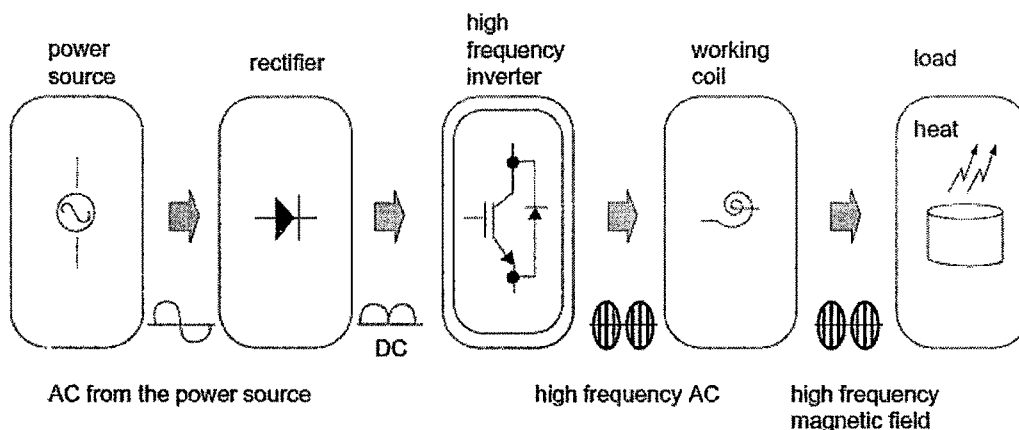


# Chapter 3

## DESIGN AND IMPLEMENTATION OF A QUASI-RESONANT CONVERTER

### 3.1 Introduction

The concept of induction heating employed in the application of gold melting can be simplified as the following. First, convert the AC current coming from the power source to DC using a rectifier. Then, connect this DC current to a high frequency switching circuit to administer high frequency current to the heating coil. According to the Ampere's Law, a high frequency magnetic field is created around the heated coil. If a conductive object, e.g. the graphite crucible with gold/silver metal, is put inside the magnetic field, induced Voltage and Eddy current is created on the skin depth as a result of Skin Effect and the Faraday's Law, generating heat energy.



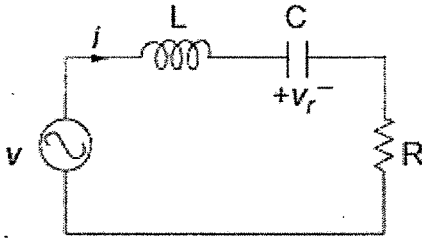
**Figure 3-1 Operating Principle**

Increasing the frequency of operation of power converters is desirable, as it allows the size of magnet circuit and capacitors to be reduced, leading to cheaper and more compact circuits. However, increasing the frequency of operation also increases switching losses and hence reduces system efficiency. One solution to this problem is to replace the "chopper" switch of a standard SMPS topology (Buck, Boost etc.) with a "resonant" switch, which uses the resonances of circuit capacitances and inductances to shape the waveform of either the current or the voltage across the switching element, such that when switching takes place, there is no current through or voltage across it, and hence no power dissipation.

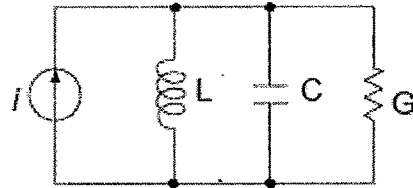
A circuit employing this technique is known as a resonant converter (or, more accurately, a quasi-resonant converter, as only part of the resonant sinusoid is utilized).

### 3.2 Resonant Converter

The resonant circuit of a resonant converter consists of a capacitor, an inductor, and resistance and there are two types of resonant converter generally used: a series resonant circuit and a parallel resonant circuit.



**Figure 3-2a Series Resonant**



**Figure 3-2b Parallel Resonant**

Figure 3-2a & 3-2b shows these two common types. When power is connected, electric energy as in Equation 3-3 is stored in the inductor and transferred to the capacitor. Equation 3-4 simplifies the calculation of the amount of the energy stored in the capacitor, to be sent to the inductor. Resonance occurs while the inductor and the capacitor exchange the energy. And the total amount of energy stored in the circuit during resonance remains unchanged. This total amount is the same as the amount of energy in peak stored in the inductor or capacitor.

$$i = \sqrt{2}I \sin \omega t \text{ [A]} \quad (\text{Equation 3-1})$$

$$V_c = -\frac{\sqrt{2}I}{\omega C} \cos \omega t \text{ [V]} \quad (\text{Equation 3-2})$$

$$E_L = \frac{1}{2} Li^2 = LI^2 \sin^2 \omega t \text{ [J]} \quad (\text{Equation 3-3})$$

$$E_C = \frac{1}{2} CV_c^2 = \frac{I^2}{\omega^2 C} \cos^2 \omega t = LI^2 \cos^2 \omega t \text{ [J]} \quad (\text{Equation 3-4})$$

$$E_L + E_C = LI^2 (\sin^2 \omega t \cos^2 \omega t) = LI^2 \frac{I^2}{\omega^2 C} \text{ [J]} \quad (\text{Equation 3-5})$$

As, some energy is lost by the resistance in the process of resonance, the total amount of energy stored in the inductor decrements in each resonant exchange. The resonance frequency, which is the speed of energy transfer, is determined by capacitance (C) and inductance (L) as in Equation 3-9.

### Chapter 3 DESIGN AND IMPLEMENTATION OF A QUASI-RESONANT CONVERTER

The inductive reactance and the capacitive reactance are summarized in Equation 3-6, and 3-7, respectively, and the size of impedance in a series resonant circuit is determined as in Equation 3-8.

$$X_L = j2\pi fL \quad (\text{Equation 3-6})$$

$$X_C = \frac{1}{j2\pi fC} \quad (\text{Equation 3-7})$$

$$|Z| = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2} \quad (\text{Equation 3-8})$$

At the resonance frequency, the inductive reactance of Equation 3-6 and the capacitive reactance of Equation 3-7 become the same, i.e. the voltage of the power source and the current in the circuit stay on the same level. The resonance frequency can be summarized as in Equation 3-9. The current in the circuit reaches its peak when the source frequency becomes identical to the resonance frequency. It decrements when the source frequency gets higher or lower than the resonance frequency.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \text{ [Hz]} \quad (\text{Equation 3-9})$$

And the selection ratio of a half-bridge series resonant circuit is as in the following Equation 3-10.

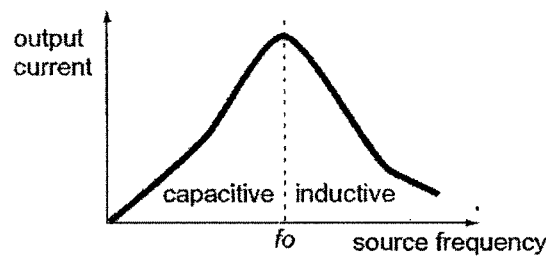
$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR} = \frac{Z}{R} \quad (\text{Equation 3-10})$$

As shown in the formula above, the smaller becomes the resistance than the inductance, i.e. when the source frequency gets closer to the resonance frequency, the sharper gets the frequency curve of Figure 3-3 and the bigger becomes the value of Q. The numerator is the energy accumulated in the inductor during resonance and the denominator is the average amount of energy consumed in resistance in each cycle. The frequency curve below demonstrates the relationship between current/output energy and the source frequency when the source voltage of the resonant circuit is set equal. The current and output energy reaches its maximum value at the resonance frequency.

In the area where the switching frequency is lower than the resonance frequency, the inductive reactance has a direct relationship with the switching frequency, in other words, the lower the frequency, the smaller the inductive reactance. And according to Equation 3-7, the capacitive reactance is in inverse relationship with the frequency. As the reactance becomes more capacitive, the current gets higher than the voltage in status. When the switching frequency increases (in Equation 3-8), impedance gets bigger, enlarging the amount of output energy as in Figure 3-3. In the opposite

situation, a lower switching frequency leads to smaller impedance, causing the output energy to decrement.

In the area where the switching frequency is higher than the resonance frequency, the higher the switching frequency the bigger is the inductive reactance. Here, the value of the capacitive reactance gets smaller according to Equation 3-7. The more inductive reactance causes the current to be lower than the voltage in status. In this situation, a higher switching frequency is accompanied by an increase of impedance (Equation 3-8), causing the output energy to be lower (as in Figure 3-3). When the switching frequency goes down, the impedance is decreased, raising the output energy (as in Equation 3-8).



**Figure 3-3 Frequency Curve**

### **3.3 Power System of Induction Melter**

There are two kinds of topology used in a power system, a half-bridge series resonant converter and a quasi-resonant converter. These two topologies have their own merits and demerits.

The merits of a half-bridge series resonant converter are: stable switching, low cost, and a streamlined design. As the voltage of the circuit is limited to the level of the input voltage, the switching circuit can have low internal pressure, which helps reduce the cost.

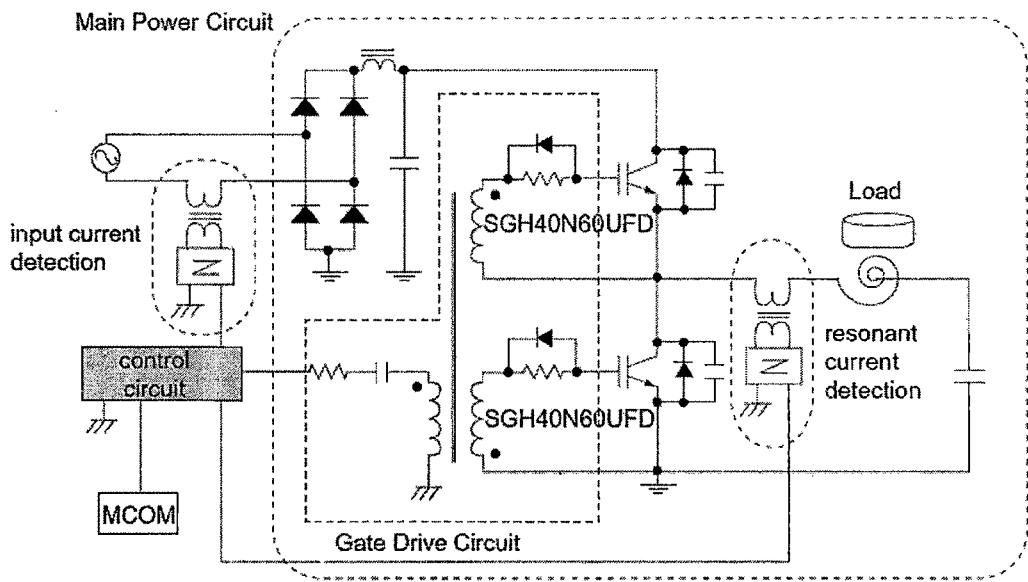
The design for the switching control part inside a circuit can be streamlined. There are also some demerits. As the half-bridge method requires two switching circuits, the overall working process becomes more complicated and the size of heat sink and PCB should be also bigger. In addition, the gate operating circuits must be insulated.

One of the merits of a quasi-resonant converter is that there needs only one switching circuit inside. This enables a relatively smaller design for the heat sink and PCB, making the working process far simpler. Another strong point is the fact that the system ground can be shared. A quasi-resonant converter is not free from defects. Most of all, switching is relatively unstable. And high internal pressure of the switching circuit, caused by the resonant voltage administered to both sides of the circuit, pushes the cost of the circuit higher. Besides, the design for the controlling part is more complicated. But as mentioned earlier, technological development in high frequency semiconductor switching devices has lead to an innovation in terms of low price, high performance, and reliability.

Quasi-resonant converters are now more generally used because of the smaller heat sink and PCB size and simpler operation process. We discuss in following section the operation of a half-bridge series resonant converter and a quasi-resonant converter.

**3.4 Half-bridge Series Resonant Converter**

A number of designing methods are available for a power system using a half-bridge series resonant converter. The power system demonstrated in Figure 3-4 is comprised of the AC power supply, main power circuit, control circuit, input current detection circuit, resonant current detection circuit, and gate operation circuit. The following figure illustrates the operation of a power system as a whole.



**Figure 3-4 Power System Using Half-bridge Series Resonant Converter**

The AC power passes through the rectifier to be transmitted to the capacitor. In this system, the leveling capacitor serves as a filter preventing the high frequency current flowing toward the inverter from entering the input part. Input current becomes the average of the inverter current, and the ripples flow to the leveling capacitor.

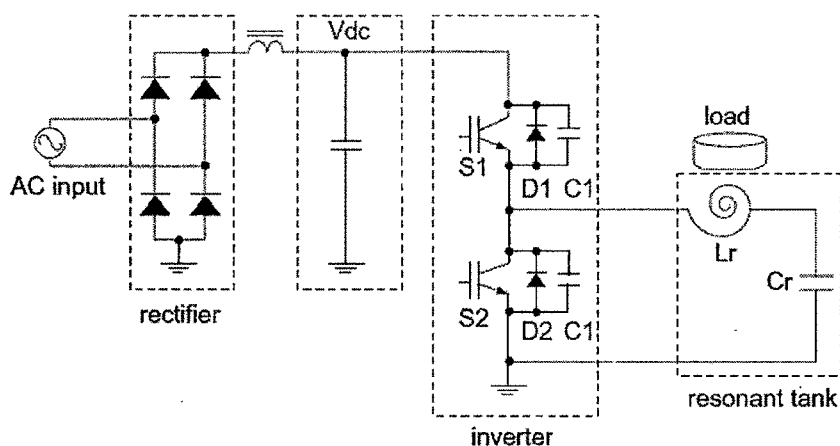
The voltage passing the leveling capacitor is turned into square wave in the process of high frequency switching in the inverter. The high frequency harmonics contained in the square wave are eliminated by the Lr, Cr filter. The square wave enables resonance in the resonant circuit, which, in turn, creates a magnetic field around the resonant inductor affecting the load. Eddy currents are formed around the surface of the object, generating heat energy.

The input current flowing through the AC input section to the rectifier and the resonant current flowing through the inverter to the resonant circuit are input to the control circuit. In order to control the maximum level of input and resonant current, the control circuit sets the switching frequency of the inverter, administering it to the gate of the inverter switch via the gate operating circuit.

Microcontroller allows the detection circuit to examine the input current to determine the presence of a conductive object, protecting the system by manipulating the on/off status of the control circuit. More detailed demonstrations of each part are presented below.

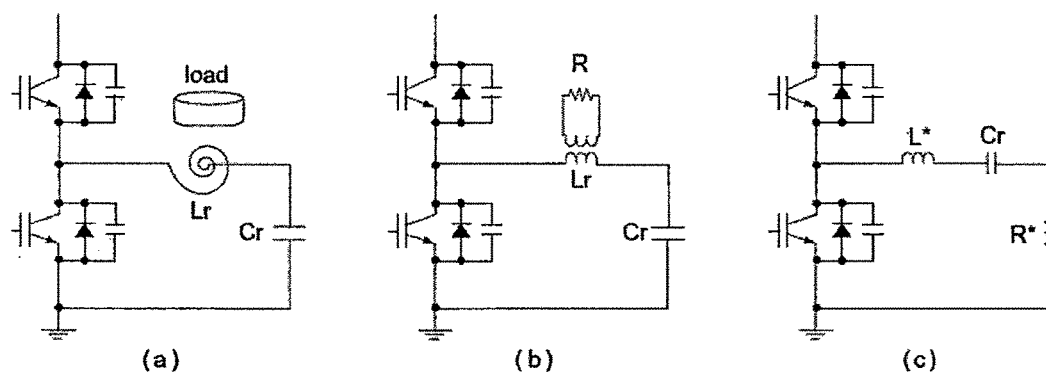
### 3.4.1 Main Power Circuit

The main power circuit employs a half-bridge series converter switching at a high frequency as shown in Figure 3-5. The switching circuit consists of an IGBT (Insulated-gate Bipolar Transistor). Zero voltage/current turn-on switching is enabled by turning on the IGBT while the diode is in turn on period. The resonant circuit comprises resonant inductance ( $L_r$ ) and resonant capacitance ( $C_r$ ). The capacitors,  $C_1$  and  $C_2$ , are the lossless turn-off snubber for the switches,  $S_1$  and  $S_2$ .



**Figure 3-5 Main Power Circuit**

Equivalent circuits to a resonant circuit are described in Figure 3-6. The load in circuit (a) is equivalent to the circuit in (b) where the transformer has resistance connected to the secondary circuit. And this can more simplified as in the circuit (c), where  $R^*$ ,  $L^*$ , and  $C_r$  are directly connected.  $R^*$  in (c) indicates the resistance of the primary circuit of the transformer converted from the secondary.  $L^*$  means the inductor on the primary side of the transformer ( $L_r$ ), which is a resonant inductor combining the leakage inductor and the secondary inductor.



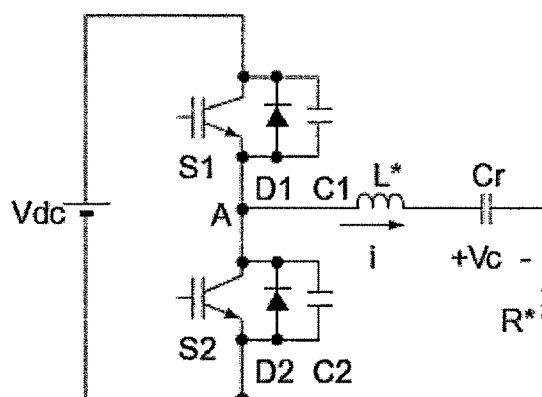
**Figure 3-6 Equivalent Circuit**

### 3.4.2 Operation Theory

By connecting the IGBT switching circuit, S1 and S2, in parallel to diodes, D1 and D2, current loss can be minimized. When S1 is turned-off, D2 helps S2 stay on zero voltage/current before being turned on, substantially reducing current loss (this is also the same case with S1). There occurs no reverse-recovery problem as the voltage on both sides remains zero after the diode is turned off.

However, as the switching circuit is turned off at around the upper limit of voltage and current, some switching loss results on turn-off. The capacitors, C1 and C2, acting as a turn-off snubber connected in parallel to S1 and S2, can check the level of this loss to a minimum level. Upon turn on, the switching circuit starts from zero voltage/current, so these turn-off snubbers operate as lossless turn-off snubbers.

The configuration of a half-bridge series resonant converter (Figure 3-5) can be simplified as an equivalent circuit illustrated in Figure 3-7. Figure 3-8 is a wave form of a frequency cycle in each part of the main power circuit. Turn on S1, when the current of the  $L^*$ - $C_r$  resonant circuit flows in opposite direction through D1 (S1 and S2 remain off).



**Figure 3-7 Equivalent of Main Power Circuit**

#### MODE I: $t_0$ - $t_1$

The resonant current flowing in inverse direction changes its direction at the point of  $t=t_0$  flowing through S1. In this mode, DC-LINK voltage of  $V_{dc}$  lets the resonant circuit accumulate energy by supplying power through S1.

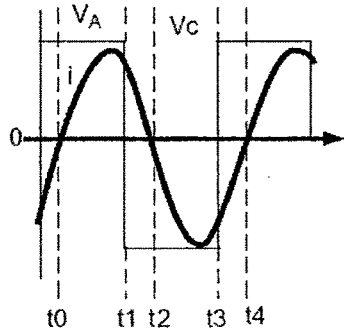


Figure 3-8 Waveforms of Main Power Circuit

#### MODE II: $t_1$ - $t_2$

When S1 is turned off at the point of  $t=t_1$ , the resonant current flowing through S1 begins freewheeling through the D2 diode. In this process, a small amount of switching turn-off loss occurs as the S1 switch is turned off while retaining some values in voltage and current. For the following mode, S2 is turned on when  $t_1 < t < t_2$ . As the S2 switch remains at zero voltage/current, no switching loss takes place upon turn-on. And the reverse-recovery of D1 does not necessarily have to be fast.

#### MODE III: $t_2$ - $t_3$

Right after  $t=t_2$ , the current freely resonates flowing in inverse direction through S2 which is already turned on. Here, the resonant capacitor,  $C_r$ , serves as a source of voltage.

#### MODE IV: $t_3$ - $t_4$

When S2 is turned off at  $t=t_3$ , the resonant current flowing through S2 starts freewheeling through the D1 diode. In this process, a small amount of switching loss occurs on turn-off. For the following mode, the S1 switch is turned on at a proper point ( $t_3 < t < t_4$ ). At this point, there happens no switching loss upon turn-on as the S1 switch remains at zero voltage/current. And the reverse-recovery of D2 does not have to be fast. In this mode, the energy of the resonant circuit is converted to  $V_{dc}$ , passing D1. The operating mode after  $t > t_4$  repeats Mode I through IV, explained above.



### 3.5 Quasi-resonant Converter

The following Figure 3-9 features a block diagram of a quasi-resonant converter in a streamlined form.

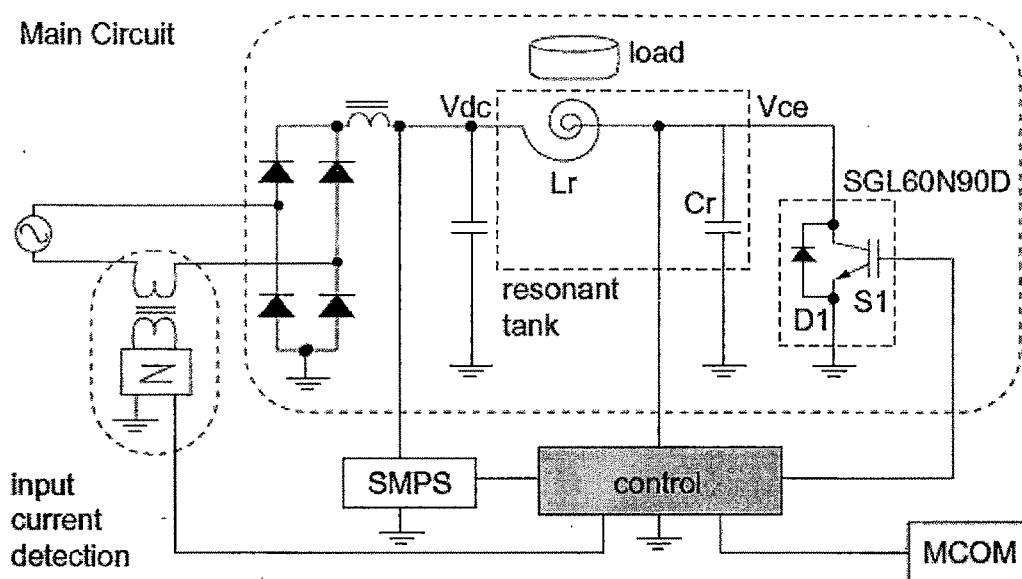


Figure 3-9 Power Circuit of Quasi-resonant Converter

The total system block is comprised of main power circuit, input current detection circuit, control circuit, and SMPS circuit, as shown in Figure 3-9. The basic operating concept of quasi-resonant circuit is similar to that of half-bridge series resonant converter in the fact that heat energy is generated. However, the methods of controlling the gate in the switching circuit are totally different. Major functions of each block are as follows.

#### 3.5.1 Main power circuit

The main power circuit features a quasi-resonant converter consisting of the IGBT and a diode connected to it in parallel the circuit executes high frequency switching. By turning on the IGBT while the diode is in turn-on it is possible to do a turn-on switching with the voltage and current remaining at zero. The resonant circuit is composed of resonant inductance ( $L_r$ ) and resonant capacitance ( $C_r$ ).

#### 3.5.2 Operating Concept

Figure 3-10 illustrates an equivalent of the main power circuit. When  $D1$ , connected to the  $S1$  switching circuit, is turn-on a zero voltage turn-on switching is available as  $V_{ce}$  of the circuit becomes zero. In this circuit, the switch must be endurable to high internal pressure to accommodate the high voltage of  $V_{ce}$  administered to the both ends of the switch.

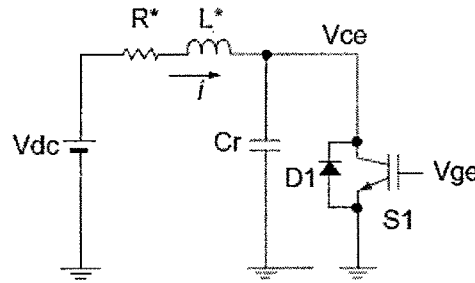


Figure 3-10 Equivalent Circuit

Figure 3-11 shows the waveforms of each block of the main power circuit in a cycle. In the initial stage, S1 is turned off by the control circuit when the current flowing through  $L^*$  and S1 reaches its peak. At this point,  $V_c(0)=0V$ . There are four modes available.

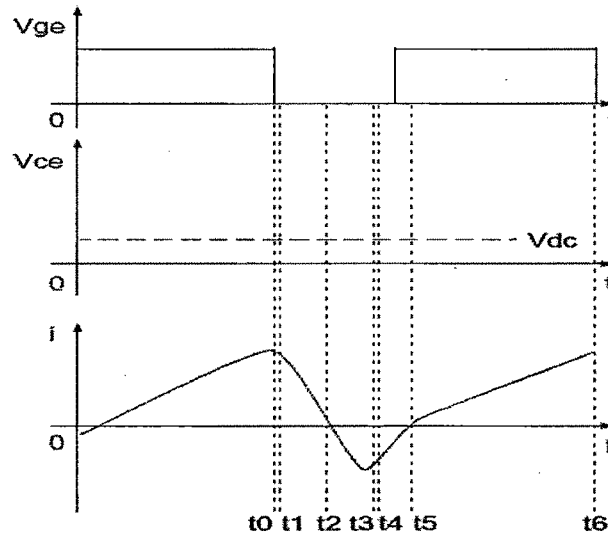


Figure 3-11 Waveforms of Main Power Circuit

#### MODE I: $t_0$ - $t_1$

As mentioned earlier, the switching circuit is turned off at the point the resonant current flowing through the circuit comes to its peak, i.e. at  $t_0$ . In this process, a turn-off switching loss occurs.  $V_{ce}$  level is rapidly increased by the capacitor ( $C_r$ ) to become DC-LINK ( $V_{dc}$ ) at  $t_1$ .

Even when the switch is turned off at  $t_0$ , the current keeps incrementing to reach its peak at  $t_1$ , when  $V_{ce}$  becomes equal to  $V_{dc}$ , as DC-LINK is higher than the resonant voltage. At this point, the energy stored in the inductor begins to be transferred to the capacitor.

#### MODE II: $t_1$ - $t_4$

As  $V_{dc}$  is lower than  $V_{ce}$  after  $t_1$ , the current decreases to be zero at  $t_2$ , when the resonant voltage reaches its maximum. This is also the point when the transfer of the energy stored in the inductor to the capacitor is completed. The peak level of the resonant voltage has a direct relationship with the turn-on time of the switch (MODE IV:  $t_5$ - $t_6$ ).

After  $t_2$ , the capacitor starts discharging the energy to the inductor, which causes the voltage and the current flowing in inverse to decrement and to reach its minimum level at  $t_3$ , i.e.  $V_{ce}=V_{dc}$ , respectively. Passing  $t_3$ , the resonant current increases as  $V_{ce}<V_{dc}$  and the discharge is completed at  $t_4$ .

**MODE III:  $t_4$ - $t_5$** 

After  $t_4$ , the energy sent by the capacitor and stored in the inductor is converted to DC-LINK as the D1 diode is forward biased. The resonant current is flowing through D1, during the time S1 is turned on.

**MODE IV:  $t_5$ - $t_6$** 

As the switching circuit remains turned on while the current is freewheeling through D1, the current flows in the right direction through the circuit and the inductor starts to store the energy, which makes it possible to do a zero voltage turn-on switching.

At  $t_6$ , the switching circuit is turned off, returning to MODE I. As the peak level of the voltage is in direct relationship with the on-duty frequency, one can manipulate this level, i.e. output energy, by adding or reducing the on-duty frequency.

### **3.6 Simulation of Quasi-resonant Converter**

Simulation results were performed using Simulink block as shown in Figure 3-12. To limit the stresses in switching device to 600V & to isolate the main supply the 3-ph ac is stepped down using a 3-ph step down transformer from 415V to 140V. This is further rectified using a 3-ph rectifier and smoothened using an inductor & capacitor. The resonant circuit is composed of resonant inductance ( $L_r$ ) and resonant capacitance ( $C_r$ ). Simulation results of dc-link voltage & the inductor current are shown in Figure 3-13.



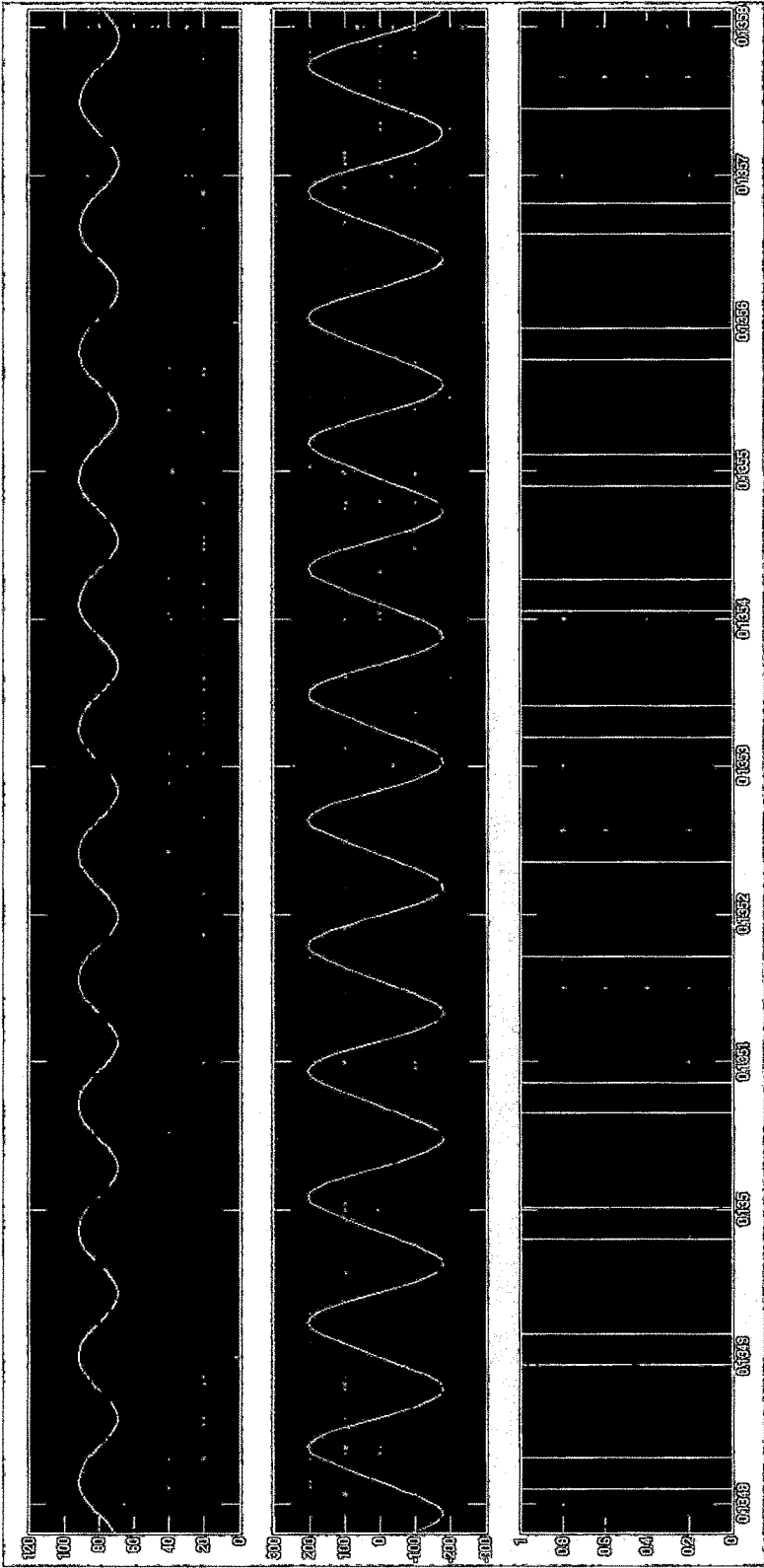


Figure 3-13 Simulation Result of Inductor Current

### **3.7 Summary**

The main findings of this chapter reveals following:

1. The half-bridge series resonant converter is having stable switching & low cost. As the voltage of the circuit is limited to the level of the input voltage, the switching circuit can have low internal pressure, which helps reduce the cost.
2. As the half-bridge method requires two switching circuits, the overall working process becomes more complicated and the size of heat sink and PCB should be also bigger. In addition, the gate operating circuits must be insulated.
3. As compared to half-bridge series resonant converter the quasi-resonant converter needs only one switching circuit inside. This enables a relatively smaller design for the heat sink and PCB, making the working process far simpler. Another strong point is the fact that the system ground can be shared.
4. In case of quasi-resonant converter the high internal pressure of the switching circuit, caused by the resonant voltage administered to both sides of the circuit, pushes the cost of the circuit higher. But as mentioned earlier, technological development in high frequency semiconductor switching devices has lead to an innovation in terms of low price, high performance, and reliability. Quasi-resonant converters are now more generally used because of the smaller heat sink and PCB size and simpler operation process.