Induction Heating System Topology Review

1. Introduction

All IH (induction heating) applied systems are developed using electromagnetic induction which was first discovered by Michael Faraday in 1831. Electromagnetic induction refers to the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. The basic principle of induction heating, which is an applied form of Faraday's discovery, is the fact that AC current flowing through a circuit affects the magnetic movement of a secondary circuit located near it. The fluctuation of current inside the primary circuit provided the answer as to how the mysterious current is generated in the neighboring secondary circuit. Faraday's discovery led to the development of electric motors, generators, transformers, and wireless communications devices. Its application, however, has not been flawless. Heat loss, which occurs during the induction heating process, was a major headache undermining the overall functionality of a system. Researchers sought to minimize heat loss by laminating the magnetic frames placed inside the motor or transformer. Faraday's Law was followed by a series of more advanced discoveries such as Lentz's Law. This law explains the fact that inductive current flows inverse to the direction of changes in induction magnetic movement.

Heat loss, occurring in the process of electromagnetic induction, could be turned into productive heat energy in an electric heating system by applying this law. Many industries have benefited from this new breakthrough by implementing induction heating for furnacing, quenching, and welding. In these applications, induction heating has made it easier to set the heating parameters without the need of an additional external power source. This substantially reduces heat loss while maintaining a more convenient working environment. Absence of any physical contact to heating devices precludes unpleasant electrical accidents. High energy density is achieved by generating sufficient heat energy within a relatively short period of time.

The demand for better quality, safe and less energy consuming products is rising. Products using IH include electronic rice cookers and pans. Safe, efficient and quick heating appliances attract more customers. This document describes induction heating, power systems, and IH applications.

2. Types of Electric Process Heating

Prior to describing induction heating, some types of electric process heating are explained below to help you understand normally used heat sources.

The types of electric heating are as follows:

- Resistance Heating
- Conduction Heating
- Infrared Radiation Heating
- **Induction Heating**
- Dielectric Hysteresis Heating
- Electric Arc Heating
- Plasma Heating
- Electron Beam Heating
- Laser Heating

Resistance heating is the most common type of electric process heating. It uses the relationship between the voltage and current of resistance in Joule's Law.

Conduction heating exploits the heat energy generated when an object is placed between two electric poles, which is another application of Joule's Law. In this case, however, a different relationship exists between voltage and current, especially when the circuit current is high, because the object itself contains both resistance and inductance features.

The main topic of this document is induction heating, which is a combination of electromagnetic induction, the skin effect, and the principle of heat transfer. In short, induction heating refers to the generation of heat energy by the current and eddy current created on the surface of a conductive object (according to Faraday's Law and the skin effect) when it is placed in the magnetic field, formed around a coil, where the AC current flows through (Ampere's Law). Detailed descriptions of induction heating are presented in the following sections of the document.

3. Basics of Induction Heating

Induction heating is comprised of three basic factors: electromagnetic induction, the skin effect, and heat transfer. The fundamental theory of IH, however, is similar to that of a transformer. Electromagnetic induction and the skin effect are described in this section. Figure 3-1 illustrates a very basic system, consisting of inductive heating coils and current, to explain electromagnetic induction and the skin effect. Figure 3-1-a shows the simplest form of a transformer, where the secondary current is in direct proportion to the primary current according to the turn ratio. The primary and secondary losses are caused by the resistance of windings and the link coefficient between the two circuits is 1. Magnetic current leakage is ignored here.

When the coil of the secondary is turned only once and short-circuited, there is a substantial heat loss due to the increased load current (secondary current). This is demonstrated in Figure 3-1-b. Figure 3-1-c shows a system where the energy supplied from the source is of the same amount as the combined loss of the primary and secondary. In these figures, the inductive coil of the primary has many turns while the secondary is turned only once and short-circuited. The inductive heating coil and the load are insulated from each other by a small aperture. The next phase of the skin effect occurring under high frequency is presented in Section 3-2.

As the primary purpose of induction heating is to maximize the heat energy generated in the secondary, the aperture of the inductive heating coil is designed to be as small as possible and the secondary is made with a substance featuring low resistance and high permeability. Nonferrous metals undermine energy efficiency because of their properties of high resistance and low permeability.
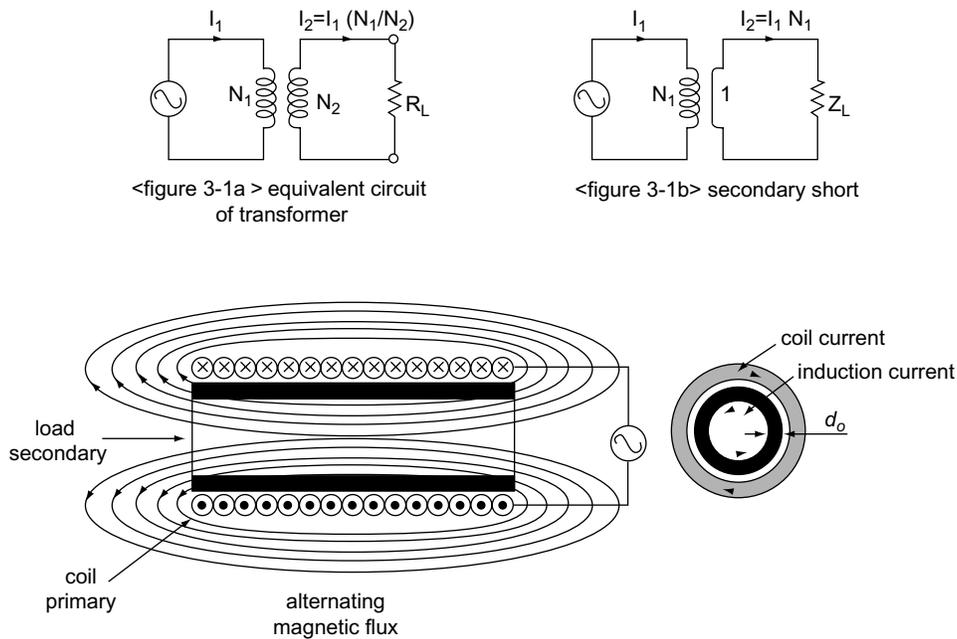
<figure 3-1a > equivalent circuit of transformer

<figure 3-1b> secondary short

Figure 3-1: Basics of Induction Heating

3-1. Electromagnetic Induction

As shown in Figure 3-1, when the AC current enters a coil, a magnetic field is formed around the coil according to Ampere's Law.

$$\int Hdl = Ni = F$$
$$\varnothing = \mu HA$$

(Formula 3-1)

An object put into the magnetic field causes a change in the velocity of the magnetic movement. The density of the magnetic field wanes as the object gets closer to the center from the surface. According to Faraday's Law, the current generated on the surface of a conductive object has an inverse relationship with the current on the inducting circuit as described in Formula 3-2. The current on the surface of the object generates an eddy current.

$$E = \frac{d\lambda}{dt} = N\frac{d\varnothing}{dt} \qquad \text{(Formula 3-2)}$$

As a result, the electric energy caused by the induced current and eddy current is converted to heat energy as shown in Formula 3-3.

$$P = E^2/R = i^2R \qquad \text{(Formula 3-3)}$$

Here, resistance is determined by the resistivity (ρ) and permeability (μ) of the conductive object. Current is determined by the intensity of the magnetic field. Heat energy is in an inverse relationship with skin depth which is described in Section 3-2.

If an object has conductive properties like iron, additional heat energy is generated due to magnetic hysteresis. The amount of heat energy created by hysteresis is in proportion to the size of the hysteresis. In this document, this additional energy is ignored because it is far smaller (less than 10%) than the energy generated by induction current.

3-2. Skin Effect

The higher the frequency of the current administered to the coil, the more intensive is the induced current flowing around the surface of the load. The density of the induced current diminishes when flowing closer to the center as shown in Formula 3-4 and 3-5 below. This is called the skin effect or kelvin effect. From this effect, one can easily infer that the heat energy converted from electric energy is concentrated on the skin depth (surface of the object).

$$i_x = i_o e^{-x/d_o} \qquad \text{(Formula 3-4)}$$

where, i_x: distance from the skin (surface) of the object, current density at x.
I_o: current density on skin depth (x=0)
d_o: a constant determined by the frequency (current penetration depth or skin depth)

$$d_o = \sqrt{\frac{2\rho}{\mu\omega}} \qquad \text{(Formula 3-5)}$$

where, ρ: resistivity
μ: permeability of the object
ω: Frequency of the current flowing through the object

Formula 3-5 states that the skin thickness is determined by the resistivity, permeability, and frequency of the object. Figure 3-2 below is the distribution chart of current density in relation to skin thickness.
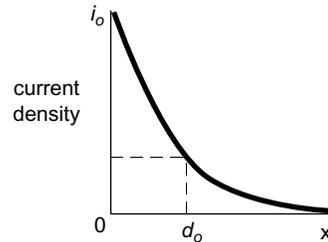

Figure 3-2: Distribution Chart of Current Density and Skin Thickness

4. Topology Of Power System

Generally, semiconductor switching devices operate in Hard Switch Mode in various types of PWM DC-DC converters and DC-AC inverter topology employed in a power system. In this mode, a specific current is turned on or off at a specific level of voltage whenever switching occurs, as shown in Figure 4-1. This process results in switching loss. The higher the frequency the more the switching loss, which obstructs efforts to raise the frequency. Switching loss can be calculated in a simple way as shown in Formula 4-1 below. Switching also causes an EMI problem, because a large amount of di/dt and dv/dt is generated in the process.

$$P_{SW} = \frac{1}{2}V_{SW}I_{SW}f_S(t_{on} + t_{off}) \qquad \text{(Formula 4-1)}$$

where, P_{sw} : switching loss [W]

       V_{sw} : switching voltage [V]

       I_{sw} : switching current [A]

       f_S : switching frequency [kHz]

       t_{on} : switch turn-on time [s]
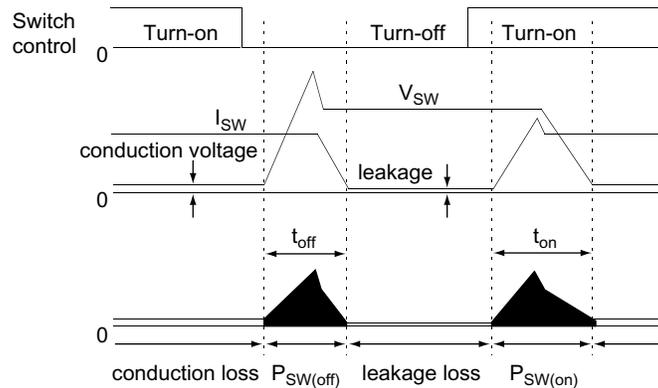
       t_{off} : switch turn-off time [s]

Figure 4-1: Wave Form of a Switching Device

By raising the switching frequency, you can reduce the size of a transformer and filter, which helps build a smaller and lighter converter with high power density. But as presented earlier, switching loss undermines the efficiency of the entire power system in converting energy, as more losses are generated at a higher frequency. Switching loss can be partly avoided by connecting a simple snubber circuit parallel to the switching circuit. However, the total amount of switching loss generated in the system remains the same. The loss avoided, has in fact, just moved to the snubber circuit.

Higher energy conversion efficiency at high frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero. This is called "Soft Switching", which can be subcategorized into two methods: Zero-voltage switching and Zero-current switching. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turning it off. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This topology is named a "resonant converter."

In Zero-current switching, the existing inductance is absorbed into the resonant circuit, eliminating the surge in voltage in a turn-off situation. A voltage surge resulting from an electric discharge of junction capacitance, which occurs upon turning on the switching circuit, cannot be avoided. This method has a defect of causing switching loss ($0.5CV^2f$). Zero-voltage switching, however, is free from such a defect by making both the existing inductance and capacitance to be absorbed by the resonant circuit. This eliminates any chance of causing a surge in current both at turn-off (caused by inductance) or turn-on (by capacitance) conditions. Zero-voltage switching enables switching with less loss while substantially reducing the problem of EMI at high frequency. This difference in features make Zero-voltage switching more desirable than Zero-current switching.

As a resonant converter provides most of the energy conversion efficiency in a power system by minimizing switching loss, it is widely used in a variety of industries. And this is also the reason why the converter is adopted in the Induction Heating Power System Topology, which is described in detail in this document. Power systems for home appliances, e.g. electronic rice cookers, and other kinds of cookers, generally employ a ZVS (Zero-voltage switching) resonant converter, which can be further classified into two major types: a half-bridge series resonant converter and a quasi-resonant converter. These types of topology are studied in detail in section 5 of this document.

Resonant Converter

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

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

$$i = \sqrt{2}I \sin \omega t [A] \qquad \text{(Formula 4-1)}$$

$$V_C = \frac{1}{C}\int i dt = -\frac{\sqrt{2}I}{\omega C}\cos \omega t [V] \qquad \text{(Formula 4-2)}$$

$$E_L = \frac{1}{2}Li^2 = LI^2 \sin^2 \omega t [J] \qquad \text{(Formula 4-3)}$$

$$E_C = \frac{1}{2}CV_C{}^2 = \frac{I^2}{\omega^2 C}\cos^2 \omega t = LI^2 \cos^2 \omega t [J] \qquad \text{(Formula 4-4)}$$

$$E_L + E_C = LI^2(\sin^2 \omega t \cos^2 \omega t) = LI^2 \frac{I^2}{\omega^2 C}[J] \qquad \text{(Formula 4-5)}$$

As some energy is lost due to resistance in the resonance process, 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 shown in Formula 4-9.

The inductive reactance and the capacitive reactance are summarized in Formula 4-6, and 4-7, respectively. The size of impedance in a series resonant circuit is determined as shown in Formula 4-8.
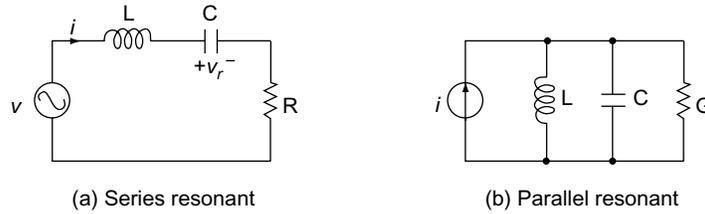

(a) Series resonant   (b) Parallel resonant

Figure 4-2: Resonant Circuit

$$X_L = j\omega L = j2\pi fL\,[\Omega] \qquad \text{(Formula 4-6)}$$

$$X_C = \frac{1}{j\omega C} = \frac{1}{j2\pi fC}[\Omega] \qquad \text{(Formula 4-7)}$$

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}\,[\Omega] \qquad \text{(Formula 4-8)}$$

At the resonance frequency, the inductive reactance of Formula 4-6 and the capacitive reactance of Formula 4-7 become the same, i.e. the voltage of the power source and the current in the circuit stay at the same level. The resonance frequency can be summarized as shown in Formula 4-9. 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.

$$2\pi fL = \frac{1}{2\pi fC} \Rightarrow f_o = \frac{1}{2\pi\sqrt{LC}}[Hz] \qquad \text{(Formula 4-9)}$$

The properties of reactance in a circuit are called special impedance, which can be described as shown in the following Formula 4-10.

$$Z_O = X_L = X_C = \omega_O L = \frac{1}{\omega_O C} = \sqrt{\frac{L}{C}}$$

$$X_O{}^2 = X_L \times X_C = \frac{L}{C} \qquad \text{(Formula 4-10)}$$

And the selection ratio of a half-bridge series resonant circuit is as shown in the following Formula 4-11.

$$Q = \frac{\omega_O L}{R} = \frac{1}{\omega_o CR} = \frac{Z_o}{R} \qquad \text{(Formula 4-11)}$$

As shown in the formula above, the smaller the resistance is than the inductance, i.e. when the source frequency gets closer to the resonance frequency, the sharper the frequency curve of Figure 4-3 and the bigger 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 source frequency when the source voltage of the resonant circuit is set at equal. The current and output energy reaches its maximum value at 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 Formula 4-7, 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 Formula 4-8), impedance gets bigger, enlarging the amount of output energy as shown in Figure 4-3. In the opposite situation, a lower switching frequency leads to a 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 the inductive reactance. Here, the value of the capacitive reactance becomes smaller according to Formula 4-7. The higher 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 (Formula 4-8), causing the output energy to be lower (as shown in Figure 4-3). When the switching frequency goes down, the impedance is decreased, raising the output energy (as in Formula 4-8).
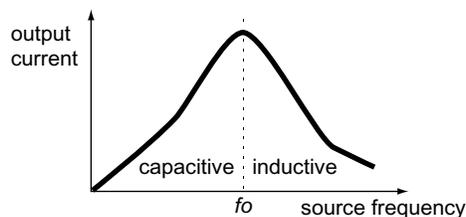

Figure 4-3: Frequency Curve

5. Induction Heating Application Systems

Advanced technology in developing semiconductor chips switching at a high frequency has made it possible to introduce new switching devices with sophisticated functions in a smaller size at a lower price. The induction heating system, once dominant only in some specific areas like guided missiles, has opened a new phase in developing highly efficient electronic home appliances, e.g. rice cookers and other kinds of cookers. This section presents the operating theory of an IH rice cooker, a power systems as a whole, and more detailed description of the controlling circuit in a power system.

5-1. Operating Theory of an IH Rice Cooker

The concept of induction heating, employed in the application of an IH rice cooker, was already explained in section 3. This concept can be simplified as follows. 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 Ampere's Law, a high frequency magnetic field is created around the heated coil. If a conductive object, e.g. the container of a rice cooker is put inside the magnetic field, then induced voltage and an eddy current are created on the skin depth of the container as a result of the skin effect and Faraday's Law. This generates heat energy on the surface of the container. Rice is cooked by using this heat energy.
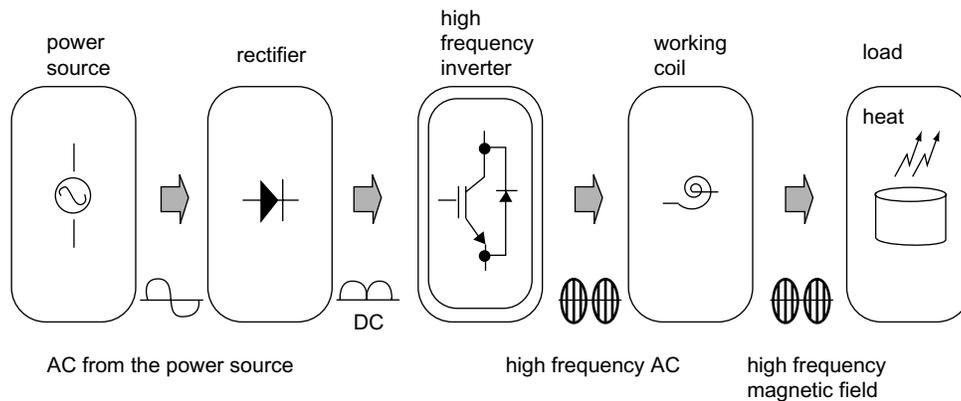
Figure 5-1: Operating Theory of IH Rice Cooker

5-2. Power System of an IH Rice Cooker

There are two types of topology used in a power system as mentioned in section 4: 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 of the switching control component, 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 the heat sink and PCB should also be larger. In addition, the gate operating circuits must be insulated.

One of the merits of a quasi-resonant converter is that it 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 component is more complicated. But as mentioned earlier, technological improvements in high frequency semi-conductor switching devices has lead to innovation in terms of low price, high performance, and

reliability. Quasi-resonant converters are now generally used because of the smaller heat sink and PCB size and a simpler operating process. The following describes the operation of a half-bridge series resonant converter and a quasi-resonant converter.

5-2-1. Half-bridge Series Resonant Converter

A variety of design methods are available for a power system using a half-bridge series resonant converter. Figure 5-2 is a block diagram of a power system in a very simplified form in which reliability and economy are factored in. This system is comprised of an AC power supply, main power circuit, control circuit, input current detection circuit, resonant current detection circuit, and gate operation circuit. All the necessary procedures for designing and testing the system are shown in the block diagram. The drawing below does not contain the heater and cooling fan. The operation of a power system as a whole is illustrated in the following figure.
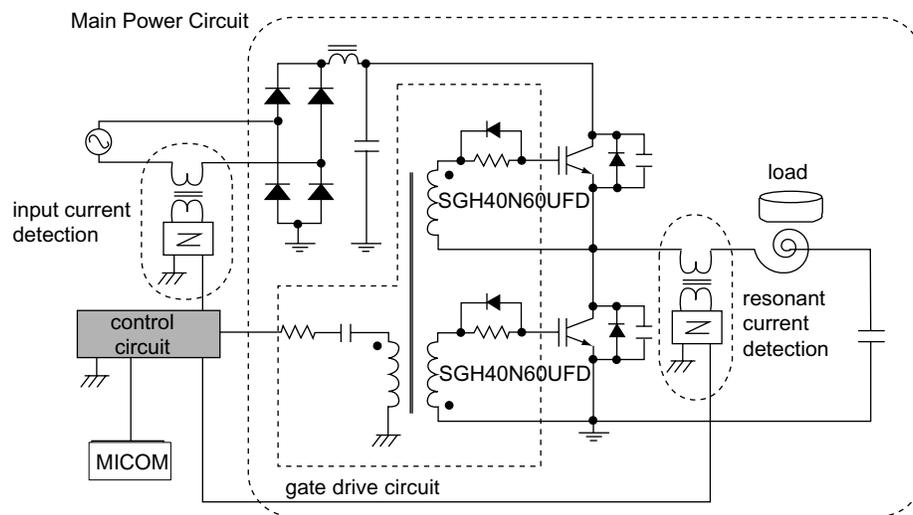
Figure 5-2: Power System Using Half-bridge Series Resonant Converter

The AC (220V/60Hz) power passes through the rectifier to be transmitted to the capacitor. Capacitors in existing power systems are too small in capacity to do the leveling work leading to the creation of rectified current in 120Hz, which is not the proper level for DC operation. The system for an IH rice cooker, however, does not require a big capacitor to make DC more leveled, as the primary purpose of the system is to generate heat energy. Rather, the rugged form of DC helps improve the power factor of the system. In this system, the leveling capacitor serves as a filter preventing the high frequency current from flowing toward the inverter and 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 a 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 (rice container). 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.

Micom 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 descriptions of each part are presented below.

1) Main Power Circuit

The main power circuit employs a half-bridge series converter switching at a high frequency as shown in Figure 5-3. The switching circuit consists of an IGBT (Insulated Gate Bipolar Transistor, SGH40N60UFD). 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 of resonant inductance (Lr) and resonant capacitance (Cr). The capacitors, C1 and C2, are the lossless turn-off snubbers for the switches, S1 and S2.
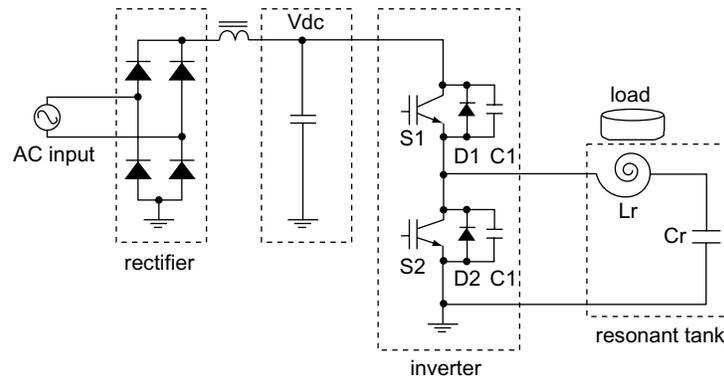
Figure 5-3: Main Power Circuit

A circuit equivalent to a resonant circuit is described in Figure 5-4. 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 be simplified as in the circuit (c), where R*, L*, and Cr 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 (Lr), which is a resonant inductor combining the leakage inductor and the secondary inductor.

According to the actual measurement of the system L*=52.7uH and Cr=0.8uF, which leads to the following formula of resonance frequency, f_0.

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 24.5[kHz] \qquad \text{(Formula 5-1)}$$

With regard to the switching frequency explained in section 4, the inductive area has more advantages than the capacitive area in many aspects (see reference number 18 for more information). Hence, the switching frequency of the system is set at 28kHz, which is higher than the resonance frequency, in order to avoid noise generated within the audio frequency band.
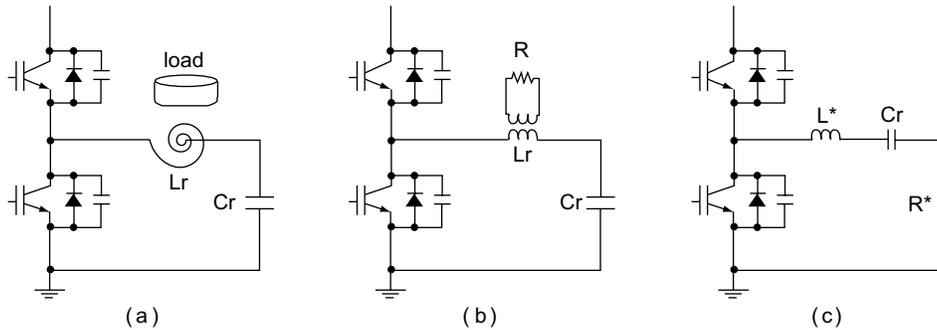

Figure 5-4: Equivalents of the Resonant Circuit

Operation Theory

By connecting the IGBT switching circuit, S1 and S2 in parallel to diodes D1 and D2, current loss is minimized. When S1 is turned-off, D2 helps S2 stay on zero voltage/current before being turned on, thereby substantially reducing current loss (the same is the case with S1). There is 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 turn-off snubbers connected in parallel to S1 and S2, keep this loss to a minimum. 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 5-3) can be simplified as an equivalent circuit illustrated in Figure 5-5. Figure 5-6 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*-Cr resonant circuit flows in the opposite direction through D1 (S1 and S2 remain off). Until t<t0, the resonant current flows in the opposite direction through D1, rather than passing directly through S1. The following Figure 5-7 describes the resonance in each mode (I-IV).
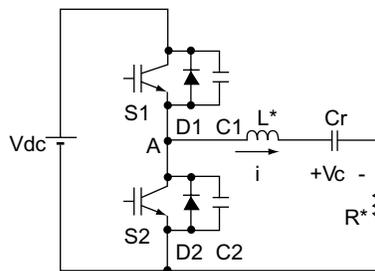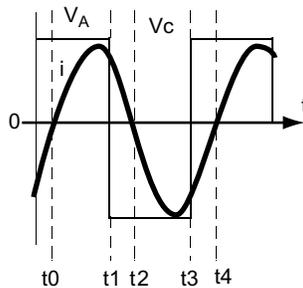

Figure 5-5: Equivalent of the Main Power Circuit

Figure 5-6: Wave Form of the Main Power Circuit

MODE I: t0-t1

The resonant current flowing in an inverse direction changes its direction at the point of t=t0 flowing through S1. In this mode the DC-LINK voltage of Vdc lets the resonant circuit accumulate energy by supplying power through S1.

MODE II: t1-t2

When S1 is turned off at the point of t=t1, the resonant current flowing through S1 begins free-wheeling 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 t1<t<t2. As the S2 switch remains at zero voltage/current, no switching loss takes place at turn-on. And the reverse-recovery of D1 does not necessarily have to be fast.

After turning off S1, the resonant current passes for a short period through the snubber C1 before freewheeling to D2. A detailed description of this period is not presented in this document.

MODE III: t2-t3

Right after t=t2, the current freely resonates and flows in an inverse direction through S2 which is already turned on. Here, the resonant capacitor, Cr, serves as a source of voltage.

MODE IV: t3-t4

When S2 is turned off at t=t3, the resonant current flowing through S2 starts freewheeling through the D1 diode. In this process, a small amount of switching loss occurs at turn-off. For the following mode, the S1 switch is turned on at a certain point (t3<t<t4). At this point, there is no switching loss at 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 Vdc passing D1. The operating mode after t>t4 cycles from mode I to mode IV again as described above.

Also in this process, the resonant current passes through the snubber C2 for a short period of time before freewheeling to D1. This period is not explained in this document.
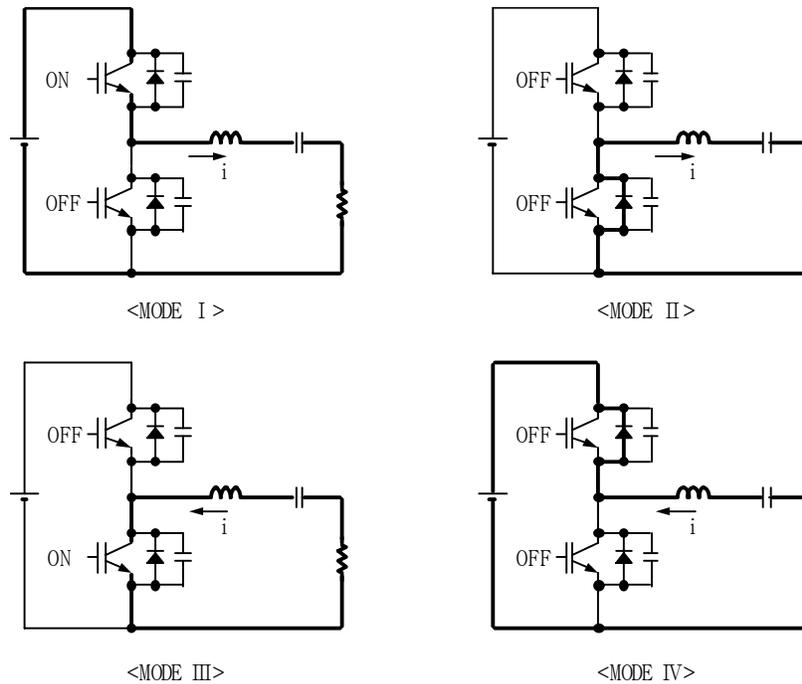
14

<MODE Ⅰ>   <MODE Ⅱ>

<MODE Ⅲ>   <MODE Ⅳ>

Figure 5-7: Operation

2) Determinants of Inductance and capacitance of a resonant circuit

As heat energy is generated in the process of energy exchange between the inductor and the capacitor in the resonant circuit, the level of inductance and capacitance is a very important factor. The following is a description of some factors which determine the value of this inductance level.

Power Consumption

As the most common size of a rice cooker is 1.8 liter (for 10 persons), the overall power supply is designed for this capacity which is a maximum of 1250W.

AC Current

A half-bridge series resonant converter is appropriate for a 220V power source. So with +/-15% of buffer range, the voltage is designed to be set at 187V to 253V in 60Hz.

Resonant Frequency

In order to avoid audio frequency, the resonant frequency is set at over 20kHz. In this document, the frequency is 24kHz.

C (capacitance)

The computation of the amount of resonant current is as follows. Here, as the input current is the average of the resonant current, the input current of a cycle is computed as (resonant current/2π).

$$I = \frac{2\pi P}{V} = \frac{2\pi \times 1250}{187 \times \sqrt{2}} = 29.7[A]$$

The capacitance of a resonant capacitor is determined as follows:

$$C = \frac{I}{2\pi fV} = \frac{29.7}{2\pi \times 24000 \times 187\sqrt{2}} = 0.74[\mu F]$$

 In this document, the standard value of capacitance is 0.8 [μF].

L (Inductance)

The inductance of the resonant inductor is computed by using the capacitance as explained above and in Formula 4-7.

$$L = \frac{1}{(2\pi f)^2 C} = \frac{1}{(2\pi \times 24000)^2 \times 0.8 \times 10^{-6}} = 55[\mu H]$$

It is important to consider whether a coil, having a value of L above, is fit for the container. The value of L is determined by the thickness of the coil, and the number of turns and errors.
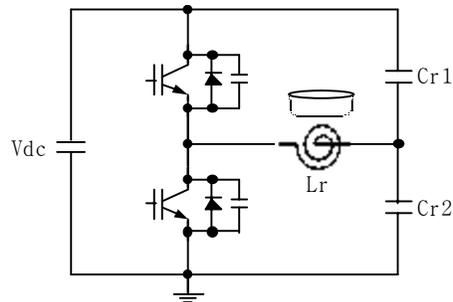
Figure 5-8: Common Type of Main Power Circuit

3) Actual Main Power Circuit

Figure 5-8 illustrates a main power circuit, which is used more commonly than the one in Figure 5-3. The resonant capacitor, Cr, is divided into two identical capacitors, Cr1 and Cr2 (Cr1=Cr2). By having two equal capacitors, the amount of current flowing through each capacitor is reduced to half while the voltage to the capacitors remains the same. This results in less heat generation caused by ESR, and the RMS value of the ripple current in the DC-LINK capacitor is also reduced to $1/(\sqrt{2})$

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As the total amount of resonant current flowing through the inductor is equal in both systems, the amount of heat energy generated is likewise. The amount of current in a capacitor, however, shows a difference. The flow chart of the current is not provided in this document.

5-2-2. Quasi-resonant Converter

There are a number of design methods for a power system employing a quasi-resonant converter. The following Figure 5-9 features a block diagram of such a system in a streamlined form. This system was actually tested. The description of the heater is omitted in this document. The SMPS is the block that supplies power to the DC cooling fan and the control circuit. It is designed using a BUCK converter. A detailed explanation about SMPS is not provided here.
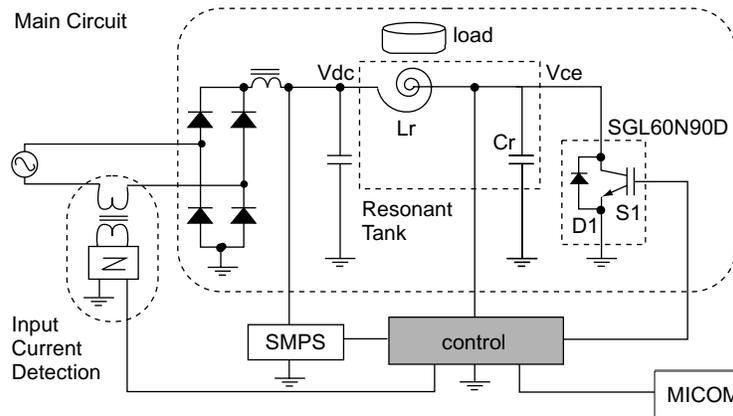
Figure 5-9: Power System Using a Quasi-resonant Converter

The total system block comprises of a main power circuit, input current detection circuit, control circuit, and SMPS circuit as shown in Figure 5-9. The basic operating concept of a quasi-resonant circuit is similar to that of a half-bridge series resonant converter in 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.

1) Main power circuit

The main power circuit features a quasi-resonant converter as in Figure 5-10. This consists of the IGBT (Insulated Gate Bipolar Transistor, SGL60N90D) 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 state, 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 (Lr) and resonant capacitance (Cr).
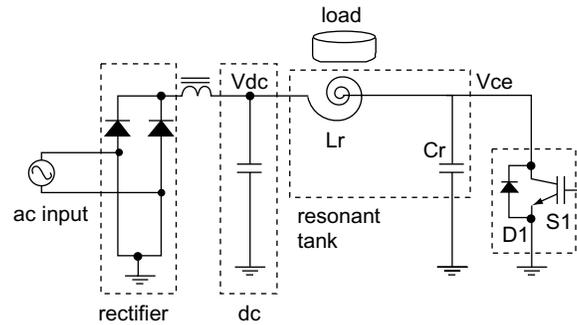
Figure 5-10: Main Power Circuit

The Equivalent of a Resonant Circuit

Figure 5-11 shows the equivalent of a resonant circuit. The resistance in circuit (b) is equivalent to the load in circuit (a). These two circuits can be remodeled in a simpler form as circuit (c), which consists of R*, L*, and Cr. R* is equivalent to R of transformer (b). L* is the resonant inductor combining Lr of the primary circuit, the leakage inductor, and the secondary inductor.
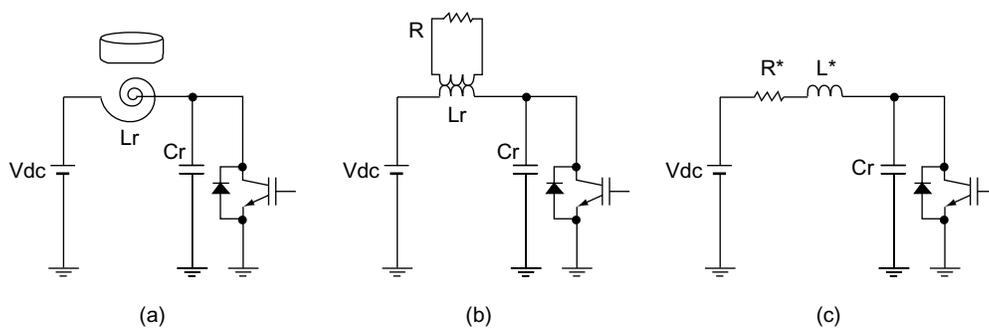

Figure 5-11: The Equivalent of a Resonant Circuit

Operating Concept

Figure 5-12 illustrates an equivalent of the main power circuit. When D1, connected to the S1 switching circuit, is in turn-on state, zero voltage turn-on switching is available as Vce of the circuit becomes zero. In this circuit, the switch must endure high internal pressure to accommodate the high voltage of Vce administered to both ends of the switch.

Figure 5-13 shows the wave forms of each block of the main power circuit in a cycle. Initially, S1 is turned off by the control circuit when the current flowing through L* and S1 reaches its peak. At this point, Vc (0)=0V. There are four modes available, as shown in Figure 5-14.
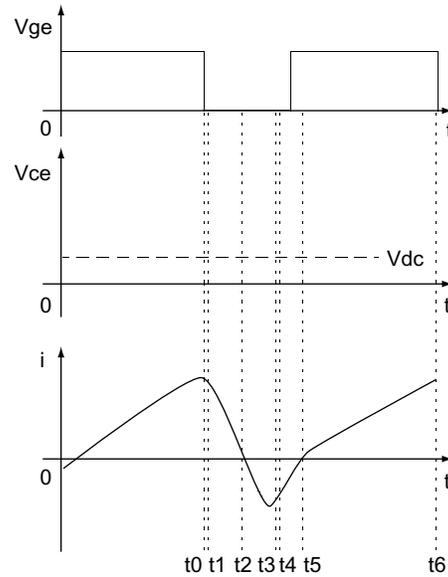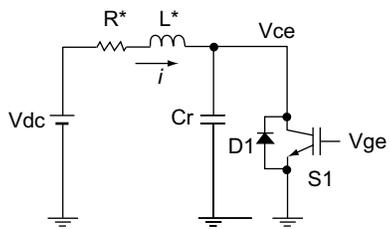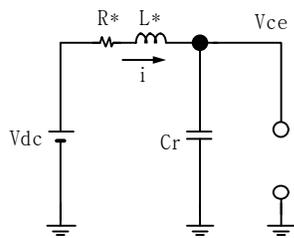
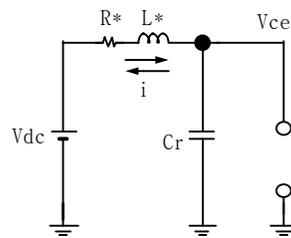Figure 5-12: Equivalent of a Main Power Circuit   Figure 5-13: Wave Forms of the Main Power Circuit
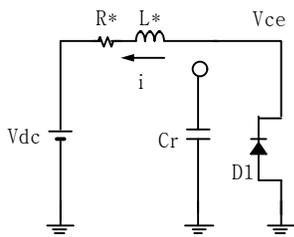
<MODE Ⅰ>   <MODE Ⅱ>
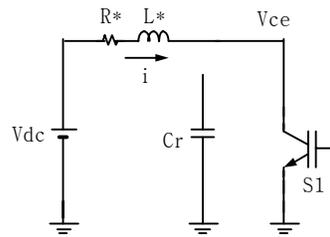
<MODE Ⅲ>   <MODE Ⅳ>

Figure 5-14: Operation

MODE I: t0-t1

As mentioned earlier, the switching circuit is turned off when the resonant current flowing through the circuit is at its peak, i.e. at t0. In this process, a turn-off switching loss occurs. The Vce level is rapidly increased by the capacitor (Cr) to become DC-LINK (Vdc) at t1.

Even when the switch is turned off at t0, the current keeps incrementing to reach its peak at t1, when Vce becomes equal to Vdc, 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: t1-t4

As Vdc is lower than Vce after t1, the current decreases to zero at t2, when the resonant voltage reaches its maximum. This is also the point where 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: t5-t6).

After t2, the capacitor starts discharging the energy to the inductor, which causes the voltage and the current flowing in inverse to decrement and reach its minimum level at t3, i.e. Vce=Vdc, respectively. Passing t3, the resonant current increases as Vce<Vdc and the discharge is completed at t4.

MODE III: t4-t5

After t4, 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: t5-t6

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 t6, 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.

Note that the wave form of the resonant voltage changes whenever DC-LINK becomes low or there is any change in load impedance. As explained earlier in the description of half-bridge series resonant converters, the bandwidth of DC-LINK (Vdc) ranges from zero to maximum as the capacitor has a small capacity. The wave forms of the resonant voltage can be divided into three types as shown in Figure 5-15.
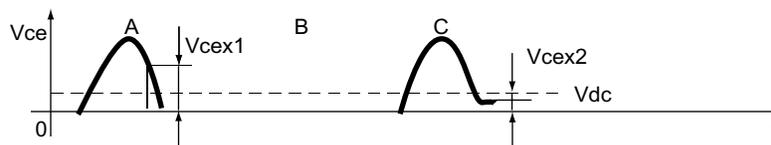

Figure 5-15: Wave Forms of Resonant Voltage

In this figure A, B, C, and D are the waveforms of the voltage at early turn-on, normal loading, light loading, and late turn-on situation, respectively. If the waveform of C is generated under normal circumstances, it means that the value of the inductor or the capacitor is not properly set. When the waveform of A or D appears in a normal situation, the turn-off time of the switching frequency should be adjusted.

While the switching circuit is on, the amount of energy stored in the inductor must be large enough. Otherwise, resonance takes place in a light loading condition. In this situation the resonant voltage has a finite value (Vcex2) other than zero, eliminating the freewheeling period of MODE III (t4-t5) and therefore disabling a zero voltage turn-on. The following amount of energy stored in the capacitor is lost as a result of turning on the circuit:

$$W = \frac{1}{2}C_r V^2_{cex2} f_s$$

The quality factor (Q) of the resonant circuit must be properly maintained to keep the maximum level of energy stored in the inductor or capacitor as high as possible. If Q is too large, it is harder to generate heat energy. And this has a lot to do with the material used in making the container of the cooker. The following computation summarizes the explanation above:

$$Q = \frac{\omega L}{R} = \omega \frac{Li^2}{Ri_2}$$

= energy stored in L/ energy consumed by load in each cycle
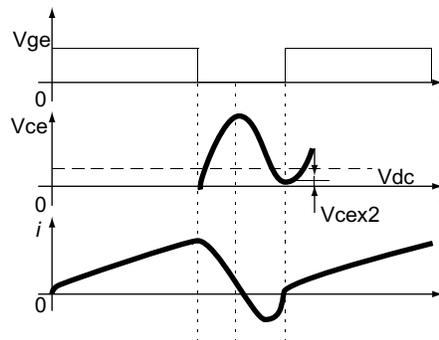

Figure 5-16: Wave Forms At a Non-zero Voltage Turn-On

2) Main Power Circuit

The main power circuit shown in Figure 5-17 is used more than the one in Figure 5-12. By relocating the capacitor as in Figure 5-17, the voltage administered to the capacitor can be substantially reduced, which results in a lower internal voltage inside the capacitor. As the amount of the current flowing to the inductor is the same in both systems, the heat energy generated in the load is also the same. However, the current flowing to the capacitor or DC-LINK is not the same in the two different main power circuits. This current is not illustrated in this document.
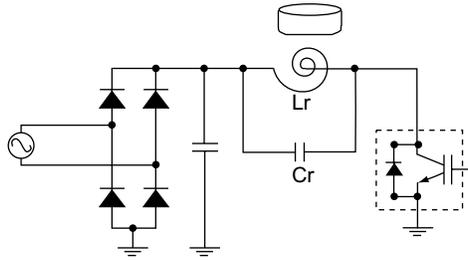
Figure 5-17: Main Power Circuit

5-3. IH Cooker

The basic operating concept and structure of the power system of an IH cooker are similar to those of an IH rice cooker except for the load. The load resistance of an IH rice cooker is always the same as there is only one kind of load used (the rice container). In this case, even in times of frequency fluctuation, the inductance and the capacitance remain stable due to a narrow variation range. This leads to a simple design of the control circuit as described earlier. An IH cooker, however, has a different operating environment, as different kinds of vessels are loaded on the cooker, depending on the customer's needs. This variance of load requires the turn-off time of frequency to be changed accordingly. This is important consideration in designing the system for an IH cooker. Otherwise, the switching circuit will be damaged due to excessive switching loss which occurs during resonance similar to A and D in Figure 5-15.

Figure 5-18 is a basic form of a control system designed to meet the requirement explained above. Illustrations of other systems are not presented in this document as they are quite similar to that of IH rice cookers.
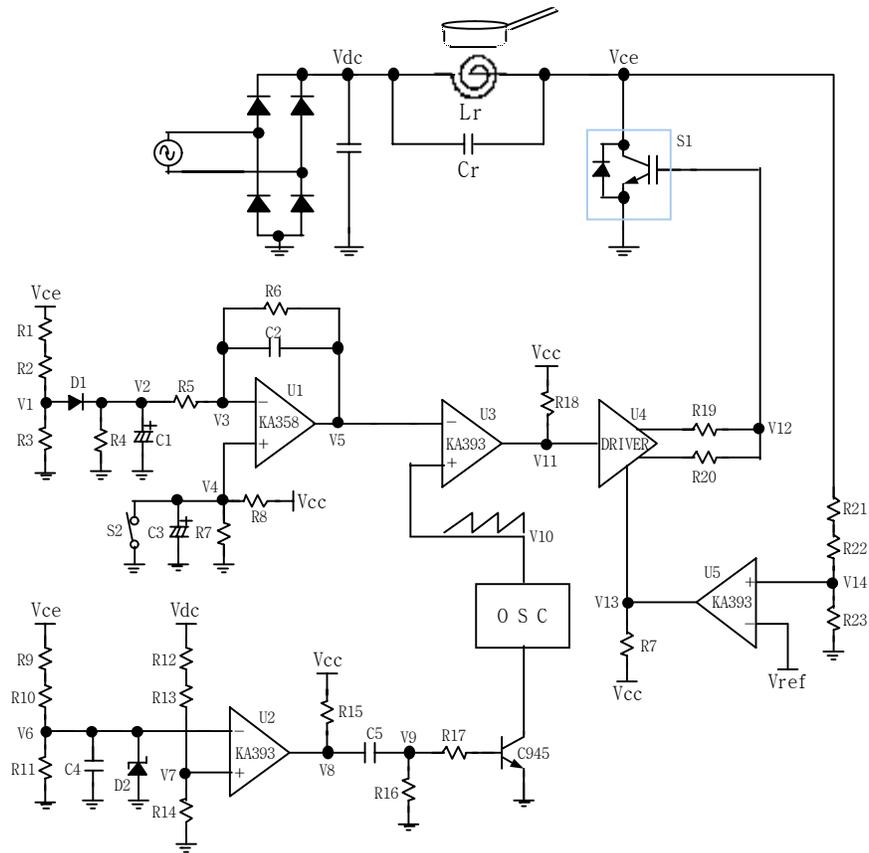
Figure 5-18: Power System for IH Cookers Using a Quasi-resonant Converter

The control system above is designed to keep the level of output energy stable by controlling the upper limit of the voltage. A picture of a circuit employing individual circuits is provided to clearly describe it.

Given below is a further description of the control system.

The wave forms of the resonant voltage and DC-LINK are shown in Figure 5-19. The frequency of the DC-LINK wave form is 120Hz, which is far smaller than the switching frequency (about 27kHz). The peak voltage level is varied depending on the size of the DC-LINK. The turn-on time of the switching circuit is determined by comparing the sizes of DC-LINK and the resonant voltage (Vce).
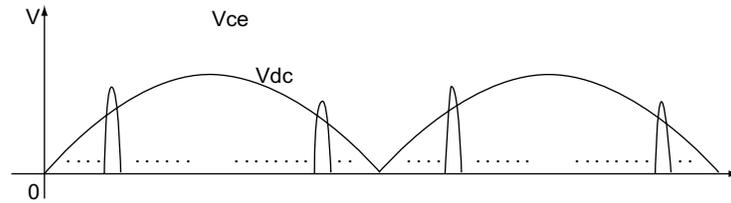
Figure 5-19: DC-LINK (Vdc) and Resonant Voltage (Vce)

At the point DC-LINK (Vdc) becomes zero in Figure 5-19, V7 in Figure 5-25-a also reaches zero, making it impossible to control the turn-on time of the switching frequency. So a maximum limit of turn-on time (0-t4) must be set at the user's discretion, otherwise the switching circuit, S1, will be permanently damaged due to the unreasonably long turn-on time.

Switching frequency is determined by comparing Vce, detected from V1, and V10, the output voltage of OSC located inside VCO. OSC is a circuit generating jagged-shaped voltage with a regular frequency, such as V10 as shown in Figure 5-20-d.

When the start switch S2 is off, the voltage of V4 increments from 0V to its maximum limit according to (τ=R7xC3) and the switching frequency of V11 decreases from maximum to normal level, enabling a soft start. Here, V5 is in direct relationship with the switching frequency. The higher the voltage V5, the faster the switching frequency.

As mentioned earlier, the length of turn-off time, or the turn-on point must be adjusted according to the type of load. In addition, abnormal waveforms of Vce in some situations must also be considered. In resolving these problems, the capacitor, C4, is employed to create delay time (td). If C4 is not used, there would be no delay time (td) for V6 in Figure 5-20-a, which can result in a considerable amount of switching loss. Figure 5-20 shows the waveform of the operation theory just described.
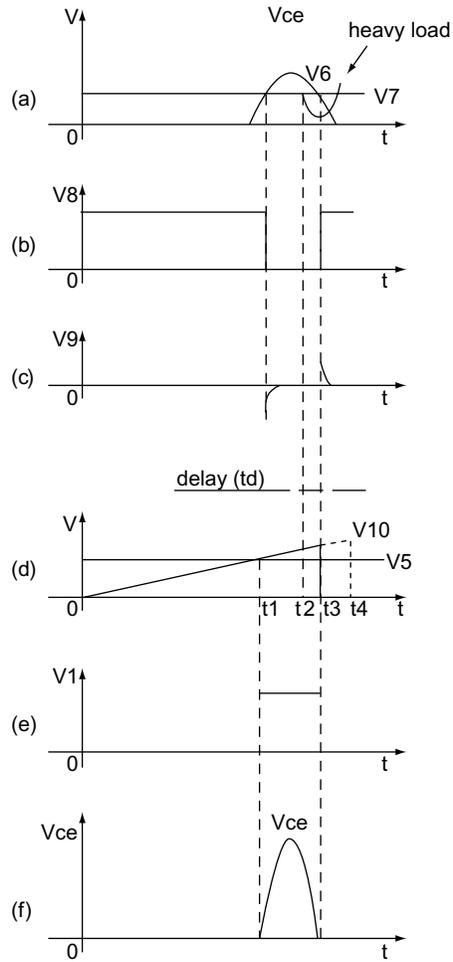
Figure 5-20: Waveform of Each Part In the Control System

When the resonant frequency is slowed by a different load, the turn-on point of the switching frequency moves from t3 to t4. If it becomes faster, the point moves from t3 to t2.

Voltage overload protection is enabled by detecting V14. As the resistance R20 is designed to be larger than R19, it is used when the voltage overload protection circuit is activated, whereas R19 operates in normal operation. There are a number of methods available for designing the gate driver (U4).

This concludes the overall description of the IH system. Understanding the basic concepts of induction heating and a power system with a resonant converter should precede any attempt at developing IH system applications. Please refer to the documents listed below for more detailed information.

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