# AND9166/D

# Induction Cooking

## Everything You Need to Know

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**APPLICATION NOTE**

### Introduction

The traditional concept of gas and the electric stoves is still the most popular in the market. There are ongoing debates, as to which is the best technology for cooking and why. Nowadays Induction heating for cooking applications is quickly gaining popularity. Induction cooking technology not only offers the advantage of having a better efficiency conversion compared to the standard solutions (Gas and electric stoves), but also offers the advantages of rapid heating, local spot heating, direct heating, high power density, high reliability, low running cost and non-acoustic noise. According to the U.S. Department of Energy the efficiency of energy transfer in these systems is about 84%, compared to 74% for a smooth-top non-induction electrical unit, providing an approximate 10% saving in energy for the same amount of heat transfer [1].

The principle behind an induction cooking stove is to excite a coil of wire and induce a current into a pot made of a material which must have high magnetic permeability and which stands in the proximity of the aforementioned coil. The way it works is similar to an inductor where the pan is a very lossy core. The generated heat is due to the eddy currents generated in the pot's bottom layer combined with the hysteresis losses from that magnetic material in the pan. For nearly all models of induction cooktop, a cooking vessel must be made of a ferromagnetic metal, or placed on an interface disk which enables non-induction cookware to be used on induction cooking surfaces.

In an induction cooker, a coil of copper wire is placed underneath the cooking pot. An alternating electric current flows through the coil, which produces an oscillating magnetic field. This field induces an electric current in the pot. Current flowing in the metal pot produces resistive heating which heats the food. While the current is large, it is produced by a low voltage.

The heart of such systems is the electronics which is the biggest challenge in terms of the design. It is a combination of a power stage coupled with a digital control system and also must deal with the thermal management issues. In Figure 1 is shown a schematic of an induction cooker.

The heat generated, follows the Joule effect R times the square of the inducted current. Figure 2 shows a block diagram of an induction cooker inverter. The main blocks are an EMI filter plus some over voltage and over current protections, a rectifier bridge plus the bus capacitor, the resonant inverter, the coil, all the sensor and actuators, an auxiliary power supply, a thermal management system and a control unit.

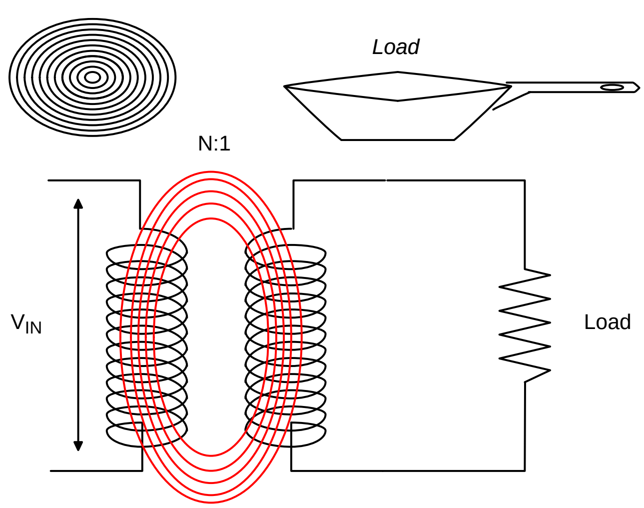



**Figure 1. Equivalent of an Induction Cooking System**

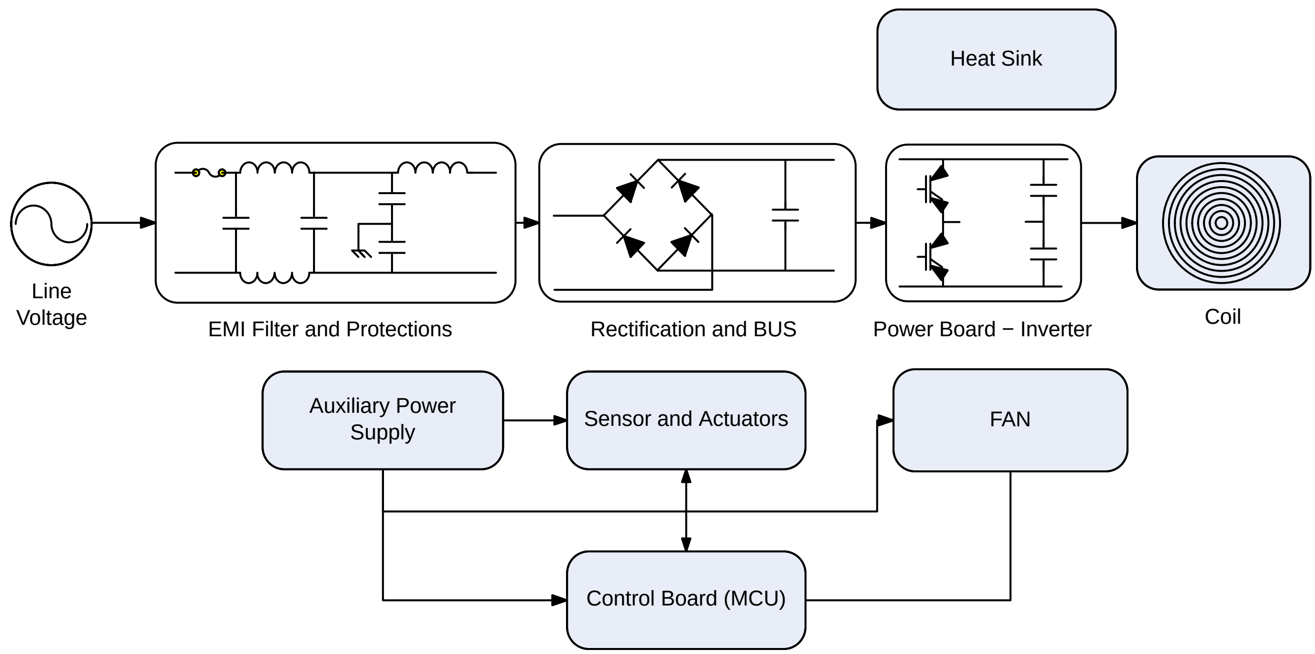



**Figure 2. Block Diagram of an Inductor Cooker**

## HOW INDUCTION HEATING WORKS

Induction heating is the process of heating a metal by electromagnetic induction. The electromagnetic induction generates Eddy currents within the metal and its resistance leads to Joule heating (as shown in Figure 3) and also generates losses due to the hysteresis of the magnetic material in the pan [1]. An induction cooker consists of a copper coil (generally), through which a high-frequency alternating current (AC) is passed. The frequency of the AC used is based on the maximum switching frequency of the switch which is usually an IGBT. Higher switching frequencies can reduce the inductance of the coil and size of the resonant capacitor, allowing for cost savings of the unit. Induction heating is based on electromagnetic laws. The overall system can be approximated by an electric transformer, where the primary is the copper coil into the induction cooker and the secondary the bottom layer of the pot (see Figure 4 and Figure 5). The heat generated is due to the loading of the equivalent resistance of the losses in the pan, which in the transformer allegory, would be a load resistor on the secondary winding.

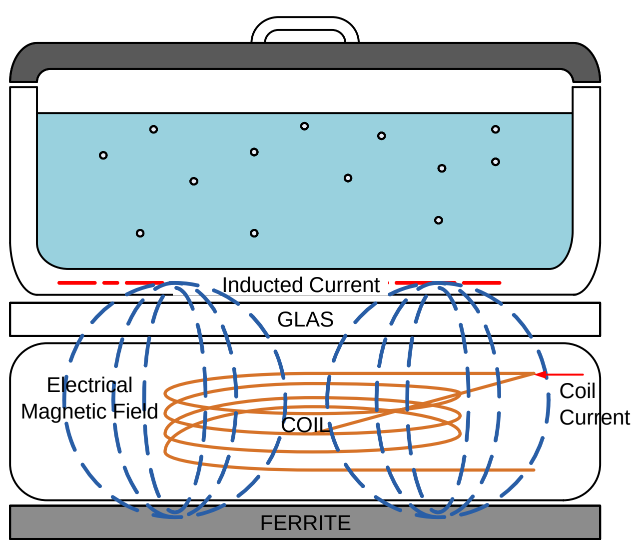



**Figure 3. Scheme of an Induction Cooking**

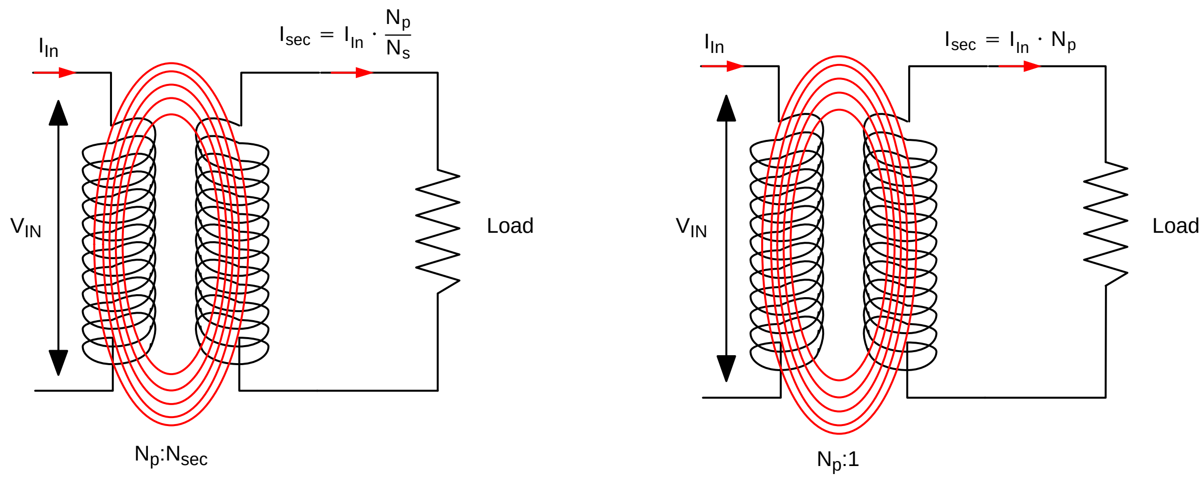



**Figure 4. Scheme of the Equivalent Transformer for an Induction Heating System**

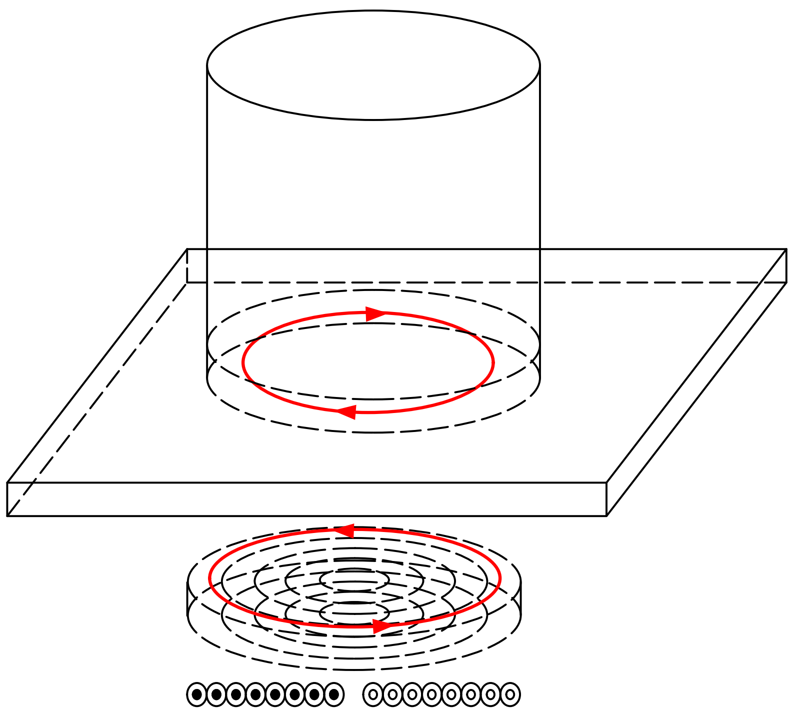


**Figure 5. Inducted Current in the Pot Bottom Layer**

### Electromagnetic Induction

Electromagnetic induction, also called induction, follows Faraday's law: "The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux through the circuit". This can be easily explained in the following form: Electromagnetic induction occurs when a circuit with an alternating current flowing through it generates current in another circuit by being placed within an alternating flux field. Going back to the point, an alternating current, which flows into a conductor, generates a magnetic field following the same equation:

$$\oint H \cdot dl = \sum i \qquad \text{(eq. 1)}$$

$$\phi = \int\int_A B \cdot dA \qquad \text{(eq. 2)}$$

$$B = \mu \cdot H \qquad \text{(eq. 3)}$$

$$\mu = \mu_0 \cdot \mu_r \qquad \text{(eq. 4)}$$

$$e = N \cdot \frac{d\phi}{dt} \qquad \text{(eq. 5)}$$

Where H [A/m] is the magnetic field intensity (see Figure 6). $d\phi$ is an infinitesimal arc length along the wire, and the line integral is evaluated along the wire. i is the current flowing in a certain conductor. B [Wb/m$^2$] is the flux density. $\mu$ is the permeability and $\mu_0$ is the permeability in free space while $\mu_r$ is the relative permeability. Where e is the electromotive force (EMF) in volts and $\Phi$ [Wb] is the magnetic flux. The direction of the electromotive force is given by Lenz's law. Where dA is an element of surface area of the moving surface A, B is the magnetic field, and $B \cdot dA$ is the infinitesimal amount of magnetic flux. In more visual terms, the magnetic flux through the wire loop is proportional to the number of magnetic flux lines that pass through the loop. Where N is the number of turns of wire and $\Phi B$ is the magnetic flux in webers through a single loop.

When the flux changes the wire loop acquires an electromotive force e [V], defined as the energy available from a unit charge that has travelled once around the wire loop. As shown in the equivalent circuit of Figure 1, e is the voltage that would be measured by cutting the wire to create an open circuit, and attaching a voltmeter to the leads.

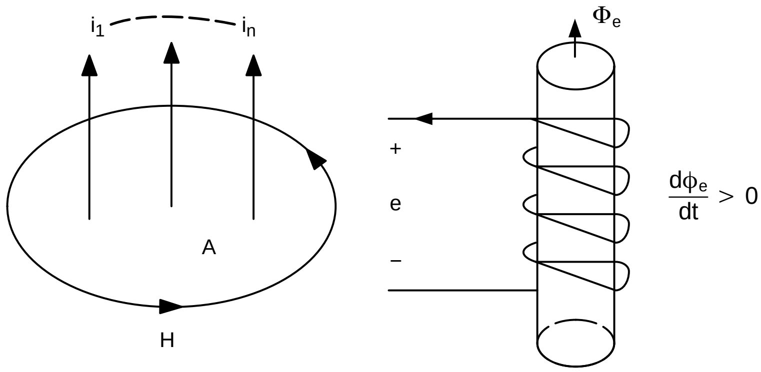



**Figure 6. Graphical Illustration of Ampere's Law and Lenz's Law**

### Skin Effect

When an AC current flows in a conductor, the distribution is not uniform within the conductor, but it has the tendency to flow mainly on the surface of the conductor with the depth based on its frequency. The equations dominating this effect are as follows:

$$J = J_S \cdot e^{\frac{d}{\delta}} \qquad \text{(eq. 6)}$$

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu}} \qquad \text{(eq. 7)}$$

Where J is the current density [A/m$^2$], $J_S$ is the current density at the surface of the conductor. $\delta$ is called the skin depth and d is the depth. In a conductor, according the Eq. 7, J the AC current density decreases exponentially from its value at the surface $J_S$ according to the depth d from the surface (as shown in Figure 7). Where $\rho$ is the resistivity of the conductor, while $\omega$ is angular frequency of current and is equal to 2 times $\pi$ times the frequency of the current. $\mu$ is the absolute magnetic permeability of the conductor.

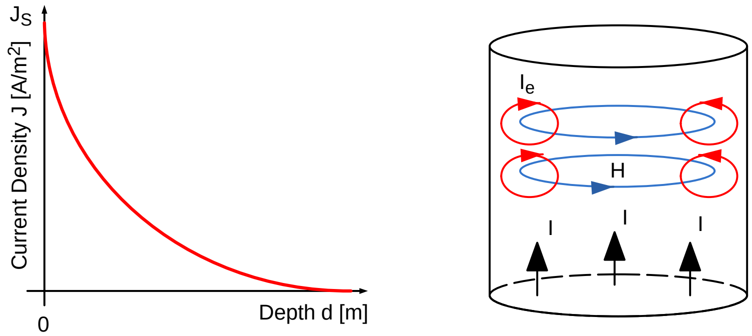



**Figure 7. Current Density as a Function of Depth and Skin Effect and Eddy Current**

Skin depth is due to the circulating eddy currents cancelling the current flow in the center of a conductor and reinforcing it in the skin. In the presence of an alternating current, due to the skin effect, the equivalent resistance increases.

### Heat Transfer

The aforementioned phenomena leads to the generation of unwanted currents into the conductor placed nearby (the so called eddy current as shown in Figure 8). These currents induced into the conductor generate heat. The amount of heat generated into the conductor follows the Joule heating law, also known as ohmic heating, which is the process by which the passage of an electric current through a conductor is dissipated as power and releases heat. This effect is also known as Joule's first law:

$$\dot{Q} = P = R \cdot i^2 = v \cdot i \qquad \text{(eq. 8)}$$

Where $\dot{Q}$ and P [W] represent the power converted from electrical energy to thermal energy, I [A] is the current that goes through the conductor (in this case the eddy current), v [V] is the voltage drop across the element (e in this case is the EMF) and R [Ω] is the equivalent resistance of the conductor (in the case of induction heating is the resistance of the bottom layer of the pot. Following Eq. 8 the amount of heat released is proportional to the square of the current. The heating technology (one of the principles of the induction heating technology) has a coefficient of performance of 1.0, meaning that every watt of electrical power is converted to 1 watt of heat. By comparison, a heat pump can have a coefficient of more than 1.0 since it also absorbs additional heating energy from the environment, moving this thermal energy to where it is needed.

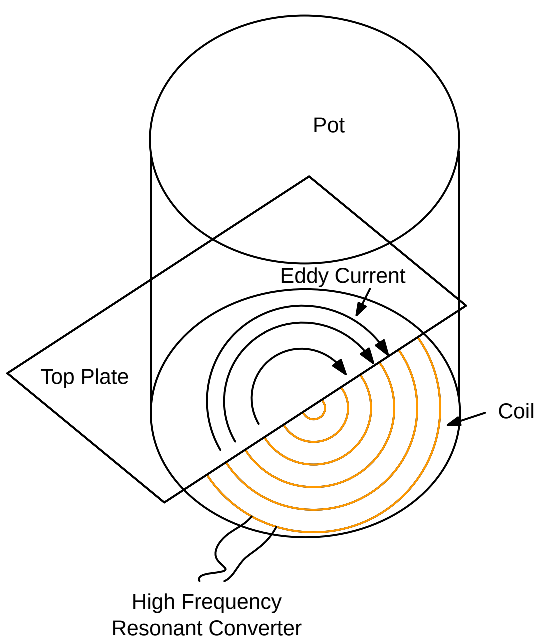



**Figure 8. Generated Eddy Current into the POT's Bottom**

## RESONANT CONVERTER FOR INDUCTION COOKING APPLICATIONS

In power electronics it is common to have conventional PWM power converters operating in switched mode. Conventionally the switches switch from high current to high voltage as shown in Figure 9 in the so called hard switching mode. The name “hard switching” refers to the stressful switching behavior of the power electronic devices. During the switch-on and switch-off processes, the power device has to withstand high voltage and current simultaneously, resulting in high power switching losses and stress. In these circuits snubbers are usually added in order to reduce the voltage transients on the power devices, and the switching loss into the power devices. The switching power losses are proportional to the switching frequency, thus limiting the maximum switching frequency of the power converters [6].

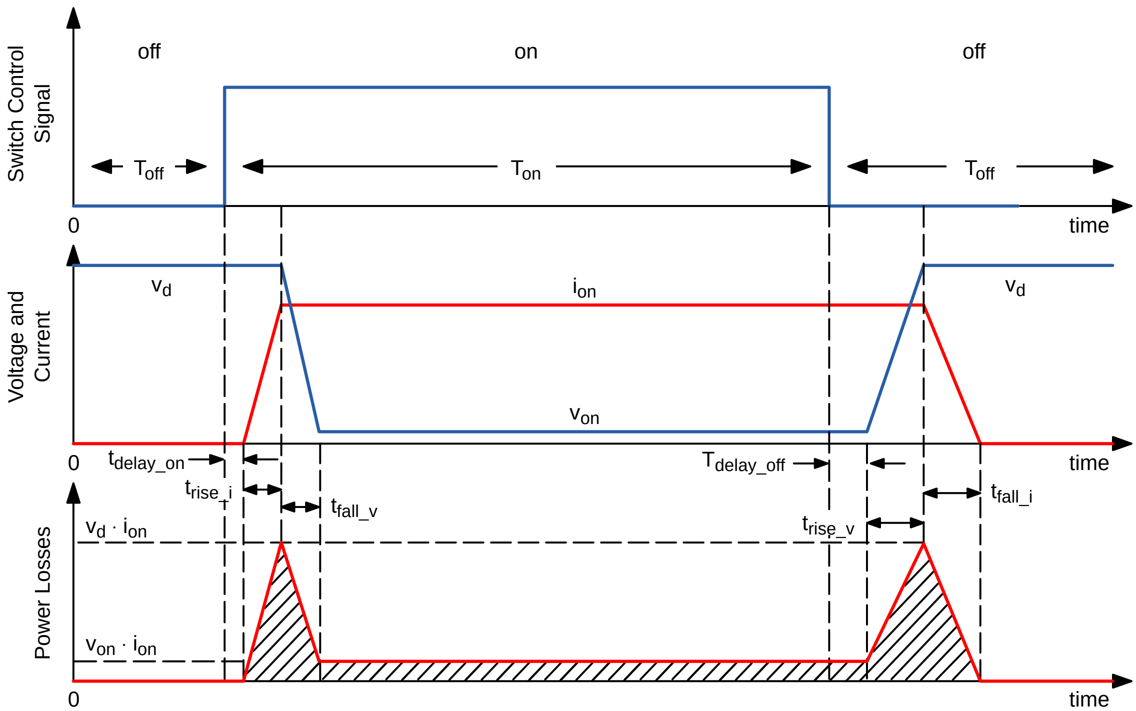



**Figure 9. Power Losses in a Conventional SMPS Converter**

Increasing the switching frequency allows smaller and less expensive inductors and capacitors to be used in the converter. This gain in smaller component sizes must be balanced by the increased switching losses of the power switch. In order to increase the frequency and get the advantages of operation at those frequencies, the resonant converter has been introduced. Resonant converters [3] incorporate resonant tanks in the converters to create oscillatory (usually sinusoidal) voltage and/or current waveforms so that zero voltage switching (ZVS) or zero current switching (ZCS) conditions can be created for the power switches. This leads to a switching power losses reduction allowing a higher working switching frequency of the resonant converters. The main advantage of resonant converters is that they can work in a very high switching frequency range with very low power losses. Several control techniques, like zero current switching (ZCS) or zero voltage switching (ZVS), can be used to reduce power loss in resonant converters.

Figure 10 shows switching area for hard-switched condition, snubber assisted commutation and soft switching [4] [5] [6]. During the hard switching turn-on and turn-off, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stress. Dissipative passive snubbers are usually added to the power circuits so that the dv/dt and voltage spikes on the power devices can be reduced. The reduction of switching losses and the continual improvement of power switches allow the switching frequency of the resonant converters to approach 100 kHz for IGBT switches. Consequently, the size of magnetic and capacitive components can be reduced and the power density of the converters increased.

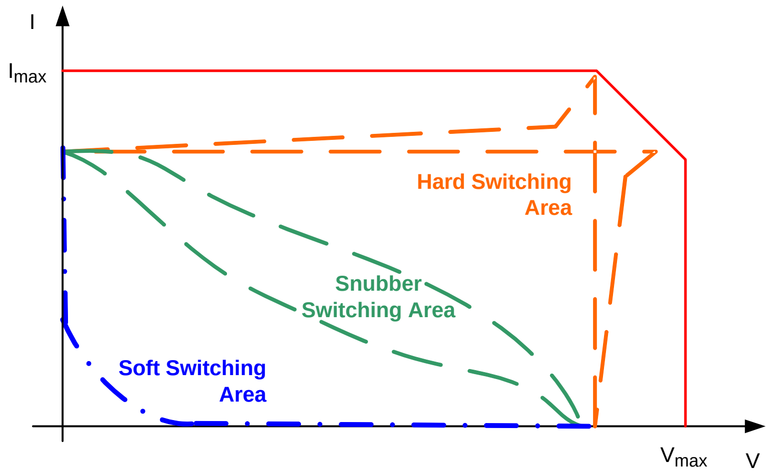



**Figure 10. Switching Area**

Some of the topologies for induction heating are shown in the following figures. Figure 11 (a) and (b) show the full bridge [8], half-bridge [9] (b), and two single switch inverter topologies with Zero Voltage Switching (ZVS) [10] (c) and Zero Current Switching (ZCS) operation [11] (d). All the modulation strategies commonly applied to control output power are based on modifying either switching frequency or duty cycle to achieve the desired power [12]. Each power converter topology offers different performance features with specific requirements in terms of costs and hardware and control complexity. Such systems are well known in literature as well as the design criteria for all their main parameters.

The most popular topologies for IH are the Half-Bridge (HB) series-resonant converter and the Single switch Quasi-Resonant (QR) or QR flyback. The Resonant Half-Bridge is very common for the four burners cooktops, and it is popular in the European market. While the Quasi-Resonant or QR flyback is very common for the single burner. and it is most popular in the Asian Market.

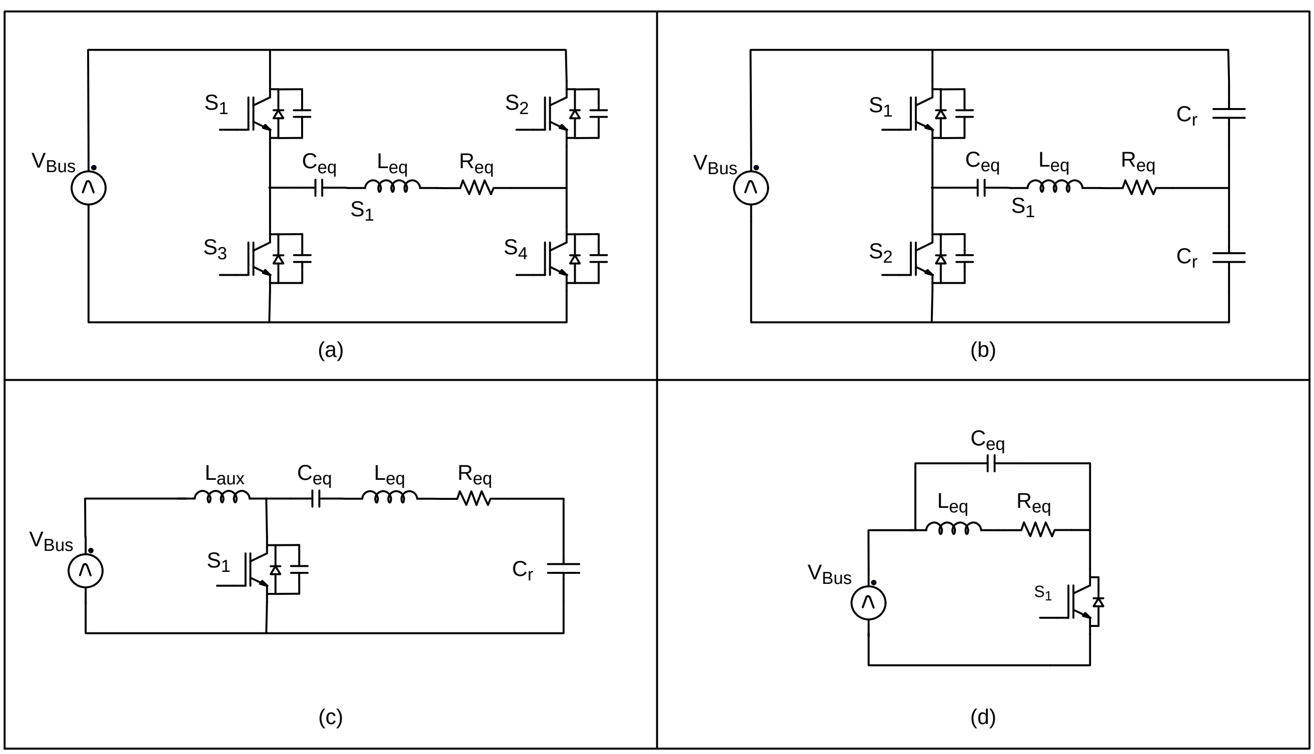



**Figure 11. Samples of the Topologies Presented in Literature in the Last Decades**

### Resonant Half-Bridge

The Resonant Half-Bridge inverter (11b) is the most employed topology in induction cookers for multiple burner, high-power systems due to its simplicity, its cost-effectiveness, and the electrical requirements of its components. These are commonly found in European markets. The equivalent load is basically the resonant tank, which consists of the inductive coil, the resonant capacitors and the equivalent resistance of the pan. Induction-coil-and-pan coupling it can be modeled as a series connection of an inductor and a resistor, based on the analogy of a transformer, and it is defined by the values of $L_r$ and $R_{load}$. These values change mainly with switching frequency applied to the switches, pan material, temperature, and inductor-pan coupling. The resonant half-bridge belongs to the resonant converter family. It is similar to a standard half-bridge, where the capacity of the bus (the resonant capacitors) is set in accordance with the coil for resonating at a certain frequency (the so called resonant frequency). The power stage is composed of two switches with antiparallel diodes, two capacitors and a coil. The circuit can be simplified for calculations as it is in Figure 12, where the two capacitor result in parallel in respect to the one in the previous figure.

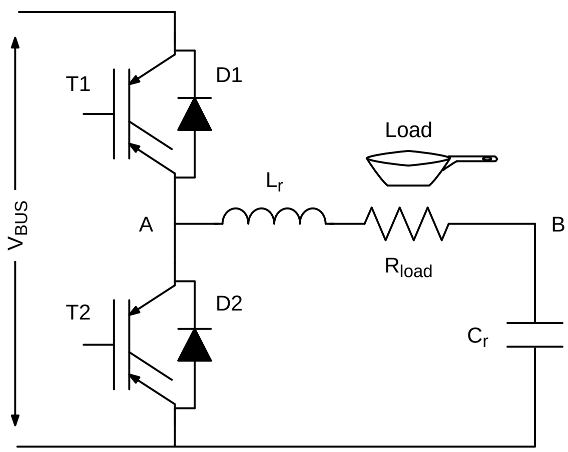



**Figure 12. Equivalent Circuit for a Resonant Half-Bridge for Cooking Application**

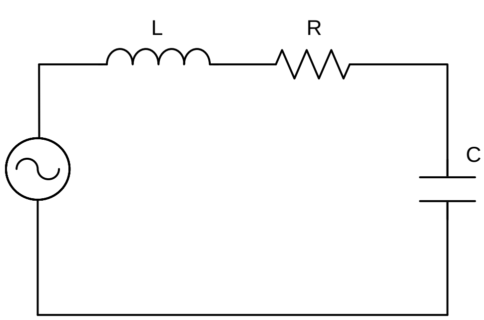



**Figure 13. Equivalent Series Resonant Circuits**

Figure 12 shows the equivalent series resonant circuit. As you can see the equivalent circuit for the resonant half-bridge is equivalent to the series circuit. The impedance of this circuit is as following:

$$Z_{series} = j\omega L + \frac{1}{j\omega C} + R \quad \text{(eq. 9)}$$

$$\omega = 2 \cdot \pi \cdot f \quad \text{(eq. 10)}$$

where $Z_{series}$ (as shown in Figure 13) is the impedance of the circuit from the generator point of view and $\omega$ is the angular frequency. The minimum of this equation is called resonant frequency $\omega_0$. At this point the reactance of the inductor is equal and opposite to the reactance of the capacitor. Another important factor to define for a resonant circuit is the quality factor Q, which in terms of physics is defined as a dimensionless parameter that describes is the ratio of the circuit impedance to the losses in that circuit. Higher Q indicates a lower rate of energy loss relative to the stored energy of the resonator; the oscillations die out more slowly.

$$Q = \frac{Z_0}{R} \quad \text{(eq. 11)}$$

where $Z_0$ is the impedance at the resonance frequency. Here following the equation that dominates this resonance.

$$f_{res} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r \cdot C_r}} \quad \text{(eq. 12)}$$

$$\omega_{res} = \frac{1}{\sqrt{L_r \cdot C_r}} \quad \text{(eq. 13)}$$

$$Z_0 = \sqrt{\frac{L_r}{C_r}} \quad \text{(eq. 14)}$$

$$Q_L = \frac{Z_0}{r_{pot}} \quad \text{(eq. 15)}$$

$$\varphi = a\ \tan\left(\frac{\frac{L_r}{C_r}}{r_{pot}}\right) \quad \text{(eq. 16)}$$

where $f_{res}$ is the resonant frequency. $L_r$ is the coil inductance, while $C_r$ is the sum of the parallel resonant capacitances. $\varphi$ is the phase between the current and the voltage.

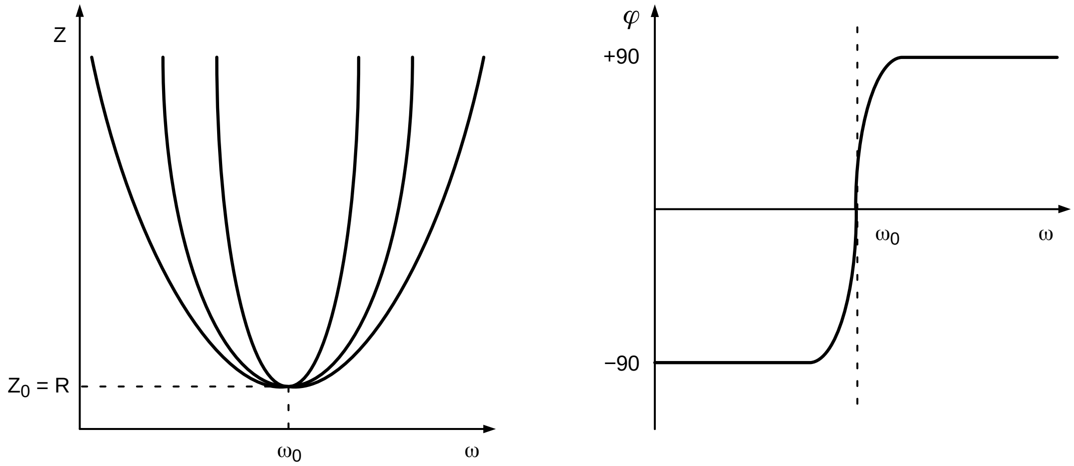



**Figure 14. Impedance Module and Phase of the Equivalent Half-Bridge Resonant Circuit**

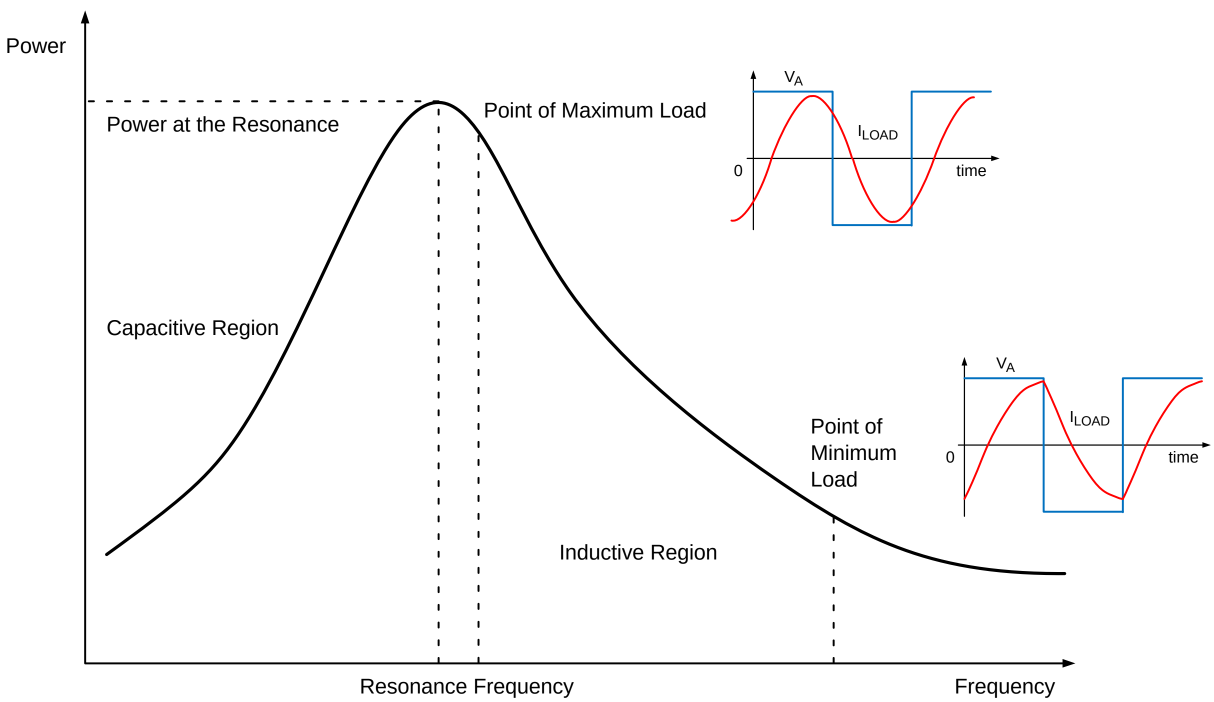



**Figure 15. Output Power vs. Switching Frequency for Maximum Load and Minimum Load**

For this type of circuit there are basically three modes of operation: below the resonance, above the resonance and at the resonance frequency. These three areas are characterized as a capacitive load when $f < f_{res}$, an inductive load when $f > f_{res}$ and a pure resistive load when $f = f_{res}$. It is possible to see also in Figure 15. In the design of a resonant half-bridge for induction heating applications that it is important to design the overall system for working in the inductive load area and in the range of the resonant frequency as well. This is due to the fact that for the capacitive load area there are three main detrimental effects that might cause damage to the device during the turn on: Reverse recovery of the antiparallel diode of the opposite switch; Discharging the transistor output capacitance and the Miller capacitance effect.

*Operating Principle of the Half-Bridge*

In this section the operating principle of an half-bridge for induction heating application will be explored. Figure 16 shows the operational waveforms of an IH cooker for the voltage for a switching frequency equal to the resonant frequency (upper graph blue waveform), the current (upper graph red waveform) into the resonant circuit, and the gate signals (lower graph blue waveform gate $T_1$ and red one $T_2$) for the two switches when the converter operates near to the resonance frequency. This mode of operation delivers the maximum power possible to the load.

At power levels below maximum, the switching frequency increases and the waveform is no longer sinusoidal. This is the case when the burner is not being operated in boost mode. Figure 17 shows the operational waveform for both switches for a switching frequency above the resonant frequency. Basically the normal operation can be split in four intervals: $t_0$−$t_1$, $t_1$−$t_2$, $t_2$−$t_3$ and $t_3$−$t_4$. Figure 18 illustrates the current in one switch. The conduction sequence of semiconductor devices is $D_1$−$T_1$−$D_2$−$T_2$. Let's consider $t_0$-$t_1$ (Figure 17). Before $t_0$ the current flows through $T_2$ and when $T_2$ is turned off $D_1$ is forced to go in conduction, while the gate of $T_1$ is still switched off. This is in order to avoid cross conduction. The time where neither the gate of $T_1$ nor the one of $T_2$ is in on state is called dead time. At $t_0$ the gate of $T_1$ is activated, but the current still flows through $D_1$ as shown in Figure 17. At $t_1$ the current goes from negative to positive and starts to flow into $T_1$. The reverse recovery current of the diode flows through the opposing IGBT without causing any further losses into the resonant half-bridge devices. At the turn on the losses into the devices are zero, while at turn off the losses are quite relevant due to the cross between the high current and the high voltage. In fact at $t_2$ the switch $T_1$ is turned off while the current is still high and this leads an overlap with the voltage causing turn off losses in the device. In addition the Miller effect is present, leading an increase of the transistor input gate charge and reducing the turn off speed resulting in an increase of the losses. The intervals $t_2$−$t_3$ and $t_3$−$t_4$ are the same as the previous ones except $T_2$ and $D_2$ are now the operational devices.

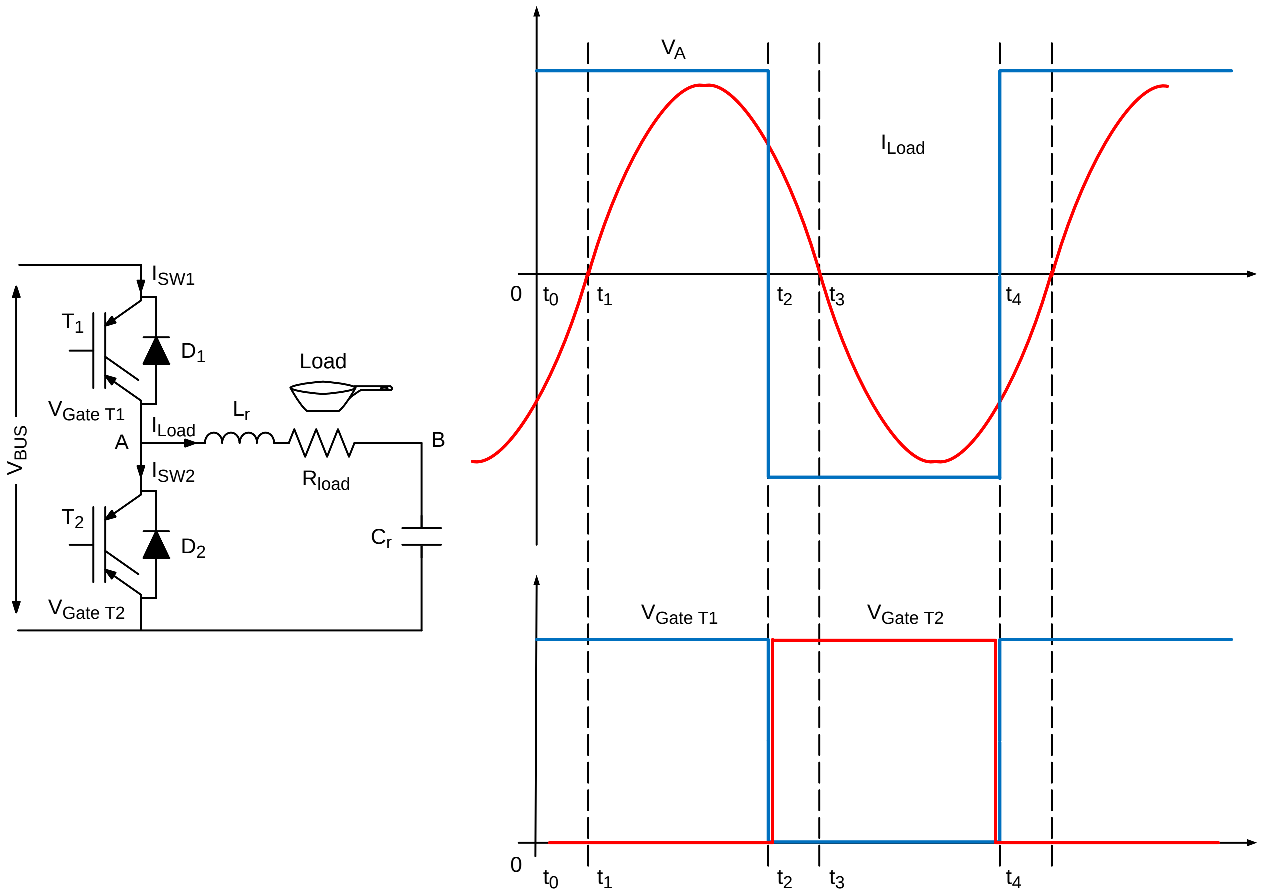



**Figure 16. Resonant Half-Bridge Waveforms.**
**Upper Graph: Load Current (Red) and Voltage at the Central Point A (Blue).**
**Lower Graph: Gate Voltage for the Higher Side IGBT (Blue) and the Lower Side IGBT (Red).**

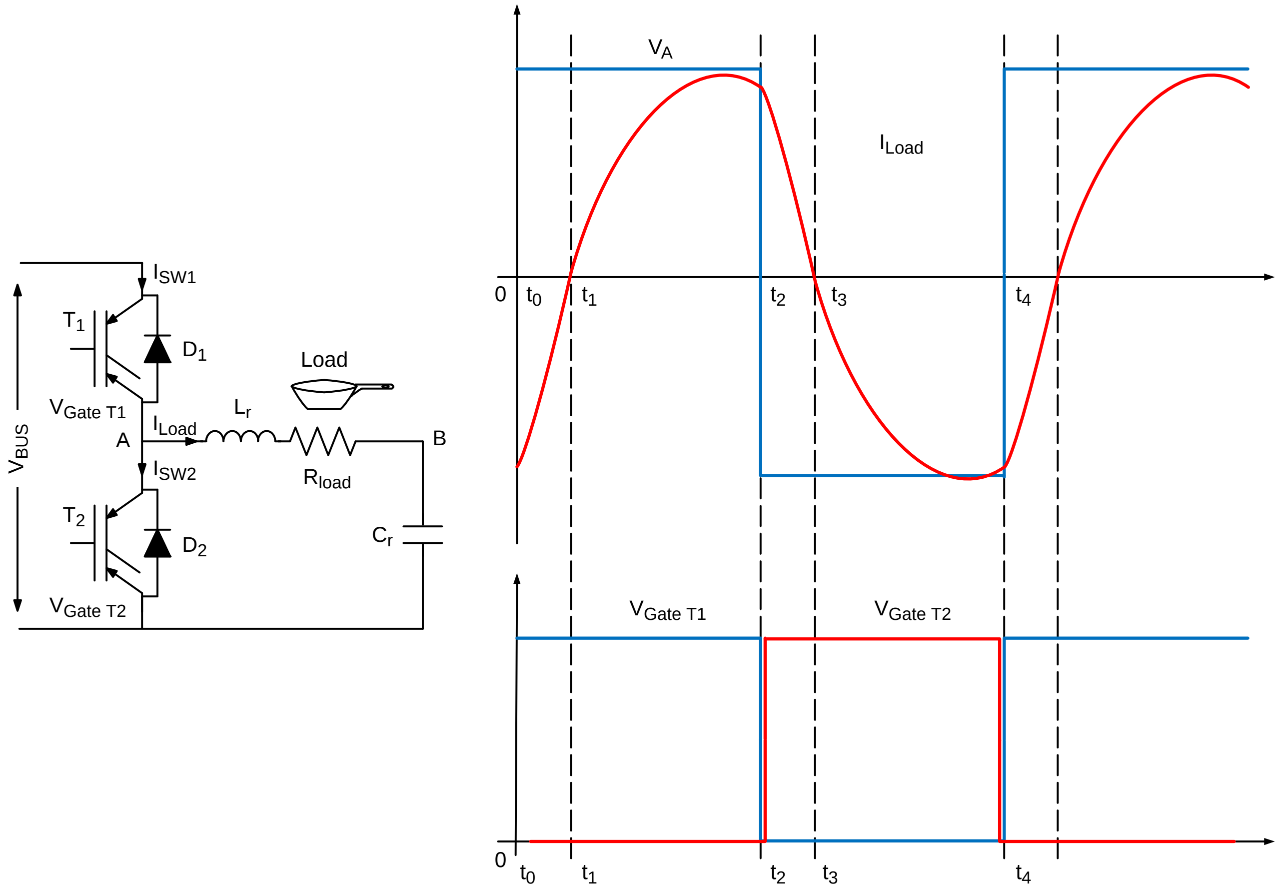



**Figure 17. Resonant Half-Bridge Waveforms for a Switching Frequency > Resonant Frequency. Upper Graph: Load Current (Red) and Voltage at the Central Point A (Blue). Lower Graph: Gate Voltage for the Higher Side IGBT (Blue) and the Lower Side IGBT (Red).**

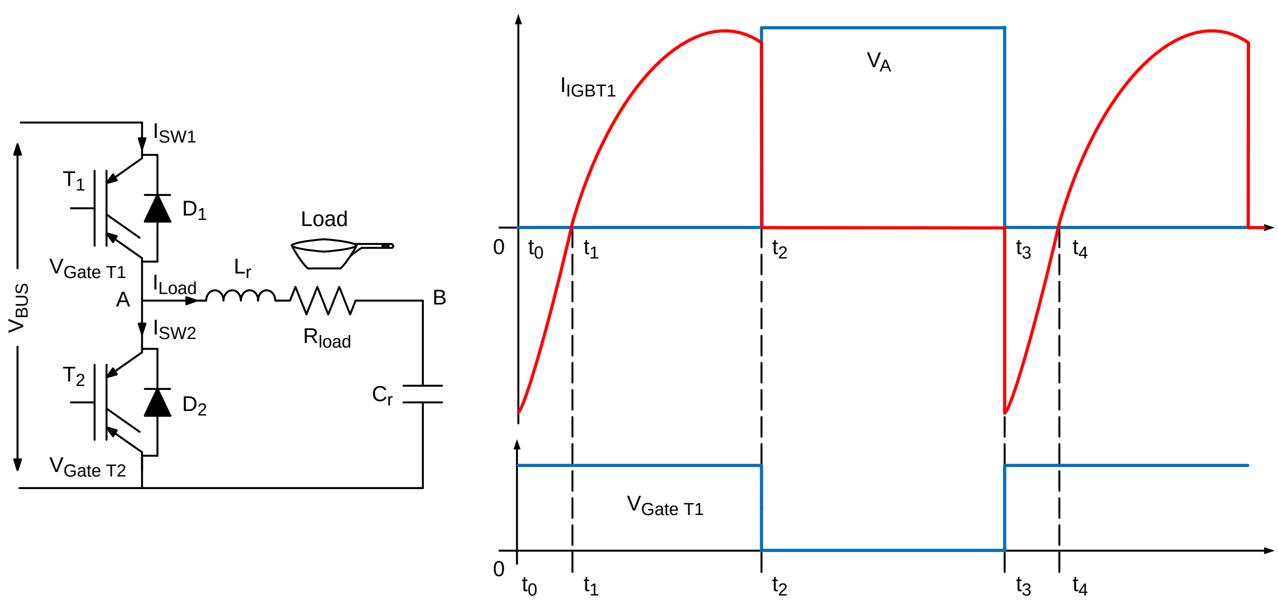



**Figure 18. Resonant Half-Bridge Waveforms for the High Side IGBT T1 for Switching Frequency > Resonant Frequency. Upper Graph: IGBT1 Current (Red) and Voltage Collector Emitter IGBT1 (Blue). Lower Graph: Gate Voltage for the Higher Side IGBT (Blue).**

**Quasi-Resonant**

Quasi-Resonant (QR) converters [13] [14] [15] [16] [17] [18] are widely used as AC power supplies like induction heating cooktop or microwave inverter applications for supplying the magnetron. Such converters are quiet attractive for the domestic appliances because it requires only one switch, usually an IGBT, and only one resonant capacitor. QR converters might be considered as a good compromise between cost and energy conversion efficiency. These are very common for single burner, counter top units in the Asian market.

One drawback of this family of converter is the limited regulation range, which is commonly defined as the ratio between the maximum power level (limited by the maximum admitted voltage across the switch), and the minimum power settable (limited by the loss of the Zero Voltage Switching condition ZVS or Soft-Switching mode). While it is desirable to operate in the ZVS mode, IH cookers are normally allowed to operate at power levels at which the resonant voltage does not quite reach zero. At power levels lower than this, the overall power modulation is pulse-width-modulated at a very low frequency to limit the losses. In this low power mode of operation, the unit may operate at the low power level for 1 second and then be off for 1 second. This is much shorter than the thermal time constant of the pan and its contents, and has no negative effect of the cooking operation; however, it does help to maximize the efficiency of the power stage and limit the temperature rise of the IGBT switch.

For a given loading condition (i.e. a certain pot), maximum power level, and maximum mains voltage, the peak voltage rating for the switch and resonant capacitor (i.e. 1,200 V), can be calculated from QR theory and can be approximated by Eq. 17.

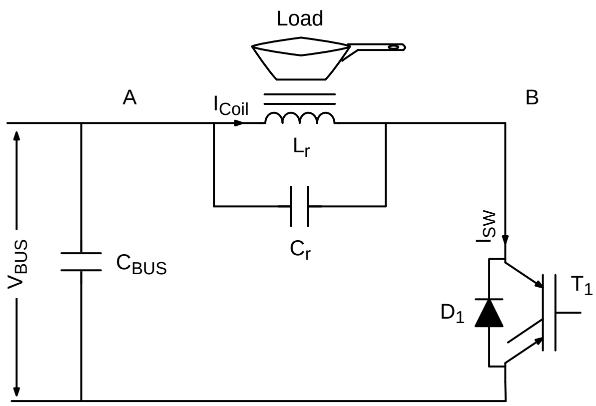



**Figure 19. Impedance Module and Phase of the Equivalent Half-Bridge Resonant Circuit**

$$V_{res} \cong \sqrt{\frac{2 \cdot E}{C}} \qquad \text{(eq. 17)}$$

where E is the energy stored into the inductive part of the load during the $T_{ON}$ phase

$$E \cong \frac{1}{2} L \cdot I_{pk}^2 \qquad \text{(eq. 18)}$$

the peak current is proportional to $T_{ON}$, $V_{dc\text{-}bus}$

$$I_{pk} = T_{ON} \cdot \frac{V_{dc-bus}}{L} \qquad \text{(eq. 19)}$$

the resonant voltage $V_{res}$ can be expresses in terms of $T_{ON}$ and $V_{dc\text{-}bus}$

$$V_{res} \cong \frac{T_{ON} \cdot V_{dc-bus}}{\sqrt{LC}} \qquad \text{(eq. 20)}$$

Usually $T_{ON}$ is kept constant throughout the mains semi period.

*Operating Principle of the Quasi-Resonant Converter*

For the operation of QR converter there are two main phases of operation (see Figure 20): a charging phase where the system behaves as a LR 1st order system and a resonant phase where the system acts as LRC 2nd order system. QR converters operate according to a two phase sequence where during the first phase the coil ($L_r$) is charged keeping the switch $T_1$ in an on state and delivering power to the load due to the current in the inductor. During the second phase the energy stored in the inductor is transferred to the resonant capacitor ($C_r$) and partially dissipated into the load, which is represented to the bottom layer of the Pot. The energy dissipated into the resistor is the actual energy delivered to the load. To evaluate the circuit operation over both the steady-state and switching portions, we will break to waveform into four intervals: ($0-t_0$), ($t_1-t_2$), ($t_2-t_3$), and ($t_3-t_4$). From the previous interval (before the time 0) the resonant thank was oscillating. At the 0 time on the graph in Figure 20 the diode $D_1$ is conducting and the gate of $T_1$ is switched off. This continues until time $t_0$. At $t_0$ the current goes from negative to positive and starts to flow through $T_1$. Therefore, in the QR converter the turn-on switching losses are theoretically eliminated, the Miller effect is absent and the reverse recovery current of the diode flows through $T_1$ without any further losses into the resonant circuit. In the QR the turn off losses are relevant due to the transition between the high current and the high voltage. In fact at $t_1$ switch $T_1$ is turned off while the current is still high and this leads to an overlap with the voltage causing turn off losses into the device. Also the Miller effect leads to an increase of the losses. After the turn off of the device the resonant thank starts to oscillate. This resonant phase can be split in to intervals $t_1-t_2$ voltage across the device positive and current into the coil positive and $t_2-t_3$ voltage across the device still positive but current into the coil negative.

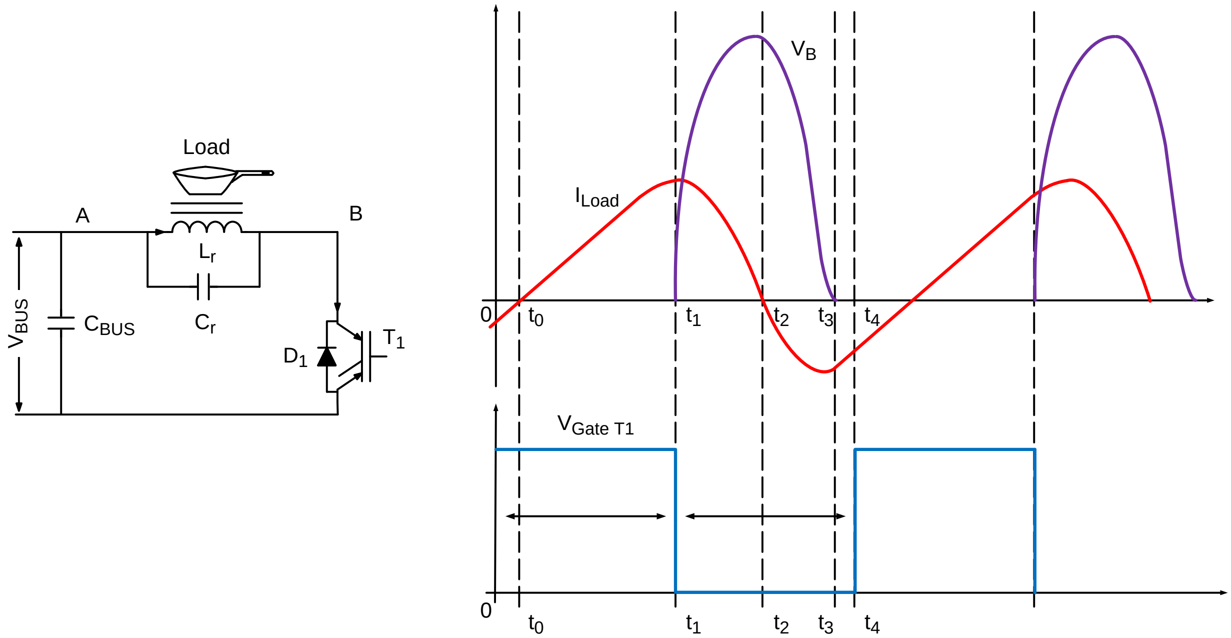



**Figure 20. Quasi-Resonant Inverter Waveforms.**
**Upper Graph: Red-waveform is the Current into the Coil $L_r$, while the Purple-waveform is the Voltage across the Power Devices (T1+D1).**
**Lower Graph: IGBT Fate voltage**

**Control**

Let's focus a bit on the control algorithm for the two structures. The control circuits for the two topologies vary greatly in their fundamental mode of operation. The Resonant half-bridge inverter is frequency controlled. The switching frequency is fixed for a given power level and the two control gate signals (for the High Side IGBT and the low side) are shifted 180° with a fixed duty of 50% (although it should be noted that there must be a dead time between the two signals in order to avoid cross conduction). Alternately, the Quasi-Resonant inverter is $T_{ON}$ controlled. The on-time ($T_{ON}$) is fixed for a certain power level and the off-time ($T_{OFF}$) is determined by the resonant tank ($L_r$ and $C_r$).

Following are flowcharts for the Quasi-Resonant and resonant half-bridge topologies. In Figure 21 a flow chart of a generic control algorithm for resonant half-bridge inverter for induction cooking is presented. The first step of the control algorithm is to check that the input voltage is within the limits (minimum and maximum input voltage range). If this condition is verified it goes to the next step and closes the main relay. After that it waits for the zero crossing in order to synchronize timers and acquisitions. After that pan detection occurs. This process consists of checking the presence of the pan. If the pan is detected the control will move to the next step otherwise it will stop. Then a frequency sweep will be performed. Upon starting, a frequency will be applied and the relative power delivered to the load will be calculated. From this point the initial frequency will be increased and/or decreased in order to generate a table where the switching frequencies are associated with their corresponding power levels. Then the user request will be processed, selecting a switching frequency from the afore mentioned table and a comparison between the power requested and the power delivered will be performed within a certain time interval in order to deliver the requested power. If the power exceeds the request, the switching frequency will be increased, otherwise it remains constant. In case the actual power is less than the request the switching frequency will be decreased. In parallel with this process all the protections will be functional.

In Figure 22 a flow chart of a generic control algorithm for Quasi-Resonant single switch inverter for induction cooking is presented. The control is pretty much the same as the one for the resonant half-bridge. One of the main differences is the driving algorithm. In the resonant half-bridge the driving quantity is the switching frequency with a constant duty ratio, whereas in the Quasi-Resonant the driving quantity is the $T_{ON}$ [13].

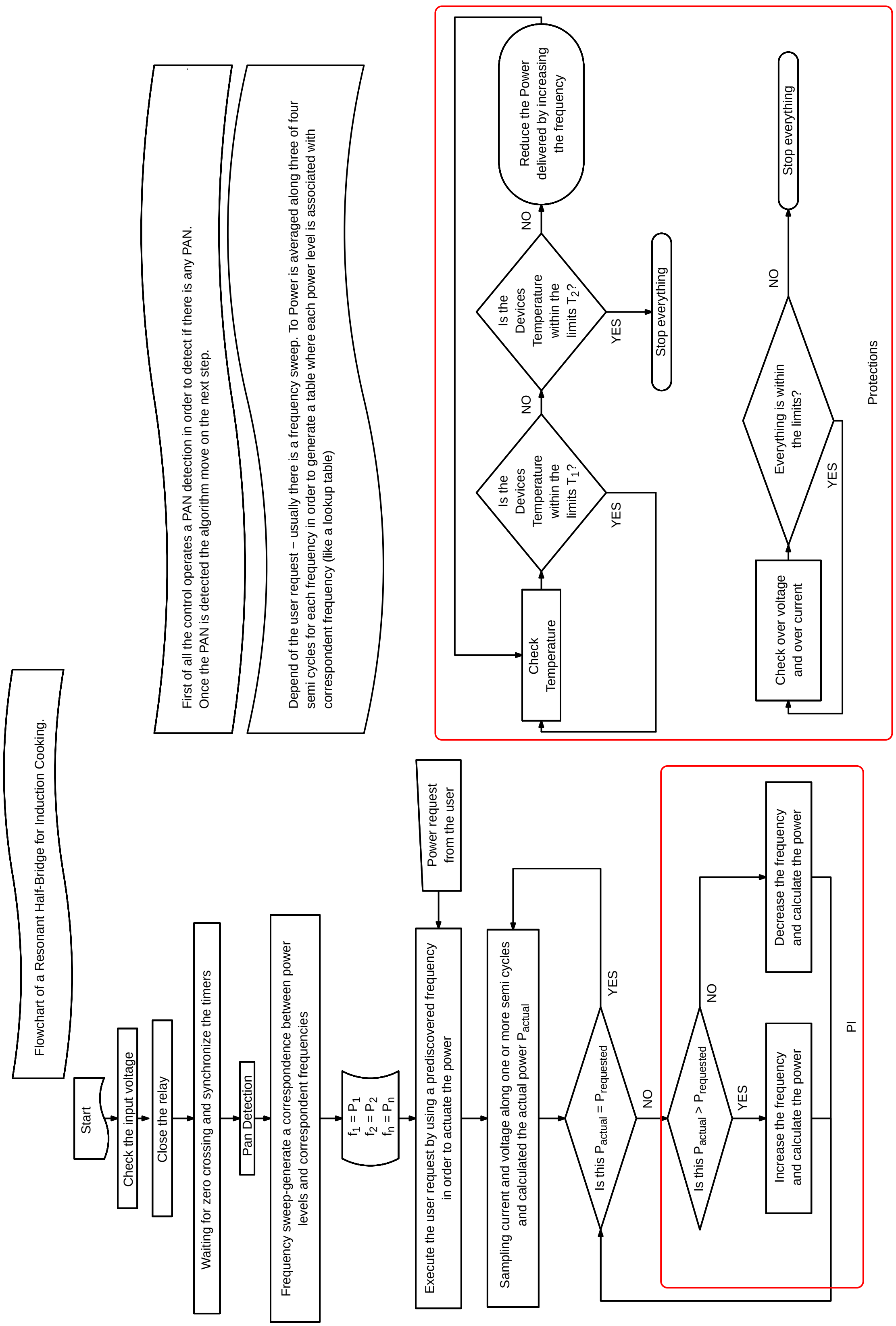



**Figure 21. Flow Chart of a Generic Resonant Half-Bridge for Induction Cooking Control Algorithm**

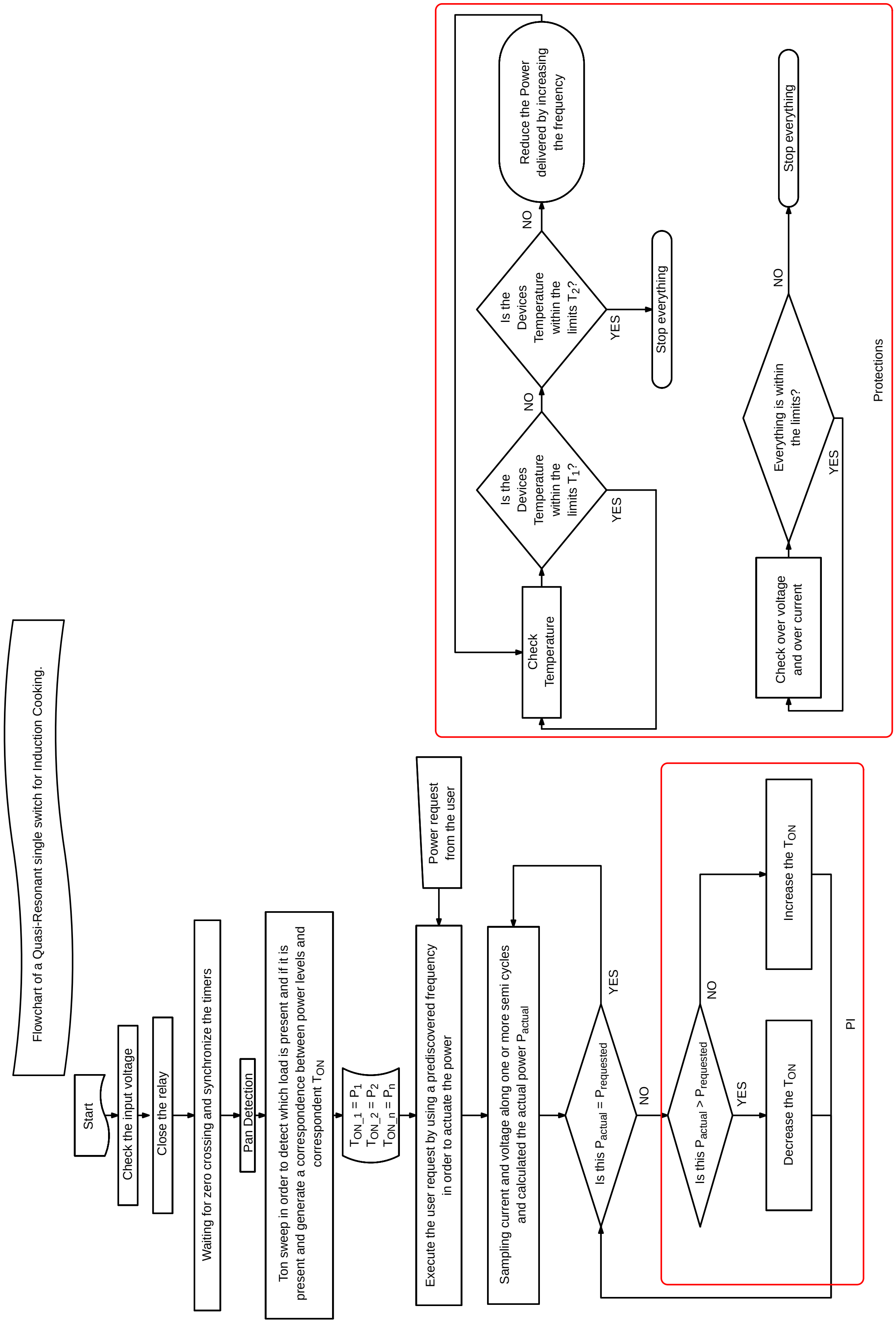
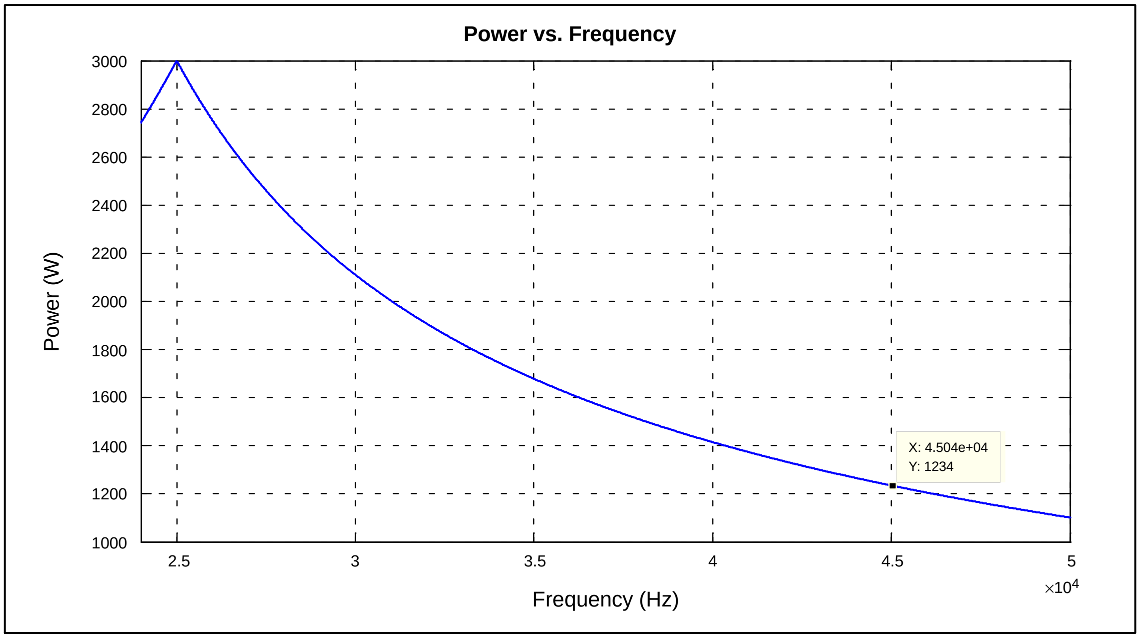



**Figure 22. Flow Chart of a Generic Quasi-Resonant for Induction Cooking Control Algorithm**

## WAVEFORMS DURING NORMAL OPERATION

In this paragraph we will show actual waveforms of the two converters during normal operation. Figure 23 shows the power and the phase of a resonant half-bridge for induction cooking with resonant tank composed of a resonant coil of 29.5 μH and a resonant capacitor of two times 680 nF.



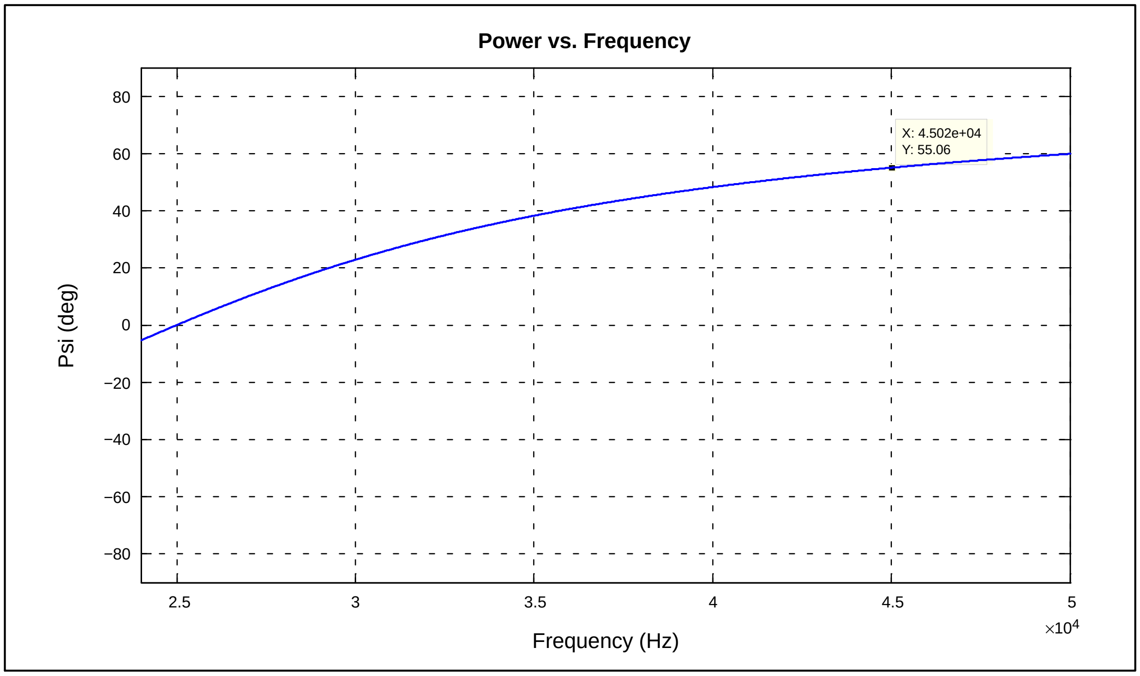




**Figure 23. $V_{in}$ 220 Vac − 1200 W Power and Phase for a Resonant Half-Bridge Inverter for a Cooking Application**

Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, and Figure 29 show the normal operation waveforms of a resonant half-bridge inverter for different switching frequencies starting from 45 kHz (1,200 W) down to 24.7 kHz (2,450 W). The current's shape changes with the frequency. As the closer that the switching frequency is to the natural resonant frequency, the more sinusoidal the current into the coil (as was presented in Figure 15).

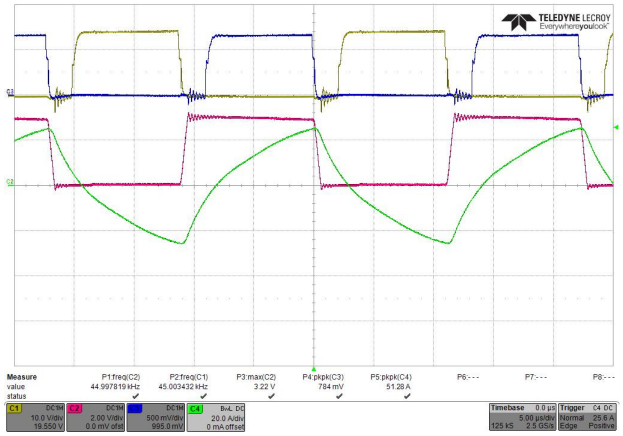


**Figure 24. $V_{in}$ 220 Vac − 1200 W – 45 kHz Switching Frequency Operation for a Resonant Half-Bridge Inverter: C1 Low Side IGBT Gate Voltage (10V/div) C2 Low side IGBT Collector Emitter Voltage (200 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Coil-Load Current (20 A/div). Time 5 μs/div**

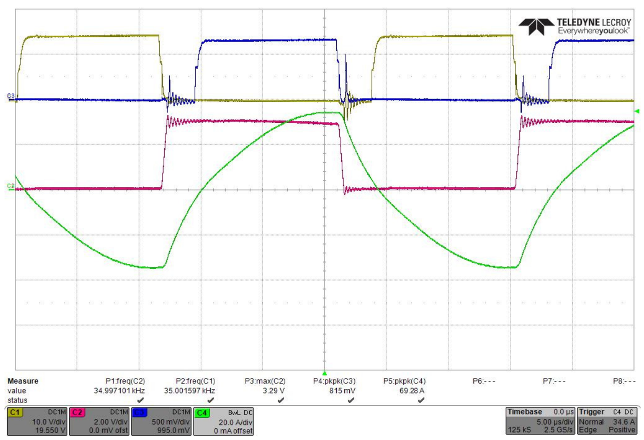


**Figure 25. $V_{in}$ 220 Vac − 1500 W – 35 kHz operation for a Resonant Half-Bridge inverter: C1 Low Side IGBT Gate Voltage (10 V/div) C2 Low side IGBT Collector Emitter Voltage (200 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Coil-Load Current (20 A/div). Time 5 μs/div**

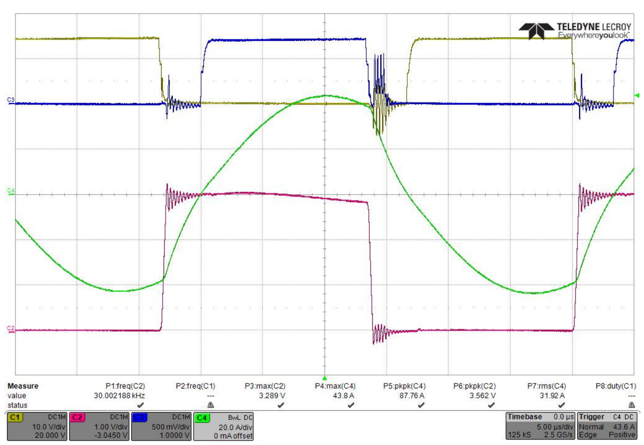


**Figure 26. $V_{in}$ 220 Vac − 1800 W – 30 kHz Operation for a Resonant Half-Bridge Inverter: C1 Low Side IGBT Gate Voltage (10 V/div) C2 Low side IGBT Collector Emitter Voltage (100 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Coil-Load Current (20 A/div). Time 5 μs/div**

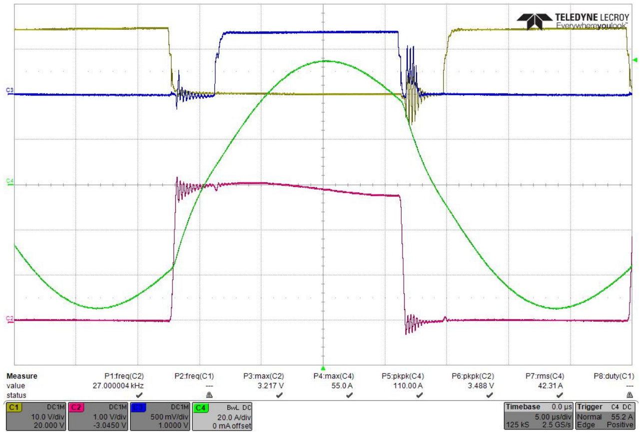



**Figure 27. $V_{in}$ 220 Vac − 2300 W – 27 kHz Operation for a Resonant Half-Bridge Inverter: C1 Low Side IGBT Gate Voltage (10 V/div) C2 Low side IGBT Collector Emitter Voltage (100 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Coil-Load Current (20 A/div). Time 5 μs/div**

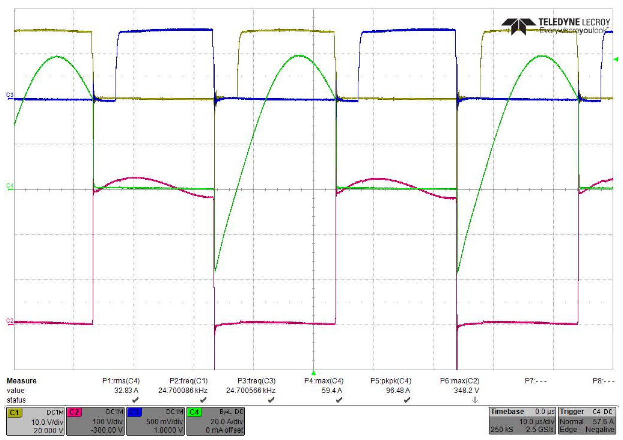



**Figure 28. $V_{in}$ 230 Vac − 2450 W – 24.7 kHz Operation for a Resonant Half-Bridge Inverter: C1 Low Side IGBT Gate Voltage (10 V/div) C2 Low side IGBT Collector Emitter Voltage (100 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Low Side IGBT Collector Emitter Current (20 A/div). Time 10 μs/div**

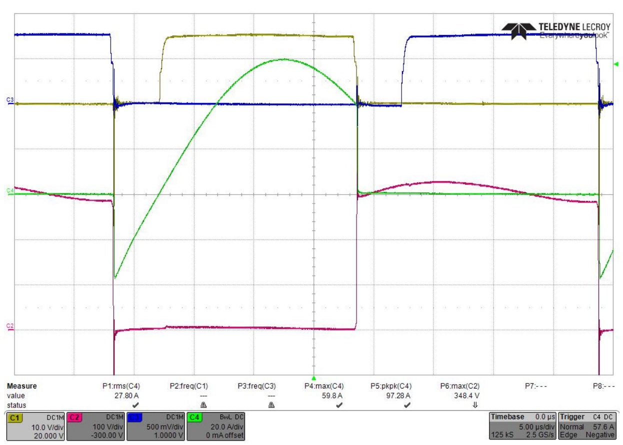



**Figure 29. $V_{in}$ 230 Vac − 2450 W – 24.7 kHz Operation for a Resonant Half-Bridge Inverter: C1 Low Side IGBT Gate Voltage (10 V/div) C2 Low side IGBT Collector Emitter Voltage (100 V/div) C3 High Side IGBT Gate Voltage (10 V/div) C4 Low Side IGBT Collector Emitter Current (20 A/div). Time 5 μs/div**

Figure 30 and Figure 31 show the normal operation waveforms of a Quasi-Resonant inverter for cooking applications. Figure 32 shows the current in the resonant coil.

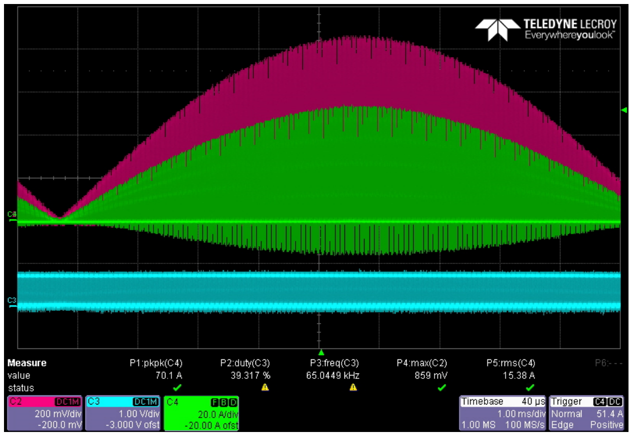



**Figure 30. $V_{in}$ 220 Vac − 2100 W – 65 kHz operation for a Quasi-Resonant Inverter: C2 IGBT Collector Emitter Voltage (200 V/div) C3 IGBT Gate Voltage (20 V/div) C4 IGBT Collector current (20 A/div). Time 1 ms/div**

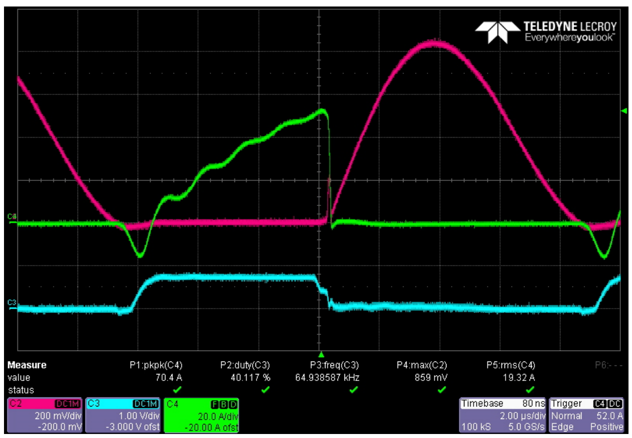



**Figure 31. $V_{in}$ 220 Vac − 2100 W – 65 kHz Operation for a Resonant Half-Bridge Inverter: C2 IGBT Collector Emitter Voltage (200 V/div) C3 IGBT Gate Voltage (20 V/div) C4 IGBT Collector current (20 A/div). Time 2 µs/div**

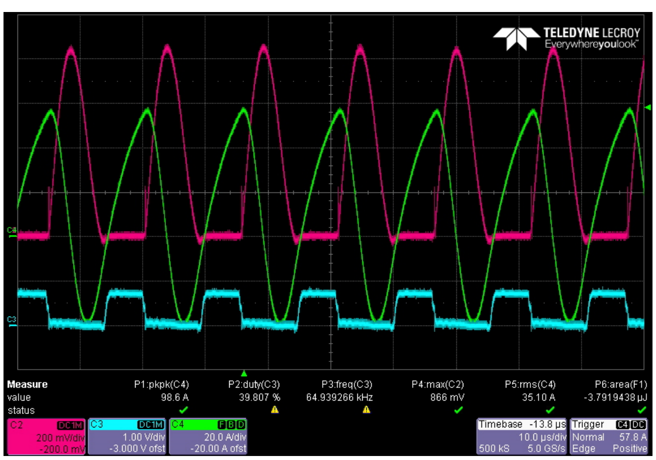



**Figure 32. $V_{in}$ 220 Vac − 2100 W – 65 kHz Operation for a Resonant Half-Bridge Inverter: C2 IGBT Collector Emitter Voltage (200 V/div) C3 IGBT Gate Voltage (20 V/div) C4 IGBT Collector current (20 A/div). Time 10 µs/div**

## CONCLUSION

Induction heating technology for cooking applications is a very attractive technology which is becoming very popular due to the high conversion efficiency. In this application note a comprehensive overall description of how induction heating for cooking systems works has been discussed. The matters described provide not only a background of the phenomena behind the concept of induction heating in general, but also an overview of the currents technologies and controls algorithms. Furthermore some practical waveforms for the most popular topologies, the Quasi-Resonant and the Resonant Half-Bridge are included.

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## GLOSSARY

| | |
|---|---|
| Induction Heating | IH |
| Alternating Current | AC |
| Magnetic Field Intensity | H |
| Flux Density | B |
| Permeability | $\mu$ |
| Permeability in Free Space | $\mu_0$ |
| Relative Permeability | $\mu_r$ |
| Electromotive Force (EMF) | e |
| Magnetic Flux | $\Phi$ |
| Number of Turns | N |
| Current Density | J |
| Current Density at the Surface of the Conductor | $J_S$ |
| Skin Depth | $\delta$ |
| Depth | d |
| Resistivity of the Conductor | $\rho$ |
| Angular Frequency | $\omega$ |
| Power Converted from Electrical Energy to Thermal Energy | $\dot{Q}$ |
| Equivalent Resistance of a Conductor | R |
| Zero Voltage Switching | ZVS |
| Zero Current Switching | ZCS |
| Half-Bridge | HB |
| Quasi-Resonant | QR |
| Impedance of the Circuit from the Generator Point of View | $Z_{series}$ |
| Angular Resonant Frequency | $\omega_0$ |
| Quality Factor | Q |
| Resonant Frequency | $f_{res}$ |
| Phase between the Current and the Voltage | $\varphi$ |
| Insulated Gate Bipolar Transistor | IGBT |
| Metal-Oxide-Semiconductor | MOS |
| Bipolar Junction Transistor | BJT |
| Punch Through | PT |
| Non Punch Through | NPT |
| Filed Stop Technology | FS |



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