Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Multi MOSFET Series Resonant Inverter for Enhancing the Efficiency of Induction Cooktops

Nimitha M[1], Sniya Sunil[2], Dr. Devi V[3]
[1]Asst. Professor, EEE Department, [2]Student (M-Tech. Power Electronics), [3]Professor, EEE Department
NSS College of Engineering, Palakkad, Kerala, India

Abstract*— One of the most threatening problems that we witness is the increasing cost and dearth of cooking gas. An alternate method is to use Induction heating system, where electricity is used for the generation of heat. Resonant inverters featuring soft switching in which the inductor vessel system is a part of resonant tank are now used in domestic induction heating application due to their high efficiency and high power density. In this paper, the design of an improved efficiency and low profile resonant inverter for induction heating system is presented. The proposed inverter is based on a multi Metal Oxide Semiconductor Field Effect Transistor (MOSFET) cell implementation with reduced equivalent ON state resistance per chip area. By using automotive grade MOSFET devices, an inverter capable of delivering up to 4 kW has been built, reducing conduction losses against the classical Insulated Gate Bipolar Transistor (IGBT) based inverter. In addition to this, the reduced switching times of MOSFET devices decrease switching losses, further increasing the conversion efficiency. The main design challenges including the device selection, gate drive circuit, and cooling have been addressed. As a conclusion, a low profile design without fan and heat sink is obtained, which significantly improves state of the art technology in terms of efficiency and power density.
Index Terms*— Induction Heating (IH), series resonant inverter, multi MOSFET cell resonant power conversion.

I. INTRODUCTION

Induction heating (IH) is becoming the technology of choice in industrial, domestic and medical applications due to its advantages in terms of efficiency, fast and accurate heating, cleanness, and safety, among others. Increasing cost and scarcity of cooking gas forced us to think about Induction heating system for domestic purpose. Induction cooktops constitute the domestic application of the induction heating phenomena. Using this technology, the cooking object is directly heated by means of a high frequency magnetic field.

Induction heating systems normally consist of inverter, induction heating coil and heating object. Alternating current flows through the surface of a conductor and induction heating systems produce heat, based on eddy current and skin effect resistance of the coil and metal pots. A high frequency current is used to supply the inductor pot system. Inverter stage is used to generate the high frequency current required for the induction heating application. High frequency induction heating appliances can save energy while serving the same temperature with less heat loss. In general, two methods are used to generate high frequency current, they are hard switching and soft switching techniques. In hard switch mode, a specific current is turned ON or OFF at a specific voltage whenever switching occurs. This process results in switching loss. Higher the frequency, greater is the switching losses, which obstructs the efforts to raise the frequency. Soft switching or sometime called resonant technique reduce those switching losses. However, it requires devices with low ON state power losses. Inverter topologies commonly used for induction heating are the full bridge and half bridge topologies. The modulation strategies commonly applied to control output power are based on modifying either switching frequency or duty cycle to achieve the desired output power. Each power converter topology offers different performance features with specific requirements in terms of costs, and hardware and control complexity.

The main blocks of an induction cooking appliance are shown in Fig. 1. The energy taken from the mains is filtered by an EMC filter, which prevents the device from inserting interferences, and it provides immunity to voltage transients. Afterward, the voltage is rectified and filtered, generating a dc bus. A low value of filter capacitor is chosen to get a high power factor, and, as a consequence, a high ripple dc bus is obtained. Then, the resonant inverter supplies high frequency current to the induction coil. This current produces an alternating magnetic field, which causes eddy currents and magnetic hysteresis heating up the pan.

In this paper a new solution for the design of high efficiency power converter for domestic induction heating application is proposed. The proposed inverter is based on the half bridge topology, where each switching device is implemented by means of a multi MOSFET cell, which reduces the equivalent ON state resistance per chip area. In addition to this, the reduced switching times

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

of MOSFET devices decrease switching losses, further increasing the conversion efficiency and reduces cooling requirements, allowing removing the heat sink and fan.

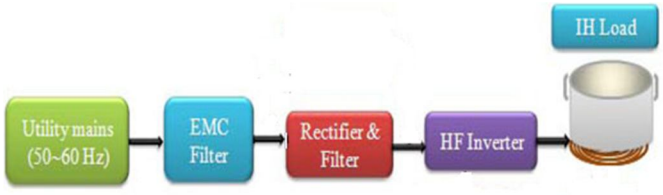


Fig. 1. Typical power conversion flow in induction heating system

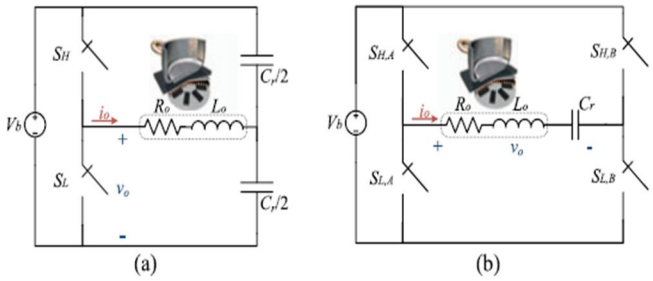


Fig. 2. Series resonant inverters for domestic induction heating application. (a) Half bridge series resonant inverter. (b) full bridge series resonant inverter

II. SERIES RESONANT INVERTERS USING MOSFET

As we are aware, the main power inverter loss occurs in the switching devices. Device losses can be divided into two terms: ON state losses, P_{ON}, caused by the current circulation through the power devices, and switching losses, P_{SW}, directly dependent on the switching frequency and the power device characteristics for a specific applied voltage and current. In order to reduce power device losses to increase efficiency, resonant converters are usually used for induction heating applications. These converters achieve either Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS), significantly improving the converter efficiency. Typically, the half bridge and the full bridge series resonant inverters operating in the ZVS region are proposed, where the resonant tank is composed of the induction load, modeled as a series resistance inductance equivalent, R_o–L_o , and the resonant capacitor C_r. The circuit diagram is shown in Fig. 2.

Normally Insulated Gate Bipolar Transistor (IGBT) devices are chosen for induction heating application, due to their output power levels, involved switching frequencies and high operation temperature. But it has large switching time, i.e. its turn OFF speed is low due to collector current tail. This results in decreased efficiency and increased magnetic component size due to restricted switching frequency. MOSFET has the advantage of reduced switching time and reduced ON state resistance. Hence MOSFETs are preferred for high frequency operation, long duty cycle, and low voltage application. The ON state resistance per area of MOSFET is

$$R_{ON} = kBV_{dss}^{\alpha} \qquad (1)$$

Blocking voltage, BV_{dss}, is the maximum voltage that can be applied to the MOSFET. Fig. 3 shows relationship between drain source blocking voltage and the ON state resistance of ideal MOSFET and commercially available MOSFET. In Fig 3 straight line graph represents the ideal MOSFET and dotted graph represents the commercially available MOSFET. From the figure it is clear that higher blocking voltage leads to higher ON state resistance.

To reduce the equivalent ON state resistance, normally proposed idea is to parallelize the devices. In this case as the ON state resistance is decreased, the equivalent device area is increased, making the ratio of ON state resistance per area constant. But, the proposed series connection of MOSFET results in a reduction of this ratio $R_{ON,N}/R_{ON,1}$, where N is the

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

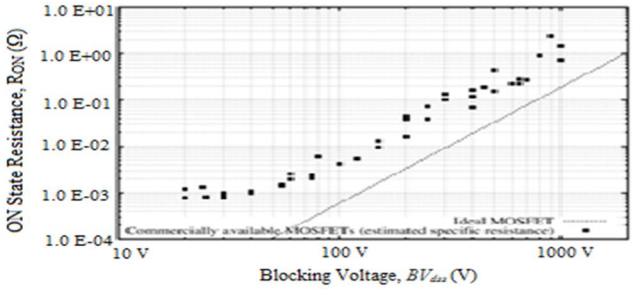


Fig. 3. ON state resistance as a function of the maximum blocking voltage

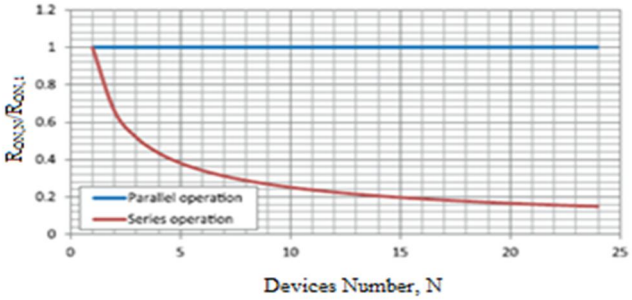


Fig. 4. The ratio of ON state resistance per area for series and parallel connection

number of series devices. The ratio of ON state resistance per area of serially connected MOSFET is,

$$\frac{R_{ON,N}}{R_{ON,1}} = \frac{N\left(\frac{k(BV_{dss}/N)^{\alpha}}{(A/N)}\right)}{kBV_{dss}^{\alpha}/A} = N^{(2-\alpha)} \qquad (2)$$

Fig. 4 shows the ON state resistance per chip area ratio as a function of the device number, N for both the series and parallel operation. From the Fig 4 it is clear that, with the proposed series arrangement, it is possible to improve the ON state performance of the converter using the same chip area. In the case of Silicon (Si) vertical N type Metal Oxide Semiconductor, the value of α is greater than 2. Thus, depending on the number of serialized devices *N*, the MOSFET serialization ideally leads to a reduction in conduction loss. For example, in the case of 600V applications, a 40V, 15 MOSFET stack achieves an ON resistance reduction up to five times, significantly reducing conduction losses with the same total silicon area. Besides, the resultant distributed cooling is more efficient, allowing, removing the heat sink and fan. Automotive grade MOSFETs can be used to obtain a cost effective solution.

III. MULTI MOSFET BASED SERIES RESONANT INVERTER

The proposed multi MOSFET based half bridge series resonant inverter for domestic induction heating application is shown in Fig. 5. The circuit mainly comprises a diode full bridge rectifier and a half bridge series resonant inverter.

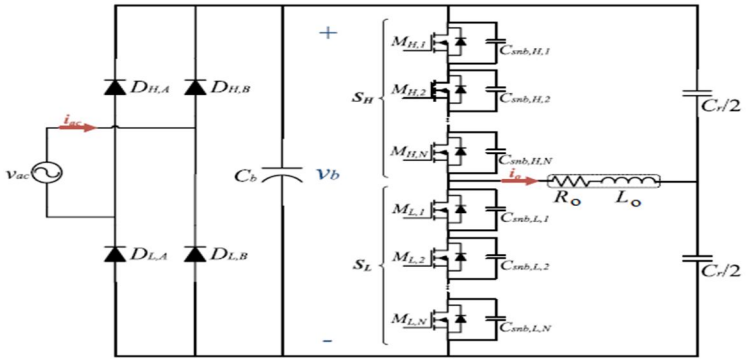


Fig. 5. Proposed Converter for Domestic Induction Heating

The operating frequencies of the rectifier and the inverter are different. The diode rectifier stage operates at mains frequency,

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

$f_{ac}=1/T_{ac}$ and the resonant inverter stage operation frequency, $f_{sw} = 1/T_{sw}$, is higher than 20 kHz to avoid acoustic noise.

A. Diode Rectifier

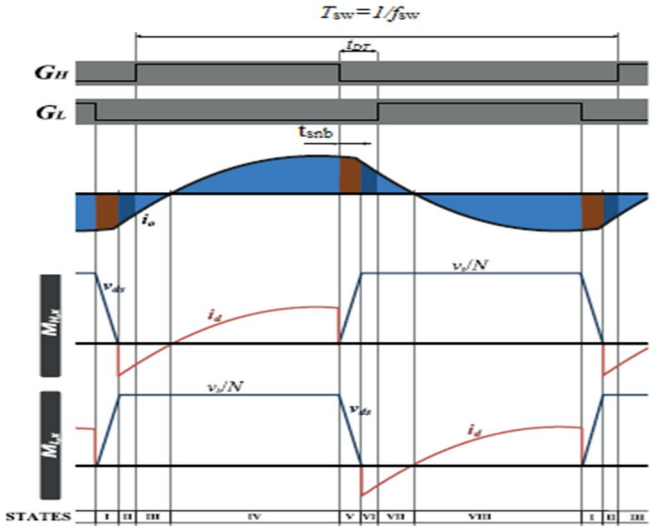
As mentioned earlier, a low value of DC link capacitor, C_b, is chosen to get an input power factor close to one for the worse operation point, i.e., at the minimum output power. This result, the DC link voltage has a big sinusoidal ripple. Consequently, during the positive mains half cycles the rectifier diodes $D_{A,H}$ and $D_{B,L}$ conducts and during the negative half cycles the rectifier diodes $D_{B,H}$ and $D_{A,L}$ conduct, resulting a DC link voltage waveform, v_b

$$v_b(t) = |v_{ac}(t)| \qquad (3)$$

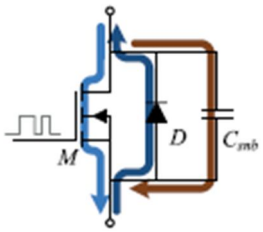
B. Multi MOSFET Based Series Resonant Inverter

The proposed inverter is based on the half bridge topology, where each switching device is implemented by means of a multi MOSFET cell. The inverter stage is composed of switching devices, S_H, and S_L, both composed of N low voltage MOSFETs, $M_{H,1}$ to $M_{H,N}$, and $M_{L,1}$ to $M_{L,N}$, respectively. To reduce the turn OFF switching losses, a lossless snubber capacitor, C_{snb}, is connected in parallel with each MOSFET. The series RLC resonant tank is composed of the equivalent induction heating load, modeled as a series resistor, R_o, and inductance, Lo, and the resonant capacitor, C_r. Usually, the resonant capacitor, C_r is split into two capacitors to reduce the EMC filter requirements.

The equivalent inverter is supplied by the output voltage of the diode rectifier stage, V_b. The main waveforms of the inverter stage and the load current flow through the MOSFET, antiparallel diode and the snubber capacitors are shown in Fig. 6. In this figure, t_{DT} is the dead time between the upper and the lower activation signals, G_H and G_L, respectively, and t_{snb} is the time required to charge/discharge the snubber capacitor.



(a)



(b)

Fig. 6. (a) Main waveforms of the proposed inverter. (b) Load current flow through different devices.

A 50% duty cycle is assumed to reduce the control complexity and ensure symmetric power loss distribution in the power devices.

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Switching frequencies higher than the resonant frequency are selected to ensure the ZVS soft switching operation. Depending on the devices activation and the load current, i_o, eight different states (I to VIII) are defined. Fig. 7 shows these eight states of the inverter stage. In states I and V, the load current flows through the snubber capacitors, resulting in a reduced d*v*/d*t* waveform during the turn OFF transition. As a result, the switching losses will be reduced during the turn OFF transition. When the snubber capacitors are fully charged/discharged, the load current flows through the antiparallel diodes of the MOSFET (States II, VI, for S_H and S_L , respectively). In order to reduce conduction losses, the MOSFET devices are activated to conduct the negative current through the device channel (States III, VII), resulting in a synchronous rectification. Finally, during states IV and VIII, the positive load current flows through the MOSFET devices.

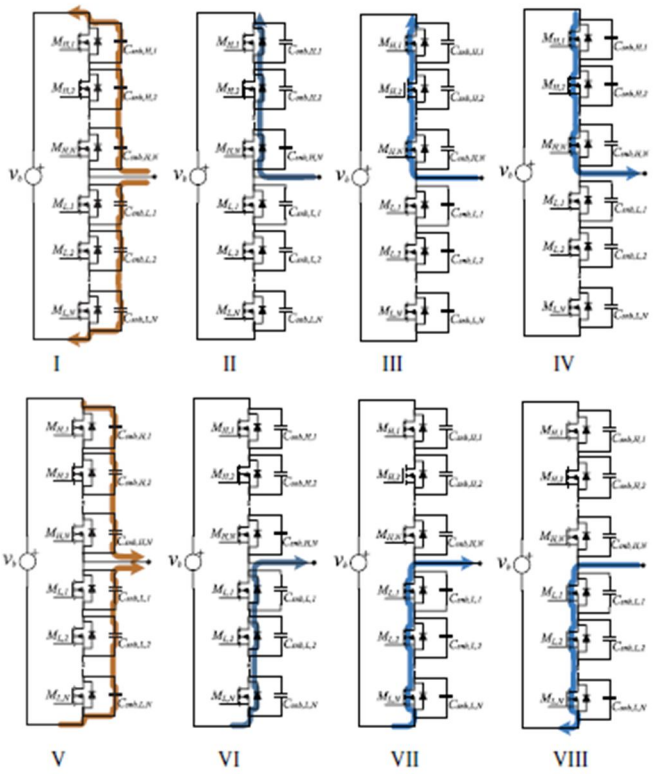


Fig. 7. Equivalent circuit states for the proposed multi MOSFET based inverter.

IV. ACTIVATION CIRCUIT

One of the main challenges when designing the multi MOSFET inverter includes the design of a reliable and cost effective gate drive circuit. The series operation of power devices was successfully used in the past for other applications, mainly for high voltage generators (10–100 kV), either by using IGBTs or MOSFETs. But it fails to ensure the correct series device activation, i.e., to ensure the proper voltage distribution in each device. Hence in this paper, a simple activation circuit with few discrete components is proposed. Unlike classical solutions based on isolated DC–DC converters or pulse transformers a cost effective solution specially designed for the ZVS behavior of the converter is suggested. As a result, the series stack of low voltage MOSFETs can be operated as an equivalent switching device, as shown in Fig. 8(b). The activation circuit is composed of a Zener diode, D_z, a low voltage P type Metal Oxide Semiconductor (PMOS), and a fast diode, D_b. As a result of this, the series combination of low MOSFET devices operates as an equivalent transistor. The activation circuit is described in Fig. 8(c).

When the activation signals, G_H and G_L for the upper and the lower series MOSFET, respectively, are turned ON i.e., during States III and VII, the equivalent gate to source capacitance of the MOSFET is sequentially charged via the series diode as shown in Fig. 9(a). Considering the higher switching devices, first $M_{H,N}$ is activated. Then, $M_{H,N-1}$ is activated by the current through $D_{b,H,N-1} - D_{z,H,N-1} - R_{g,H,N-1}$ and the channel of the $M_{H,N}$ MOSFET. The same operation is occurs until all the devices are sequentially activated.

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

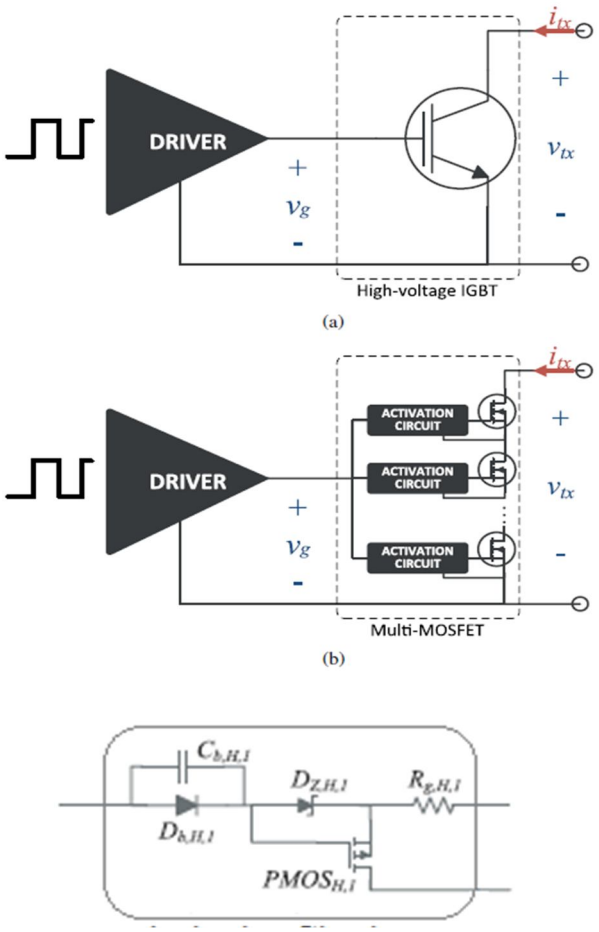


Fig. 8. (a) Classical device driver configuration. (b) Proposed approach based on a series MOSFET cell using a specific activation circuit. (c) Activation circuit

During the turn OFF transition, all the series devices must be deactivated simultaneously. In this transition, the negative voltage, typically 5V, applied by the driver stage reverse biases the Zener diodes, D_z. The breakdown voltage of the Zener diodes, v_z , activates the PMOS, short circuiting the gate to source capacitance of the power MOSFET. As a result of this, all the devices are simultaneously turned OFF as shown in Fig. 9(b). At this point, depending on the parasitic capacitance of the diode, D_b , and the Zener diode, D_z, a parallel capacitance, C_b, can be added to ensure the Zener activation during the turn OFF transition. Finally, during the OFF states, i.e., states VIII and IV, for the upper and lower switching devices, respectively, the series diode D_b blocks the blocking voltage of the devices.

V. DESIGN PROCEDURE

The main design specifications of multi MOSFET based series resonant inverter are input voltage V_{in}=200 V, output power, P_o=750 W, Quality factor, Q_{IH}=1.32, switching frequency, f_{sw}=25 kHz. At the resonant point, the maximum induction heating equivalent series resistor, inductance and capacitance can be calculated as

Volume 4 Issue IV, April 2016
ISSN: 2321-9653

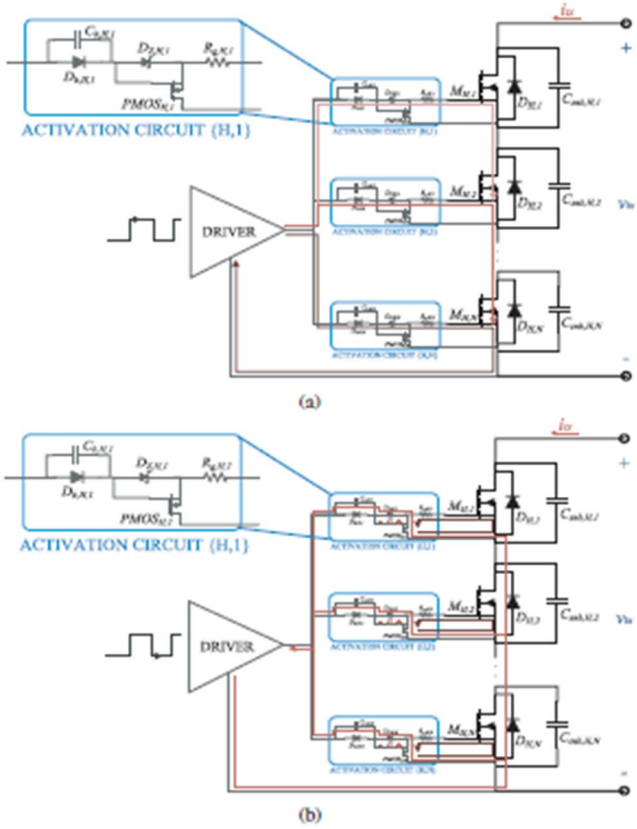


Fig. 9. Proposed activation circuit operation for the upper switching devices. (a) Equivalent circuits during turn ON and (b) turn OFF transitions.

$$R_o \langle \frac{2V_{in}^2}{\pi^2 P_o} \tag{4}$$

$$L_o = \frac{Q_{IH} R_o}{2\pi . f_{sw}} \tag{5}$$

$$C_r = \frac{1}{L_o \left(\left(\frac{R_o}{2L_o} \right)^2 + (2\pi . f_{sw})^2 \right)} \tag{6}$$

Using equations (4) R_o is obtained as 10Ω. For the selected induction heating load, Q_{IH} = 1.32, the series inductance obtained is L_o=84 µH. The maximum output power is achieved at the resonant load natural frequency, which will be the minimum operating switching frequency to ensure ZVS operation mode. As a consequence, the resonant capacitor chosen is C_r=300 nF.

A. Optimum MOSFET Devices Selection

This section is focused on the low voltage MOSFET selection in order to maximize the efficiency of the inverter stage. The first step consists on analyzing the effect of the package in the final performance. Considering the voltage and

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

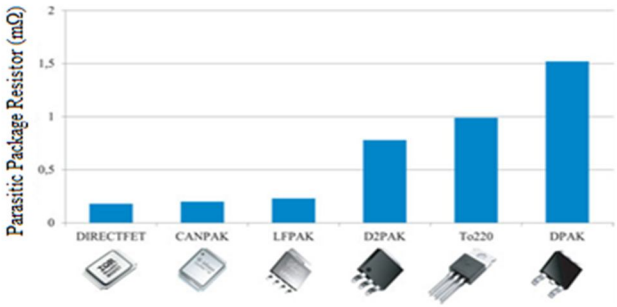


Fig. 10. Parasitic resistance of typical low-voltage MOSFET devices packages

current operation ranges, the packages commonly available can be divided into two groups: packages featuring classical bonding connection (*wire bonding*) and packages using direct clipping (*clip packing*). One of the advantages of the direct clipping connection is its increased connection area, which minimizes both the parasitic resistance and the package inductance. In addition to this, the manufacturing process results are simplified, reducing the final device cost.

The effect of the device package in the parasitic series resistance is quantified in Fig. 9 for classical low voltage MOSFETs. It can be seen that the parasitic resistance is in the milliohm range, which is comparable to the low voltage device ON state resistance and, as a consequence, it results critical in this application.

In Fig. 10, the right side devices, i.e., DPAK, TO-220 and D2PAK feature wire bonding connections, where as the left side devices (LFPAK, CANPAK, and DIRECTFET) use a direct clipping method, resulting in a reduced parasitic resistance. As a consequence, the LFPAK package has been selected and will be designed to dissipate the power losses using the printed circuit board (PCB).

Once the LFPAK package has been selected, the next step is to select the device that maximizes the converter efficiency. As it has been previously explained, due to the reduced switching times of the MOSFET devices, the main losses are caused by the conduction term. Besides, according to equation (2), the equivalent ON state resistance for the same blocking voltage is reduced if the number of series devices, *N*, is increased. Nonetheless, the effect of the parasitic case resistance leads to an optimum device number, where the ratio of the ON state resistance divided by the maximum blocking voltage [mΩ/kV] is minimized.

B. Thermal Design

Once the device is selected, the power losses can be calculated considering the design restrictions. Beginning with the conduction losses, the equivalent ON state resistance results $R_{on,S} = N_{opt} \times R_{on,1} = 16 \times 1.1\ m\Omega = 17.6\ m\Omega$ at $T_j = 90^0$C. Then, in order to calculate the switching losses, a current fall time of $t_f = 37$ ns is considered whereas the equivalent snubber capacitance is $C_{snb} = 20.6$ nF. As a result, the switching losses obtained allow neglecting them in the complete operation range.

When the power losses are determined, the next step is to compute the required PCB area to dissipate the losses. The maximum power losses in the worst case situation are 0.7 W per device. Considering an ambient temperature of $T_{amb} = 90^0$C, and a maximum junction temperature of 150^0C, the required maximum thermal resistance results 85.71^0 C/W. hence it is possible to have an optimum design of series resonant inverter for induction heating system.

VI. CONCLUSION

In this paper design of a new power converter for domestic induction heating applications is proposed. The proposed inverter is based on the full bridge topology, where each common switching device is implemented by means of a multi MOSFET cell. By using low voltage MOSFET devices, an implementation capable of delivering up to 4 kW without fan and heat sink is achieved for the domestic induction heating application.

REFERENCES

[1] He´ctor Sarnago, O´ scar Luc´ıa, Arturo Mediano, and Jos´e. M. Burd´ıo," Multi-MOSFET-Based Series Resonant Inverter for Improved Efficiency and Power Density Induction Heating Applications", IEEE Transactions On Power Electronics, Vol. 29, No. 8, August 2014

[2] He´ctor Sarnago, O´ scar Luc´ıa, Arturo Mediano, and Jos´e. M. Burd´ıo," Design and Implementation of a High-Efficiency Multiple-Output Resonant Converter for Induction Heating Applications Featuring Wide Bandgap Devices", IEEE Transactions On Power Electronics, Vol. 29, No. 5, May 2014.

[3] Bishwajit Saha and Rae-Young Kim, "High Power Density Series Resonant Inverter Using an Auxiliary Switched Capacitor Cell for Induction Heating Applications," ," IEEE Trans. Power Electron, vol. 29, no. 4, April. 2014.

[4] O. Luc´ıa, P. Maussion, E. Dede, and J. M. Burd´ıo, "Induction heating technology and its applications: Past developments, current technology, and future

challenges," IEEE Trans. Ind. Electron., vol. 61, no. 5, pp. 2509– 2520, May 2014.
[5] O. Lucia, J. M. Burdio, I. Millan, J. Acero, and D. Puyal, "Load-adaptive control algorithm of half-bridge series resonant inverter for domestic induction heating," IEEE Trans. Ind. Electron., vol. 56, no. 8, pp. 3106–3116, Aug. 2009.
[6] K. Arunyuvaraj and R. Gopalakrishnan "Sinusoidal Pwm Based T-Source Inverter For Induction Heating" ARPN Journal of Engineering and Applied Sciences, VOL. 10, NO. 7, APRIL 2015
[7] S. S. Valtchev and J. B. Klaassens, "Efficient resonant power conversion," IEEE Trans. Ind. Electron., vol. 37, no. 6, pp. 490–495, Dec. 1990.
[8] "Induction Heating System Topology Review" www.fairchildsemi.com, 2000 Fairchild Semiconductor Corporation Rev. 1.0.4 •