# ON Semiconductor

# Is Now

To learn more about onsemi™, please visit our website at
www.onsemi.com

# AND9054/D

# IGBT Power Losses in Induction Heating Applications

ON Semiconductor®

http://onsemi.com

## APPLICATION NOTE


### Abstract

IGBTs with blocking voltages of about 1200 V are widely used in single-ended induction heating applications. During turn-off, the high voltage impressed across the IGBT together with its residual current cause considerable turn-off losses. During the on-state of the IGBT, the power lost due to variation of its saturation voltage with load current and junction temperature adds to the total loss in power. These losses reduce the overall efficiency of these applications. Understanding the cause of these losses, and developing a reliable and relatively fast method to measure them is important especially during an IGBT design optimization process.

In this paper, the principle of induction heating together with the switching waveforms will be explained. Additionally, two methods to measure IGBT power losses will be presented.



### Keywords

Induction heating, soft switching, ZVS, conduction loses, turn-off losses.


### List of Symbols and Abbreviations

| | |
|---|---|
| ZVS | Zero Voltage Switching |
| $T_S$ | Switching Period |
| ZCS | Zero Current Switching |
| NPT | Non-Punch Through |
| $V_{CE(sat)}$ | Collector Emitter Saturation Voltage |
| $V_{CE}$ | Collector Emitter Voltage |
| D | Duty Cycle |
| $T_S$ | Switching Period |
| $E_{off}$ | Turn-off Losses |
| $E_{cond}$ | Conduction Losses |
| $V_{dc}$ | Rectified Voltage |
| $I_{CE}$ | Collector-Emitter Current |
| $T_J$ | Junction Temperature |

### Introduction

In recent years, increases in the number of household electrical appliances have led to an increase in energy consumption per household. The cost of energy associated with using these appliances has also increased because most present day electrical appliances, such as the electric cooker, are not very efficient. As such, a considerable amount of the power obtained from the grid is not being used to do useful work. One way to maximize the amount of power obtained from the grid is to develop more energy efficient electrical appliances.

One such energy efficient device is the induction cooker. Unlike the standard household electric cooker, the induction cooker uses electromagnetic generated heat energy for cooking. This method of cooking makes the induction cooker about 25% more efficient than the electric cooker. Moreover the heat generated through induction does not heat the air around the cooker directly. As a result, there is less adverse effect on the air conditioning of the cooking environment. Additionally, induction cookers cook faster than traditional electric and gas cookers for the same input power level.

### Principle of Induction Heating

Figure 1 shows a typical single-ended topology used for induction heating applications.

Magnetic energy is generated and transferred to the cooking vessel using the principle of electromagnetic induction and is transformed into thermal energy at the cooking vessel.

This principle involves rectifying the relatively low frequency ac line input voltage using an uncontrolled switching device such as a diode.

Switching the rectified voltage at a frequency between 20 kHz to 35 kHz produces a high frequency magnetic flux. The cooking vessel acts as a lossy magnetic core which converts the magnetic field into heat.

The main components used to generate and transfer this heat energy are the pan or cooking vessel, an inductor, a resonant capacitor, and the IGBT.

The geometry of the inductor winding is important in generating the magnetic field required to generate and transfer the heat.

The inductor windings are spiral in shape. The wires are wound around each other in a horizontal plane. This geometrical arrangement increases the surface area of the magnetic flux.

The concentration of these magnetic flux lines around the pan is further enhanced by using rectangular-shaped ferrite magnet bars, placed at equal intervals around the inductor windings.

The inductor windings are also multi-filar. The use of multiple small conductors minimizes skin effect and reduces the IR losses in the coil.

The inductor Lr is an air core inductor by design. The cooking vessel must be made of a magnetic material and acts as a core. At the switching frequency of the IH cooker, the thickness of the pan is much too great for an efficient core and the eddy current losses are substantial. These losses convert the magnetic field into thermal energy. This generates a great amount of heat in the pan and cooks the food.

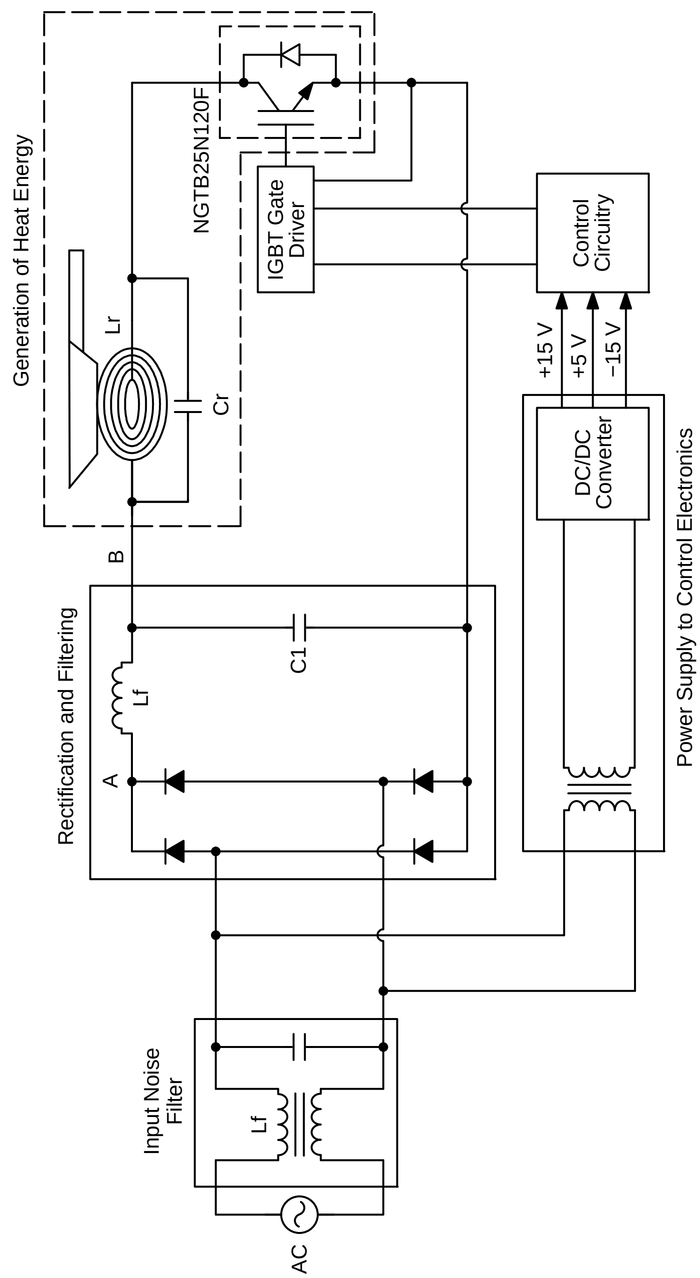


Figure 1. Block Diagram of a Single-ended Induction Cooker

### Switching Waveform Analysis

Figure 2 shows the typical switching waveforms for a single ended induction heating application. Sections of the waveform will be described based on the switching states of the co-packaged diode and the IGBT.

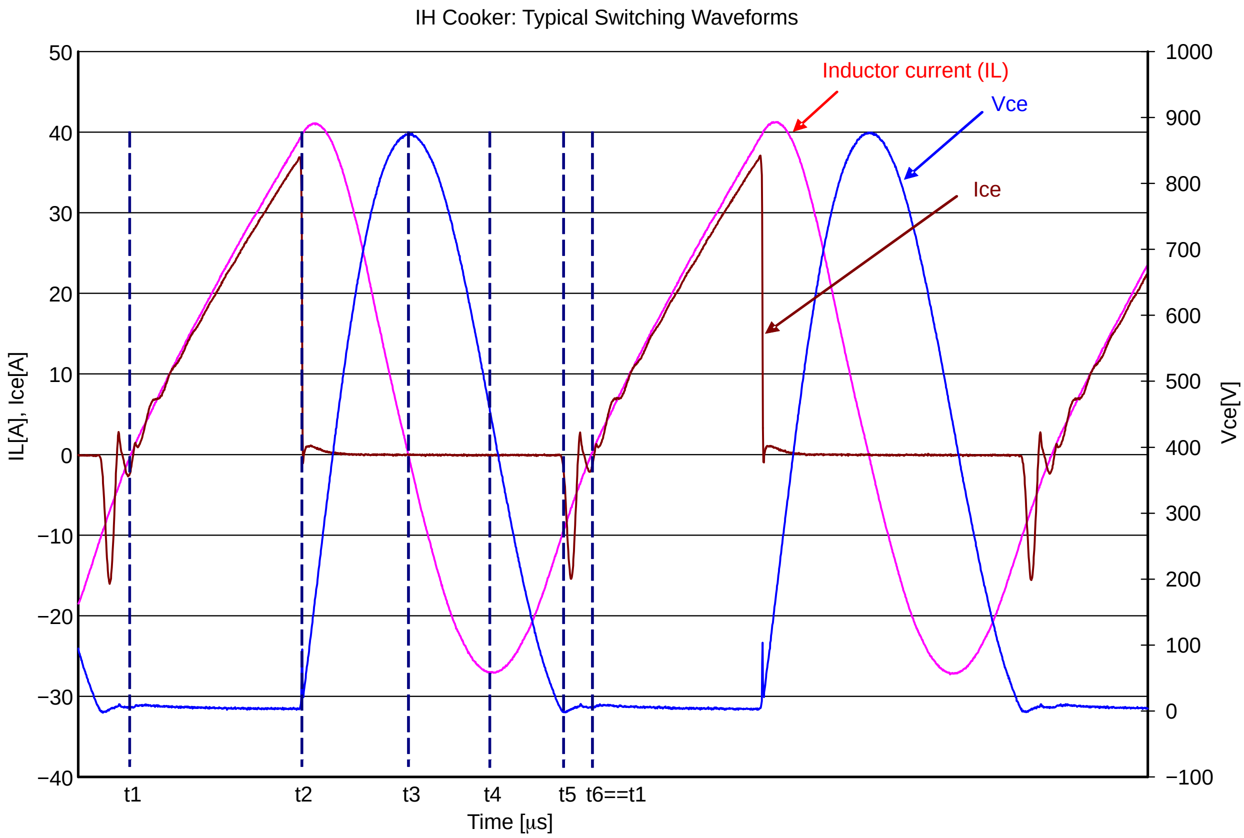


**Figure 2. Typical Switching Waveforms for a Single Ended Induction Cooker**

The initial switching state, t1, is defined as the time when the IGBT turns-on and the co-packaged diode is not conducting. Before t1, the co-packaged diode is conducting and $V_{CE}$ is one diode drop negative.

### Switching State 1: $t_1 < t \le t_2$: IGBT ON, Co-packed Diode OFF

At t1, the IGBT starts conducting and $V_{CE}$ equals $V_{CE(sat)}$. The current flowing through the IGBT rises linearly as defined by Equation 1. The LC tank inductor stores energy at this point. At t2, the IGBT is switched-off.

$$V_L = V_{dc} - V_{ce} = L\frac{di_L}{dt} = L\frac{di_{CE}}{dt}$$

$$i_{CE} = \frac{1}{L}\int_0^{t_{ON}} \left(V_{dc} - V_{ce}\right)dt \qquad \text{(eq. 1)}$$

$$= \frac{1}{L}\left(V_{dc} - V_{ce}\right) t_{ON} + i_{CE}(t = 0)$$

### Switching State 2: $t_2 < t \le t_5$ IGBT OFF, and Co-packed Diode OFF

When the IGBT is turned-off at t2, the energy stored in the LC tank inductor starts being transferred to the LC tank capacitor. $V_{CE}$ rises with a slew rate of about 100 V/μs to 200 V/μs and reaches its maximum value at the instant where the inductor current crosses the zero axes. At t3, the LC tank capacitor starts transferring energy back to the LC tank inductor. The energy is being transferred to the capacitor as long as the inductor current slope is negative. Half of the cycle current is building in the inductor (from T4 to T2) and the other half (from T2 to T4) the current is reducing. At t4, $V_{CE}$ goes lower than the dc bus voltage. The current through the LC tank reaches its maximum negative value at this point. At t5, the voltage across the inductor becomes greater than the dc bus voltage and $V_{CE}$ becomes negative.

**Switching State 3: $t_5 < t \le t_6$ IGBT OFF, and Co-packed Diode ON**

When $V_{CE}$ becomes negative, the co-packaged diode starts to conduct. To achieve ZVS, the IGBT gate signal is applied at t5. However, the IGBT does not conduct at this time. It starts conducting only when the co-packaged diode stops conducting.

This represents the full switching cycle which repeats itself beginning at switching state 1.

**IGBT Power Losses in IH Applications**

The total power lost in the IGBT in this application consists of turn-on, conduction, turn-off and diode losses. The contribution of the diode losses to the total power losses is negligible, and the turn-on losses can be significantly minimized, if the application employs ZVS techniques. However, ZVS is not achieved at all operating power levels of the IH cooker.

Since one end of the tank circuit is connected to the rectified input voltage, zero-state switching only occurs at power levels that resonate the tank circuit such that it reaches zero volts. Under some light load conditions, the tank circuit voltage will not reach zero volts on the collector of the IGBT and therefore zero-state switching is not achieved and the turn-on power losses will increase.

The most dominant contributors to the total power loss are conduction and turn-off losses.

**Conduction Losses**

The average power dissipated by the IGBT is expressed mathematically in Equation 2.

$$P_{Ave} = \frac{1}{T_S} \int_0^{T_S} \left[ V_{CE}(t) \times I_{CE}(t) \right] dt \qquad \text{(eq. 2)}$$

For conduction losses, Equation 2 can be re-written as follows.

$$P_{Ave} = V_{CE(sat)}\left(t,\ I_{CE},\ T_j\right) \times I_{CE} \times D \qquad \text{(eq. 3)}$$

Equation 3 shows that conduction losses are dependent on the load current, $V_{CE(sat)}$, and the duty cycle. The value of $V_{CE(sat)}$ is not constant but varies over time. It is also dependent on the load current, and the IGBT's junction temperature.

In the IH cooker application, the control circuitry varies the duty cycle in direct proportion to the demand in cooking power. Consequently, conduction losses will therefore be highest at the highest cooking power level because all the parameters in Equation 3 will have their maximum values at the highest cooking power level.

Figure 3 shows the variation of $V_{CE(sat)}$ with $I_{CE}$ at $T_J = 67°C$ for a selected switching cycle. The data in Figure 3 was obtained from a commercially available IH cooker, and a clamped circuit was used to measure $V_{CE(sat)}$. This circuit clamps Vce at 10 V when the IGBT is switched-off which allows the oscilloscope to use a low volt/div setting so that $V_{CE}$ can be accurately measured.

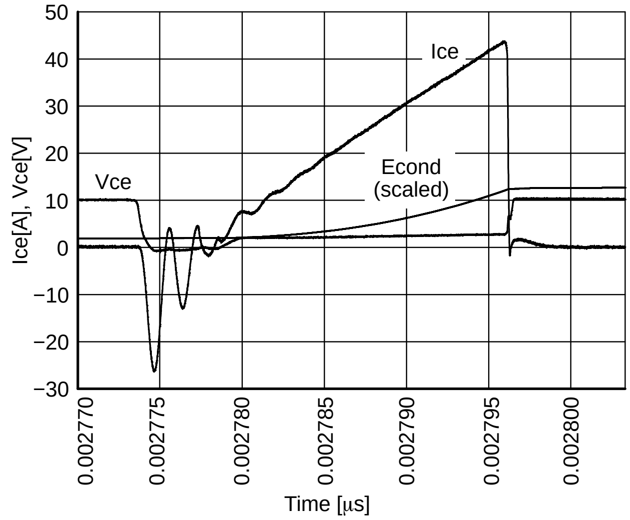


**Figure 3. Variation of $V_{CE(sat)}$ with $I_{CE}$ at $T_J = 67°C$**

**Turn-off Losses**

Figure 4 shows the turn-off section of the IH cooker waveforms.

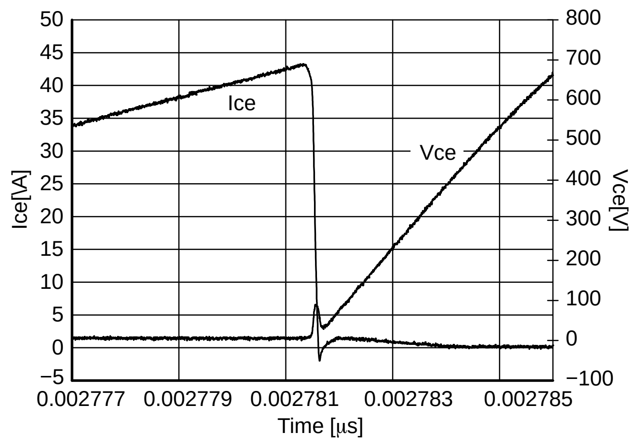


**Figure 4. Measurement of Turn-off Losses using a Digital Storage Oscilloscope**

These losses are influenced by the IGBT's residual current, the slew rate of $V_{CE}$, and the switching frequency.

The residual current results from minority carriers trapped in the drift region after the IGBT is switched-off. Factors which influence the rate of combination of these minority charge carriers include the doping concentration, the buffer layer thickness, and doping technology. The switching frequency is determined by the desired cooking power level, and the switching control algorithm of the application.

During the design, and development stages of an IGBT process, it is important to verify its performance in the target application during each development stage. This performance verification can be done by measuring the IGBT's losses in the application. If conduction and turn-off losses are to be measured separately, then a digital storage oscilloscope can be used. On the other hand, heat sink temperature measurements can be employed if measurement of the total power losses is desired.

### Measuring Conduction and Turn-off Losses Using a Digital Storage Oscilloscope

Accurate power loss measurement is obtained by setting-up the oscilloscope, and measurement probes correctly.

The following steps should be taken to properly set-up, and calibrate the measurement probes, as well as the oscilloscope measurement channels. This example uses channels 3 and 4 of the TDS5054B Tektronix oscilloscope as measurement inputs.

1. **Calibrating channels 3 and 4.** Disconnect all probes connected to the oscilloscope channels. Go to the main menu of the oscilloscope and select Utilities−>Calibrate channels. This process may take about 10 minutes.
2. **Setting-up the Current Probe.** Connect the current probe to channel 4 of the TDS5054B. Then connect the current probe ground terminal to the ground connector of the oscilloscope. Close the loop of the current probe and press the ‘Degause’ knob on the current probe. Use the scroll knob on the current probe and set the offset to as close to zero as possible. Use oscilloscope vertical waveform cursors to note the value of the offset.
3. **Setting-up the Voltage Differential Probe.** Connect the voltage probe to channel 3. Set the scale intended to be used to take measurements. Select the scale such that the voltage waveform will fill the entire oscilloscope. Use the offset knob on the voltage probe to set the offset to as close to zero as possible.
4. **Compute Energy Losses.** Equation 4 can be used to compute the energy lost during conduction and turn-off using the built−in oscilloscope math functions.

$$W(t) = \int_0^t \left[V_{CE}(t) \times I_{CE}(t)\right] dt \qquad \text{(eq. 4)}$$

Using the TDS5054B Tektronix oscilloscope, for example, this expression can be entered into the ‘Math Equation Editor’. After capturing $I_{CE}$ and $V_{CE}$ waveforms as shown in Figures 3 and 4, the oscilloscope cursors can be placed at sections of the waveforms corresponding to the IGBT conduction, and turn-off time periods.

Next, the cursors are switched to the math function representing Equation 5. The math function then computes automatically the dissipated power within the selected waveform interval. Isolated differential probes such as the P5205 should be used to measure $V_{CE}$. The TCP202 current probe can be used to measure $I_{CE}$.

### Measuring Total Losses Using Heat Sink Temperature Measurements

In this procedure, a known amount of power is dissipated on the IH heat sink, using a switching device which can be operated in its linear region. The heat sink temperature rise is then measured, and its difference from ambient temperature, $\Delta T_{SA}$ is plotted against the known dissipated power. A suitable switching device to use is a Darlington Bipolar Transistor, and the test should be done with the transistor as the only device on the heat sink.

This method requires that the reference heat sink data use the same air flow as in the cooker to be able to correlate the heat sink temperature in the cooker to a known power level.

Next, the IGBT is mounted on the same heat sink in the IH cooker, and the cooker is operated under identical environmental conditions. Only the IGBT should be mounted on the heat sink. Using the measured heat sink temperature, and the gradient of the plot previously obtained, the value of the total dissipated power can be calculated.

Figure 5 shows the relation between $\Delta T_{SA}$ and the total dissipated power using the above method. ON Semiconductor’s MJ11032 Darlington Transistor was used to provide this data, and the test was done in an IH cooker test environment.

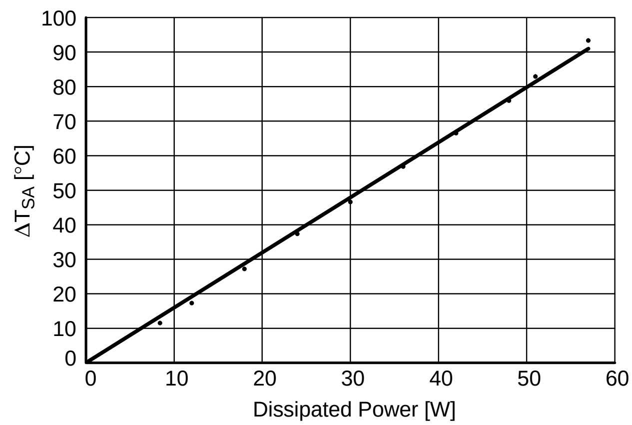


**Figure 5. Variation of $\Delta T_{SA}$ with Total Dissipated Power**

## Summary and Conclusion

In soft-switching IH cooker applications, conduction losses and turn-off losses are the most important losses to be considered when designing an IGBT for use in these applications. Both losses contribute comparably to the overall power losses. Therefore, measuring these losses reliably provides important data which can be used to evaluate the IGBT's performance during the design process.

Two methods to measure these losses have been presented. Using a digital oscilloscope, conduction, and turn-off losses can be measured individually. Total IGBT losses on the other hand can be determined by measuring the temperature of a heat sink dedicated only to the IGBT in the application.



**PUBLICATION ORDERING INFORMATION**

**LITERATURE FULFILLMENT**:
Literature Distribution Center for ON Semiconductor
P.O. Box 5163, Denver, Colorado 80217 USA
**Phone**: 303−675−2175 or 800−344−3860 Toll Free USA/Canada
**Fax**: 303−675−2176 or 800−344−3867 Toll Free USA/Canada
**Email**: orderlit@onsemi.com

**N. American Technical Support**: 800−282−9855 Toll Free USA/Canada
**Europe, Middle East and Africa Technical Support:**
Phone: 421 33 790 2910
**Japan Customer Focus Center**
Phone: 81−3−5817−1050

**ON Semiconductor Website**: **www.onsemi.com**

**Order Literature**: http://www.onsemi.com/orderlit

For additional information, please contact your local Sales Representative