows the waveforms of voltage and current at the semiconductor device during turn-off under hard and soft-switching. Changes in voltage are moderated under soft-switching and surge voltage is suppressed. However, oscillation occurred in the voltage waveform because resonance condensers were attached. It was confirmed that this oscillation could be reduced by attaching the resonance condensers to the semiconductor switching devices with the shortest possible leads. By creating semiconductor modules for soft-switching which include resonance condensers in the semiconductor switching device

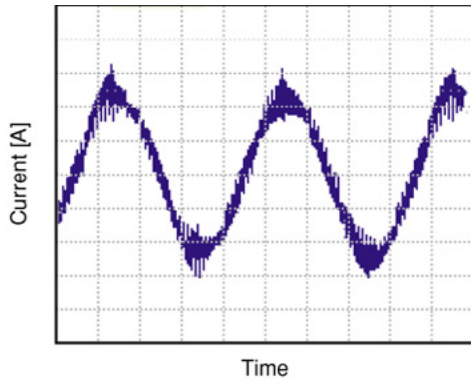


Fig. 13 Load current of 3 phase AC link soft-switching inverter

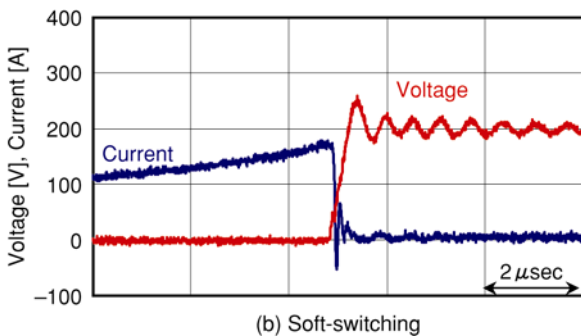
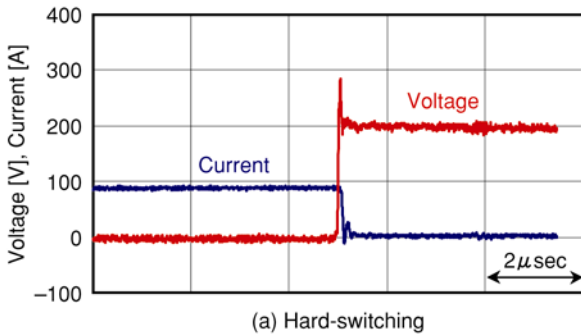


Fig. 14 Voltage and current at turn off

package, it is expected to be possible to reduce the oscillations. However, since the resonance condensers in this configuration are physically close to the semiconductor switching devices, which emit heat, they must be of a heat-resistant type.

4.3.2. Efficiency

Figure 15 shows the results of measurements of efficiency under hard-switching and the single inductor auxiliary resonant AC link inverter. As in the noise measurements, described below, the hard-switching measurements were taken by removing the resonant circuits from the single inductor auxiliary resonant AC link inverter. First, it was found that soft-switching yielded a higher efficiency than hard-switching in the high load region above 3.2 kW; on the other hand, efficiency was lower than in hard-switching in the low load region. One of the causes of the inferior efficiency is that resonance current is superimposed on the load current, so it appears that conduction losses are higher than in hard-switching. Because of this, the previously described non-resonant operation can be used to expand the range over which efficiency can be improved. Nevertheless, at very low load levels, the load current is too small to charge and discharge the condensers, necessitating operation of auxiliary resonant circuit, so efficiency cannot be improved here.

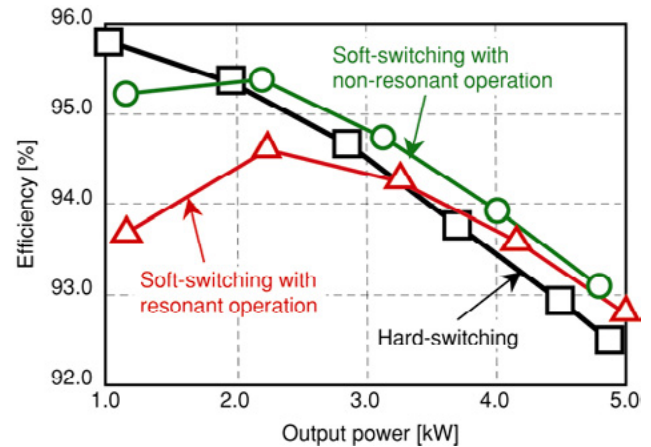


Fig. 15 Comparison of inverter efficiency

4.3.3. Noise

Conduction noise (common mode) was measured using a line impedance stabilization network and radiation noise was measured using an electric field probe. Figure 16 provides the results for measurements of conduction noise. The conduction noise levels under soft-switching with resonant operation was several dB worse than under hard-switching in the several hundred kHz and several MHz bands, but otherwise, noise levels were lower at frequencies up to 30 MHz. The reason for the higher noise was the superimposition of the resonance current on the load current mentioned above, causing higher currents than under hard-switching. This was successfully countered at all frequencies but a small band at several MHz with non-resonant operation. The reason for the persistent noise in this band was oscillation by the resonance condensers attached at both sides of the semiconductor switching

devices, as shown in Fig. 14(b).

Figure 17 shows the results of measurements of radiation noise. As a result of suppression of the rate of change of voltage and current in all the circuit components, the noise levels under soft-switching were lower at all frequency bands under 30 MHz than those under hard-switching. Noise reduction was effective, with a maximum decrease of about 20 dB.

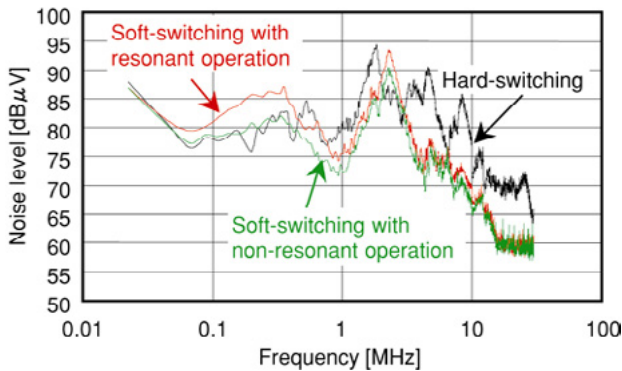


Fig. 16 Conduction noise

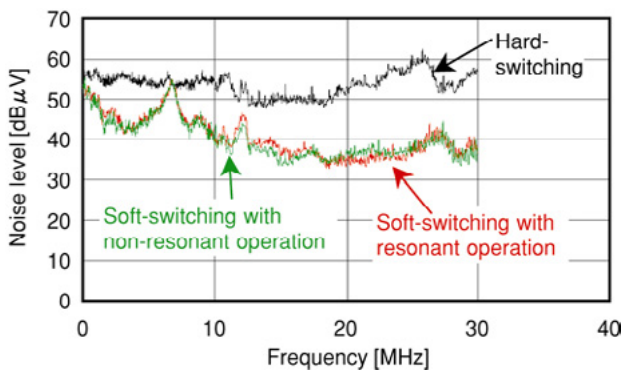


Fig. 17 Radiation noise

5. Conclusion

Efficiency and noise were compared under the single inductor auxiliary resonant AC link inverter and hard-switching and the following results were obtained.

- (1) The efficiency under soft-switching was enhanced in the high load region over that under hard-switching, but in the low load region, the efficiency was degraded. Using non-resonant operation allowed improved efficiency throughout the load range when the load current and resonance current flowed in the same direction. An improvement in efficiency of 0.5% over hard-switching was found in the high load range.
- (2) Conduction noise was reduced to lower levels under soft-switching than under hard-switching, except for the frequency bands of several hundred kHz and several MHz. Noise was also reduced to levels lower than under

hard-switching in the several hundred kHz band by using non-resonant operation.

- (3) Radiation noise under soft-switching was reduced at all frequencies below 30 MHz than under hard-switching. The maximum reduction was approx. 20 dB.

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