Review of transistor inverter circuits for induction heating

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I. INTRODUCTION

Present stage of development of world technologies for induction heating is marked by dominant development of generation of power electronic devices, based on powerful semiconductor elements MOSFET and IGBT, started in mid 80 – ties and still going on.

Gradually inverter circuits for induction heating based on MOSFET and IGBT, replace lamp generators working in the radio frequency range, as well as thyristor generators working in the sound range above 10 kHz. Main element in the inverter part of a transistor converter for induction heating is the powerful MOSFET or IGBT transistor, which is most often made as transistor module of one or several transistors with integrated reverse diodes and circuits for control and protection – Fig. 1. There is a parallel development of technologies for production of passive elements – capacitors (Fig. 2) and smaller size transformers with fewer losses.

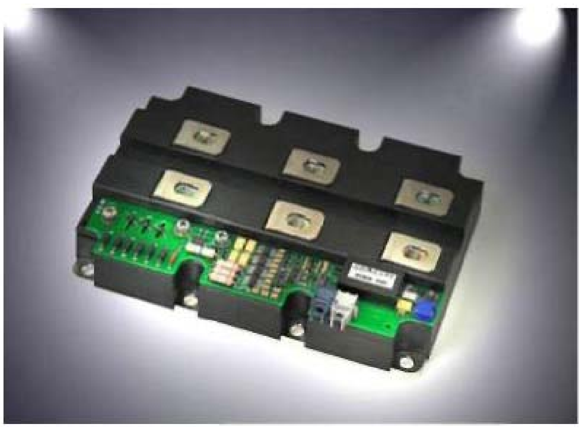

Fig.1. IGBT Transistor module with integrated reverse diodes, protection circuit and optical control

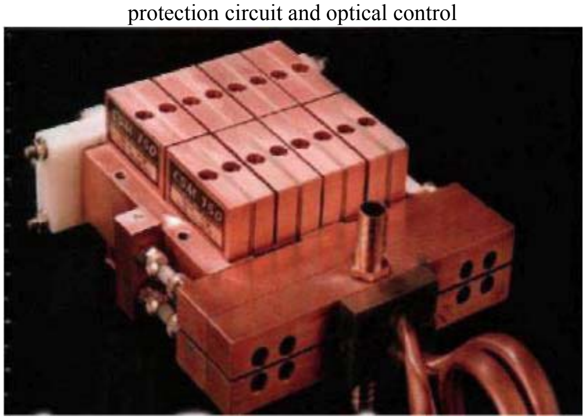

Fig.2. High-power water-cooling capacitor for inverters

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Improvement of power supply sources for induction heating is mainly based on development of algorhythms and control circuits, which optimize the process of switching over the transistors, aiming to lower the dynamic losses, which are most common at high frequency and determine the loading capacity of transistors. Particularity of load at induction heaters is the relatively high quality factor ($3 < Q < 20$) and alteration of parameters of its substitution circuit in the technology cycle process. Because of that, there is a necessity for compensation of the jet power of the inductor by in series or parallel switching of capacitors and necessity of automatic adjustment of the frequency to the change of the resonance parameters of the loading circuit. Present day transistor sources for induction heating are featured by the following peculiarities [1, 3, 5, 9, 11, 13]:

1. Resonance or quasi resonance inverter circuit, where the inverter is frequency co-ordinate with the fluctuation circle, thus minimizing the commutation losses in the units and increasing the coefficient of efficiency of converter (CE).
2. Converters CE is 85 – 93 %, which is nearly double compared with the lamp generators - 55 – 60 %. That requires less usage of electricity and less water for cooling.
3. Contrary to thyristors, transistors do not hold out against big electrical overloading – hence precautions are taken for their quick switch-off before reach of dangerous electricity parameters.
4. Transistor feeding sources for induction heaters have complicated control. In most cases they have a joint system for control of the DC converter and inverter, combined with execution of the chosen induction technology.

Transistor sources are very compact and usually incorporate the inverter with coordinated capacitors and converter.

In relation to the topology of construction of an inverter circuit, transistor sources can be divided in two large groups – full bridge or half bridge and single switch mode, which shall be discussed in detail.

Present day **full-bridge and half-bridge transistor inverters for induction heating** are mostly resonance. It should be noted that transistor inverters with middle point of the transformer are also developed, but they are not so common as the other types of inverters. Following special features are noted in their performance and definition [2, 4, 6, 8, 9]:

1. Electric current and voltage of load have almost sinuous form. That statement could be unconditionally accepted in connection to the voltage, but for the electrical current of the inverter – only in principle.
2. Actual form of the two components and in particular of the electric current is determined by the design of the inverter and the parameters of all its elements.

3. Fluctuation processes with frequency close to the switching frequency of the controlled devices are developed in the structure of the inverter.

That helps to ease the working conditions of transistors and lack of overloading and peaks.

Power factor of the load is different from the inverter's power factor, but often are taken as equal from engineering point of view due to the fact that inverters work closely to the resonance frequency of the circuit and difference between the two quality factors is small.

There are two main types of inverter designs – serial resonance inverters on tension and parallel resonance inverters on current. They themselves are subdivided into: rectifier – controlled and uncontrolled, manner of control / adjustment of outgoing capacity, power connection etc.

Single switch transistor inverter circuits for inverter heating are characterized by relatively large variation in relation to current/technical solutions, as well as in relation to the way of performance and used elements. More important signs, which can unify them, are[14, 16]:

- single switch topology;
- single tact performance – i.e. the energy transformed by the power supply source is used only till the switch is on or off;
- simple and saving topology with minimum elements, securing reliable work of the power supply unit for induction heating.

First came the single switch inverters based on impulse thyratrons and thyristors, which supplement the then existing current inverters and resonance inverters and based on them began construction of power supply units for induction heating in the supersonic frequency range - 20 – 100 kHz. The single switch thyratron inverters perform "percussive" effect in the fluctuation circle, which allows widening of frequency qualities of the used switching elements. That way, the supersonic frequency range, which is above the limits of bridge resonance and power thyristor inverters (10 Hz – 20 kHz) and under the limits of lamp generators for induction heating (66 kHz) can be used.

Such inverter circuits are used as simple sources for induction knit together of electrodes for electronic tubes and kinescopes. Developments in semiconductor technologies allow thyristors to replace the impulse thyratrons in the inverter circuits with accelerated impact, passing over to single keys resonance inverter circuits, researched in details by many Russian authors at the end of 70s and early 80s. At present the single key inverter circuits for inverter heating are mostly transistor type. As transistors do not hold against large overloading in current and voltage, there is a need for "soft commutation", for limiting the shock impact over them at the commutation moment, as well as for minimizing their losses. "Soft commutation" is achieved by use of additional resonance chains, connected to the switching transistor.

After implementation of powerful MOSFET and IGBT transistors at the end of the 80s, new single key inverter circuits were developed, thus using in full the advantages of the new two operational devices – quasi-resonance inverters. Many resonance switching (quasi-resonance) transistor inverter circuits are described in technical literature. They use an additional resonance chain for realization of switchover at zero current (ZCS quasi-resonance inverters) or voltage (ZVS quasi-resonance inverters), in order to limit the dynamic losses at the key elements. That allows increase of working frequency of inverter and reducing the size and weight of capacitors, inductors and transformers. Period of switch on/off of the key is determined by resonance process period, as switch on/off of the transistor is achieved at its end. In that context, period of conductivity or time in blocked condition is fixed at constant resonance frequency. This approach is not new – it is used in thyristor converters. Although ZCS is used in thyristor converters, they work at relatively low frequency – up to few Kilohertz, due to long period of switching off and recovery of thyristors. Powerful elements as MOSFET, MCT and IGBT's are available at present, which have short timing of switching off, but increase of converter working frequency and quick switch off, leading to overloads and shocks caused by influence of parasitic inductances and capacitances.

Furthermore, losses from switch over in transistors are broadly speaking in linear subordination to the working frequency. Because of that and in spite the fact that transistors are two operational devices, it is imperative to use ZCS/ZVS commutations, aimed to reduce losses at switch on/off operations. It is very much debatable which commutation is better and at what application.

Normally ZCS commutation is used at high power, as current passing through transistor is usually with high value, but as a rule work at high frequency is connected to availability of large peaks of voltage, caused by influence of parasitic inductance.

It is worth to note, that in order to lower those peaks, it is necessary to use passive or scattering chains connected in parallel or in series on transistors, so applying mixed ZCS/ZVS commutations for switching on/off.

When ZVS commutations are used, current through transistor must be switched over through another auxiliary chain. That requires parasitic inductances to be the first to charge, after they are discharged through transistor, which leads to peaks of voltage at commutation of current.

Furthermore, after switch over transistor current through auxiliary chain, it must be reduced to zero at switched off state of transistor and energy accumulated in auxiliary chains must be dissipated. In contrast to that, at ZCS commutation, current is commutated from transistor towards auxiliary chain. Transistor is switched off only when current passing through it and the chain in which it is connected goes down to zero.

Moreover current through parasitic inductances in transistor chain is also zero.

Another difference between ZCS and ZVS commutation is the voltage value over transistor. It is obvious that ZVS transistors must be high voltage compared to those used in ZCS. The latter has current peaks at switching on in established rate, but devices such as MCT and IGBT can accept current peaks from 5 to 10 times compared with their nominal current [10, 11, 12, 14, 15, 16].

II. Quasi-Resonance Single Key Inverter Switch Over At Current Zero (ZCS)

Various inverter designs with switch over at current zero of powerful commutation elements used in the area of power supply devices, can be found in the radio frequency range of present induction heating for relatively small power (< 5 kW).

One practical application of quasi-resonance ZCS inverter for induction heating is shown on fig.3 [1, 15, 16].

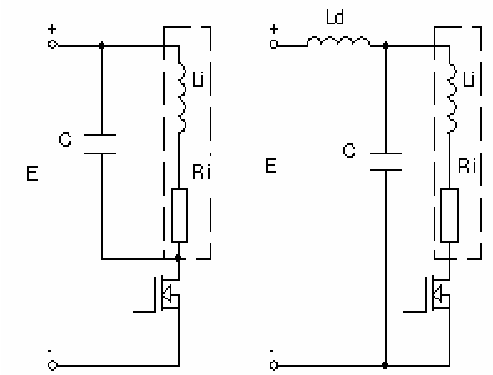

Fig.3.

That type of converters are most often used for power supply of induction heaters for kitchen appliances and hot plates with working frequency < 25 kHz and power range 2 – 5 kW. As temperature is relatively low 300 – 400 °C (under curie t) parameters of load are almost not changed in heating process, which helps a lot in managing and normal work of inverter. Besides, load of inverter, system inductor – detail is high ohm (high resistant), (inductor is multi-winded, with magnetic core). Fig. 4 ÷ 6 show time diagrams which are indicative for the electro-magnetic processes in the inverter. One can clearly see ZCS transistor commutation and its relatively small losses at switching off. Power peak is clearly visible at switching on, which determines commutation losses and frequency range of inverter. Transistor current is with resonance character and that is why it is high. Furthermore tension over transistor is several times higher than the feeding one. That thrust upon the usage of high voltage transistor for powerful current, which puts extra value on inverter, but considering the quality of powerful MOSFET transistors for parallel work, that problem can be solved.

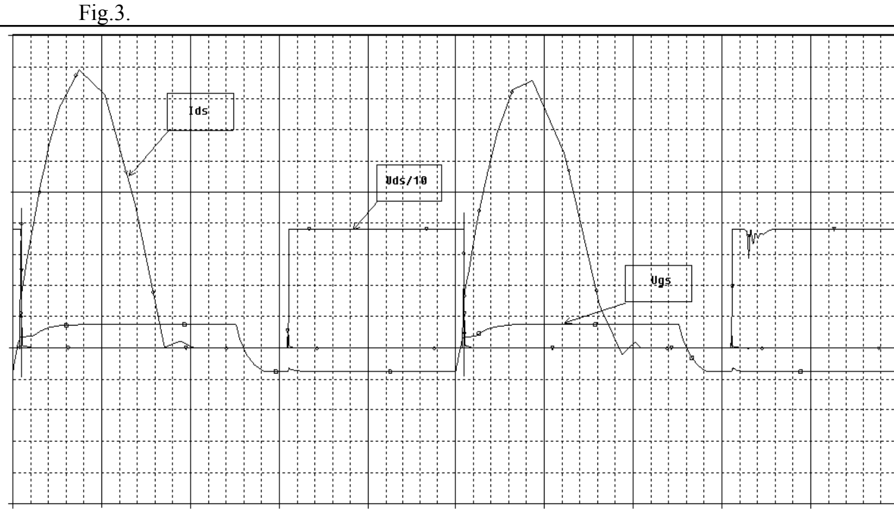

Fig.4. Voltage UDS (100V/div) and current ID (10A/div) of transistor in quasi-resonance single key inverter switching over at current zero (ZCS)

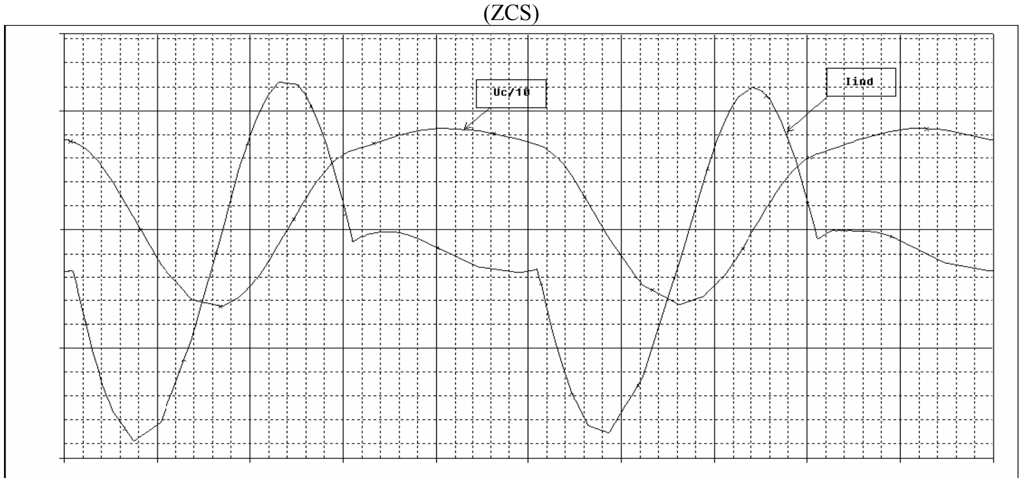

Fig. 5. Voltage UC (100V/div) and current Iind (10A/div) for inductor in quasi-resonance single key inverter switching over at current zero (ZCS)

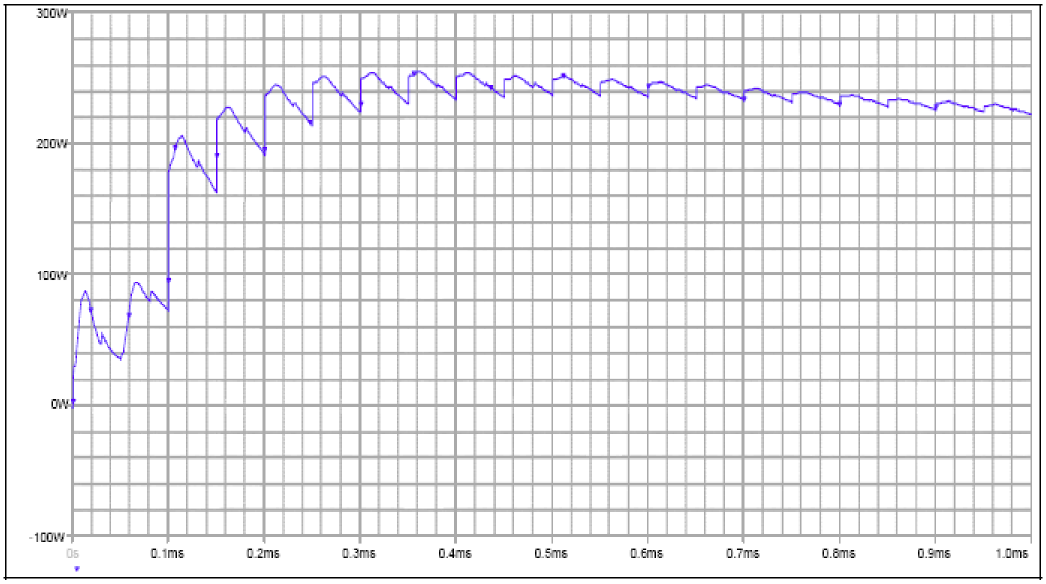

Fig 6 Transistor losses (static and dynamic) in 2 kW, 100 kHz quasi-resonance single key inverter switching over at current zero (ZCS) supplying induction hot plate.

III. Quasi-Resonance ZVS Single Key Inverter

Quasi-resonance ZVS single key inverter / ZVS / is used for the needs of induction heating due to low commutation losses in the key at switching off, as well as the slow increase of voltage. Because full commutation losses are very small, work at high frequency is suitable for the needs of induction heating.

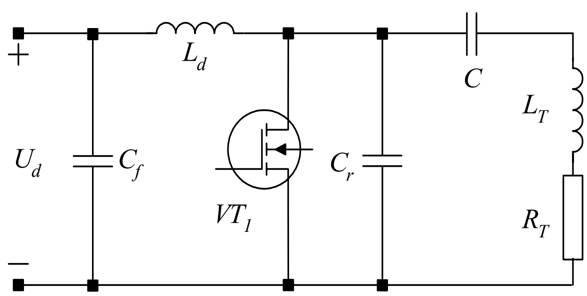

Fig.7. ZVS quasi-resonance inverter for induction heating

Fig 7 shows the main design of ZVS. Design includes key VT1, the resonance capacitor Cr, as well as L and R, which represent an equivalent duplicating scheme of the loading chain. Feeding of inverter is 160 V; output power 2400 W. Working frequency is 65 kHz. Design excludes regime of “impact action” which helps electrically the commutation device. Design can be in two variants – capacitor Cr to be connected in parallel or in series to the load. Both topologies work in quasi-resonance regime. Fluctuations in the circuit of the load exist only when the key T is switched off. Current through key has exponent form. Commutation losses in the design are put down to a minimum, owing to provision for switching on the key at current zero of voltage. ZVS is suitable for induction heating of loads with low quality factor. Design has a disadvantage – high voltage over the key.

IV. Quasi-Resonance ZVS Class “E” Inverter With Complex Resonant Circuit

Inverter is good for induction heating of small quantities non-ferrous metals and alloys for laboratory needs [9, 10, 12] Working frequency is 1.25 MHz and output power is 1.2 kW. Inverter design is shown on Fig. 8.

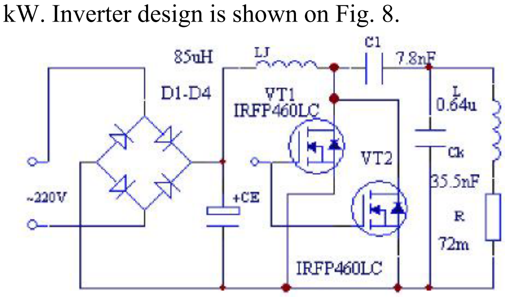

Fig.8. Quasi-resonance inverter class “E” with oscillatory circuit

Basically that is a modification of the classical class “E” inverter, described in previous paragraph, as the resonance capacitor Ck is not connected in parallel to the transistor, but is connected in parallel to the load. Advantages of class “E” inverter in relation to low commutation losses (ZVS+ZCS at switching on transistor, and ZVS + quasi-ZCS at switching off), working with constant loads are known.

V. Requirements To The Power Supply Sources. Resonance And Quasi-Resonance Inverters

It is known from discussions on induction heating at many conferences, meetings, specialized literature, that nearly 90 % from the manufactured at present inverter circuits for induction heating, are from semiconductors, most of them are transistor type.

They cover users' requirements, namely [5, 6, 9]:

1. Acceptable cost price of inverter for induction heating in relation to power unit.
2. Reliability and efficiency at different loads.
3. Power regulation conformable to working process of induction heater.
4. Work in a wide frequency range and possibility for heating regime, conformable to working process.
5. Flexibility in disposition of induction heating source in relation to heating module and possibility for mobility.
6. Possibilities for remote control and monitoring of heating process at any time.
7. Coefficient of efficiency 0,85 ÷ 0,92 for induction heating transformer. Small consumption of electrical power and water.
8. Easy to meet industrial standards related to noise factor and ecologically friendly to power supply.

Common trends in inverters for induction heating are shown, based on the already discussed circuit variants, regardless of technological implementations, power and frequency range. They can be used as a base for further developments of certain technical solutions of transistor inverter in induction heating feeding sources.

VI. Decreasing Quantity Of Used Components

Smaller the number of components, cheaper the source manufacture. At high power and frequency cost price of passive components – capacitors, transformers and inductors is over cost price of used active components – transistors, diodes and integrated circuits. Using fewer components a priory increase reliability of the whole device. There is a clear drive for using of single key circuits for smaller capacity at all frequency ranges and substitution of transformer circuit with non transformer one at higher capacity and frequencies by using complex oscillation circles.

VI.1 Possibility Of Power Regulation

Almost all transistor-feeding sources comply with above criteria. Point is that to be achieved without putting an extra transformer at entrance, but by lower regulation with the help of an inverter.

That is connected not only to satisfying the first criteria, but is a sign for high technology at technical make of the transformer.

VI.2 Workability At Change Of Load Parameters, As Well As Quick Exit From Emergencies Without Switching Off Power Supply

This feature is connected to the supplying source ability not to be at all influenced by the type and change of load in the heating process, as well as the possibility to work with inductors of different type and parameters. Extreme conditions should have minimal influence over inverter's work, as protection switch off and stop of work should be avoided if possible. Two basic trends to achieve these inverter circuit characteristics should be noted.

First is the use of new topologies inverter circuit – inverters with energy dose control. Second is for complex management, aimed at coordination of working conditions for converters with change of load.

VI.3 Low Losses At Inverter And High Coefficient Of Efficiency (CE)

One of main directions in which scientific and research labs of leading manufacturers of induction heating equipment are working, is improvement of techno economy parameters of the developed current supply transformers and generators. CE is one of main features important for current supply device.

As a whole, transistor power sources are with high CE compared with lamp generators, where CE is not more of 60 %. Present tendencies impose that inverter heating power supply devices are with CE over 90 %. Important factor, which influence the CE of the whole unit, are losses in key appliances, as they can reach nearly half of total loss.

Losses in semiconductor appliances not only decrease CE of the whole powerful electronic equipment for induction heating, but usually limit the capacity and working frequency, also causing big problems with effective cooling. It is known that losses in key elements could be split in two groups: static and dynamic (commutation). [1, 2, 3, 4, 9, 10]

Static losses include the ones from conductance in switched on state and losses for working conditions for the key in static state. Voltage drop in conduction key causes losses in switched on state. Current leakage is the reason for losses in switched off state and the starting energy, which is dispersed by driver, is related to the latter type of losses.

Conductivity losses are determinant for static losses. Voltage drop over appliances is determined by its own resistance and voltage of appliances switching on and depends from current through key and its temperature. Driver's signal amplitude also influences the voltage drop in appliance conductance state.

Static losses are independent from work, they only depend from working current, voltage and appliance parameters. Little drop in voltage and little leakage of current lead to high CE of the transformer and because of that, cooling requirements are small.

Switching on/off losses are accumulation from losses at switching on and losses at switching off. At any of them, energy impulse is dispersed from the key, which leads to average losses. They depend on working frequency, current and voltage, appliance parameters and availability of protection RC group ("snubber").

If working frequency is high, losses from switch on/off are higher then static, which leads to general losses increase. As the appliances in use are for small power dissipation, commutation losses as well as static must be minimal.

On the other hand, increase of working frequency is very important. To achieve that, precautions are taken to limit overloading and decrease losses at switching. In theory, switching losses could be avoided by choosing correct working point or by choosing a suitable parallel "snubber" group, which determines losses at switch off. When using devices and circuits, which have to work without added elements, working frequency is limited by losses at switch.

In case, when working frequency has to go up, inverters with " hard " commutation are substituted with soft switching circuit, which contain special connections or resonance circuit for decreasing switching losses – i.e. resonance commutation. In general, under the name quasi-resonance inverter, we understand a converter, where resonance commutation is used for change of state of key elements. Resonance transistor inverters switching off at zero current, in relation to transistors performance, could be treated as quasi-resonance. Condition is to have a "soft" transistor commutation, as resonance connection for switching of transistors is the oscillation circuit itself.

V. Conclusions

Main fault of resonance circuits – troubled adjustment, is overcome in various ways, including new circuit developments for control of key appliances. Complicated control circuit achieves that, with many back connections for tracking of several parameters. Resonance processes cause disturbing signals from power connections to control of powerful transistor keys, which can cause unwanted switch of power device and possible short cut in the arm – emergency. That fact imposes the use of galvanic divided control circuits, protection of powerful MOSFET and UBT transistor keys and application of constructive methods aimed at decreasing of parasitic inductance and capacity. Most commonly used drivers are those, which provide galvanic outcome and device protection from current, voltage and unallowable increase of deck temperature (overheating). Almost all manufacturers of powerful MOSFET and UBT offer special integral drivers for their control – the so called "intelligent" drivers, which perform requirements for optimal control and device protection. Parallel with improvement of traditional circuits for inverters as source of high frequency energy, there is work done in the field of induction heating over different circuits and circuit modifications, which allow increase of frequency range, simpler control and adjustment.

While static losses mostly depend upon type of key element (Thyristor, MOSFET, UBT) and its characteristics determined in the company's manufacturing process, then mostly technically designed measures are applied for decreasing of commutation losses.

References

[1] Andreycak B.; Zero Voltage Switching Resonant Power Conversion; Unitrode Application Note, pp.329-355.

[2] Andreychak B.; Phase-shifted, Zero Voltage Transition Design Considerations; UNITRODE application note U-136A

[3] Bachmann G.; Resonant Switching in IGBT Converters; PCIM Europe 10/2000 pp.34-36.

[4] Baha B.; Design and Analysis of Buck Quasi-Resonant Converter using IGBT's; EPE Journal, Vol.2, No. 3, October 1992, pp.165-172.

[5] Bo-Tao Lin, Kam-Wah Siu, Yim-Shu Lee; Actively Clamped Zero-Current Switching Quasi-Resonant Converters using IGBT's; IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, Vol. 46, No. 1; FEBRUARY 1999, pp.75-81

[6] Brambilla A., D'Amore D., Santomauro M.; Simulation of autonomous circuits in the time domain; in Proc. ECCTD, Istanbul, Turkey, Aug 28th – Sept. 1st, 1995, pp. 399–402.

[7] Cheng K., Evans P.; Parallel-mode extended-period quasiresonant convertor; IEEE Proceedings-B, Vol.138, No 5, September 1991, pp.243-251.

[8] Cho J. G., J. Sabat´e, G. Hua, and F. C. Lee; Zero voltage and zero current switching full-bridge PWM converter for high power applications; in Conf. Rec. IEEE PESC'94, 1994, pp. 102–108.

[9] Dede E., Espi J., Esteve V., Jordan J., Casans S.; Trends in Converters for Induction Heating Applications; Power Conversion – June 1999 proceedings, Nurnberg, Germany, pp.155-160.

[10] Dede E., Gonzalez J., Esteve V., Jordan J.; State of the Art and Future Trends of Solid State Power Supplies for Induction Heating; International Induction Heating Seminar Proceedings – 98, pp.3-11.

[11] Dierberger K.; Resonant Switching for Power System Designs; Power Electronics Engineering Europe, September 1999, pp.10-14.

[12] Grunewald C.; A New Quasi-Resonant Zero-Voltage-Switching Synchronous Buck-Converter; PCIM 2000, 6-8.June, Nurnberg, Germany, pp.413-418.

[13] Grzesik B., Kaczmarczyk Z., Junak J.; A Class E Inverter – the Influence of Inverter Parameters on its characteristics; IEEE Transactions on Power Electronics 1996, pp.1832-1837.

[14] Ivensky G., Zeltser I., Kats A., Ben-Yaakov S.; Reducing IGBT Losses in ZCS Series Resonant Converters; IEEE Transactions on Industrial Electronics, Vol. 46, No. 1, February 1999, pp.67-74.

[15] Lee J., Moon G., Park H., Youn M.; Integrated ZCS Quasi-Resonant Power Factor Correction Converter Based on Flyback Topology; IEEE Transactions on Power Electronics, Vol. 15, No. 4, JULY 2000, pp.634-643.

[16] Lee F.C.; High frequency quasi-resonant converter topologies; Proceedings IEEE, Vol.76, pp. 377–390, Feb 1998.