International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 12 Dec 2021, pp: 1428-1433 www.ijaem.net ISSN: 2395-5252

Design of 100 kHz Series Resonant Inverter for Induction Heating Applications

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Date of Submission: 15-12-2021 Revised: 27-12-2021 Date of Acceptance: 30-12-2021

ABSTRACT: This research paper presents the study on design of voltage fed series resonant converters for inducting heating applications. The proposed system presents the development and design of an inductionheating system, which enables optimum and economical operation over a frequency range of 100kHz. The system primarily includes a DC-AC voltage fed series resonant inverter, driving a series resonant load circuit. The resonant load consists of a capacitor and an inductionheating coil.
The induction heating system provides contactless, fast, quick and efficient heating of conductive materials. It is becoming one of the preferred heating technologies in industrial, domestic, and medical applications, among other applications, due to its advantages when compared with other conventional heating techniques such as flame heating, resistance heating or traditional applications. It has many advantages compared to other heating systems such as quicker heating, faster start-up, more energy saving and higher production rates.

KEYWORDS: Voltage fed series resonant converters, Pulse Density Modulation(PDM), Zero-Voltage Switching, Zero- Current Switching, Dead-time

I. INTRODUCTION

The most basic elements composing an IH system are the piece to be heated, denotedas workpiece and the induction coil that produces the magnetic field needed to generate heat. The inductor and the workpiece can have any shape and the piece is usually placed inside the coil to have a better coupling. Considering that this study focuses on the heating of round wires, the inductor used is a solenoid and the workpiece a round wire. IH phenomenon is based on two mechanisms of energy dissipation:

1. Energy losses due to Joule effect: When an alternating voltage is applied to an induction coil, an alternating current is produced in the coil. This alternating current produces an alternating magnetic field that induces voltage in the workpiece, which opposes to the variation of magnetic field. This voltage creates currents in the workpiece, called eddy or Foucault currents, which have the same frequency but opposite direction than the original current. These eddy currents produce heat in the piece by Joule effect.
2. Energy losses due to hysteresis: These losses are caused by friction between dipoles when ferromagnetic materials are magnetized in one direction and another. They appear in ferromagnetic materials below their Curie temperature (temperature at which the material becomes non-magnetic). In most of IH applications, hysteresis losses represent less than the 7 % of the eddy current losses.

1.1Penetration depth and critical frequency

When an alternating current flows through a conductor, the current distribution within its cross-sectional area is not uniform. In IH, the currents that create heat in the workpiece are not continuous and its distribution is not uniform. The frequency of these currents, which is the same as the magnetic fields and the currents in the coil, define the area where these currents flow and where the heat is induced.

In case of a solenoid heating a wire, the currents induced in the workpiece create a magnetic field that opposes to the original magnetic field. These magnetic fields cancel each other and the resultant magnetic field in the centre is weak. Therefore, the induced currents in the centre of the workpiece are lesser compared to that of the surface and tend to flow near the surface of the workpiece.This phenomenon is known as skin effect and causes the concentration of eddy currents in the surface layer of the workpiece.In case of flat thick bodies with constant electromagnetic properties and the current decrease is exponential

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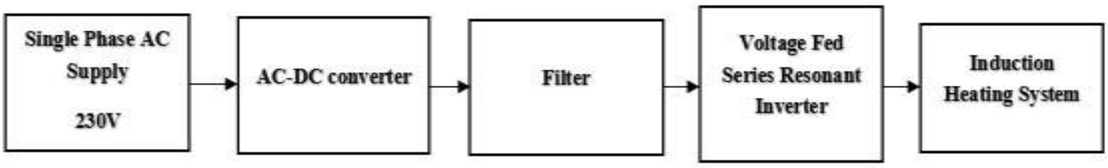
and only the 63 % of current and the 86 % of power are located in the surface layer of depth δ.It is noted that penetration depth varies during a heating treatment due to the changes of the material's properties with temperature.



Block Diagram of Induction Heating System

II. LITERATURE SURVEY

Pradeep Vishnurambestowed the idea of induction heating is graduallylaunching as it has the qualities of homogeneous heating, zero pollution and higher power density and efficient operation. To achieve these charactersrealistically, there is a need to develop energy efficient converter topologies, which are useful in achieving power regulation of soft switching and very high frequency for efficient operation. It also depicts some of the salient features of converter topologies which is used for domestic and industrial heating applications governing power conversion, power density, load handling capacity, soft switching, reliability and size. The performance of these converter topologies is analysed in terms of power rating of the system, converter switching frequency, flicker level, modulation techniques, user performance and resonant converter'sefficiency. Moreover, it also predicts the future trends associated with the adaptation ofvariable frequency control scheme with minimum losses, wide band-gap power semiconductor materials and filter design to improve source-side power factor. The detailed technology review will be useful for researchersand engineers for choosing the appropriate topology for the preferred application.

Umar Shami bestowed that the induction heating systems employ non-contact heating. This system employs electromagnetically heating the conductive materials rather than using a heating element in contact with a part to heat conduction, as done in resistance heating. This paper presents a technique to calculate the parameters of the coil to be used to heat an iron piece of given parameters, to 850^{o}C. A design of the full bridge power resonant inverter is presented followed by the results. When a ferromagnetic material is placed in a time varying magnetic field, an E.M.F is induced in the ferromagnetic material. This induced E.M.F causes the flow of eddy currents along the surface of the conductive material. The factors thatare significant for the control of the magnitude of these eddy currents are (i) magnitude of time varying magnetic field, (ii)resistivity of material, and (iii)frequency of time varying magnetic field.

L. Grajales bestowed a phase-shift-controlled series-resonant inverter is used as a power supply for a 10 kW, 500 kHz induction heating system. The induction heating system analysis for power regulation with zero-voltage-switching is presented, including the effect of MOSFET parasitic capacitance. A control algorithm is developed to ensure the switch turn on with zero-voltage for all load conditions. The switching frequency is kept as close as possible to resonance for maintaining minimum circulating energy. This paper describes the design and implementation of a 10 kW, 500 kHz PSC-SRT. The power and high switching frequency leaves MOSFETs as the only present alternative for the switch'soperation. Also, soft switching is required to achieve efficient and reliable operation of the inverter. Zerovoltage-switching (ZVS) is the most preferred soft switching technique for MOSFETs in a bridge topology as it allows the use of the MOSFETs internal body diodes since no fast recovery diodes are desirable. To obtain ZVS, the MOSFET is turned on while its body diode is conducting. The charge stored in the MOSFETs output capacitance must be removed for the body diode to start conducting.

V. Bukanin deals with investigating of heat treatment and forging steel billets of round and rectangular cross-section using induction method of heating. Some industrial processes and induction heating installations used nowadays are ancient techniques and have to be sufficiently improved from technical and economical point of interpretation. The general-purpose FEM programs such as Flux 2D and 3D, Ansys, etc. are rather complex and time-consuming software to realise computer simulation. In multi-stage induction lines, the number of stages and the overall space are very big, that creates complicationsfor using these programs. The philosophy of ELTA programs is different. The engineering programs do not require special knowledge in computer simulation due to simple understandable interfaces, preinstalled design options and database. The software used for manipulating the induction heating systems are ELTA 6.0 and 2DELTA. ELTA is a program based on 1D and 2D Finite Difference Method (FDM) with semianalytical account for the lengths of individual inductors and loads. The calculations in ELTA software are designed to analyse the power and temperature which are calculated from each heating stage inside the induction coils.

O. Lucia presented that theinduction heating technology is nowadays the emerging heating technology in many industrial, domestic, and medical applications due to its advantages regarding efficiency, fast heating, safety, cleanness, and precise control. Advances in key technologies such as power electronics, control techniques, and magnetic component design, have allowed the development of highly reliable and cost-effective systems, making this technology readily available and abundant. This paper analyses induction heating technology summarizing the main milestones in its development, and analysing the current state-of-art of induction heating systems in industrial, domestic and medical applications, giving attention to the key enabling technologies involved. Finally, an overview of future research trends and challenges is given, highlighting the promising future of induction heating technology. This paper has reviewed the current state-of-art of induction heating systems, focusing on the enabling technologies involved and the main applications. From a design point of view, there are three main empowering technologies to tackle while the designing an induction heating system: power converter, modulation and control architecture, and the inductor design. Wide research has been carried out in recent years, leading to the enhancement ofinduction heating systems that have empoweredinduction heating systems usage to several industrial, domestic, and medical applications.

J. M. Ho M.T. Lee presented thatin the induction heating applications, the heating coils may have different types for different loads. A suitable control method is often needed to let the power electronic circuit working in most applicable condition to supply the input power to the load. A simple novel control strategy for an induction heating systemhas been described. The advantage of this method is to design a simple PWM (Pulse-Width-Modulation) gate signal driving circuitry for dead time setting, Zero Voltage Switching operation, and less components architecture. Another advantage of this technique is using a very simple method for thealternative two complementary PWM output signals into different switching devices in heating period for balancing the operation of duty cycles. In modern induction heating applications, a voltage-fed PWM switching mode inverter is commonly used, and the PWM IC chip UC-I825 is also mostly adopted. However, in high frequency there is an overlapping between the two complementary PWM output signals of UC-1825, which will cause a short circuit in either leg, and the delay time of power devices exaggerates this overlapping when input capacitance is in charging or discharging under high frequency switching. Therefore, there should be a “dead time” for preventing this overlapping.

Leo Saro SICON S.R.Lgave a study on theaids of soft-switching converters, and in zero-voltage switching (ZVS, additionally referred to as zerovoltage-transition [ZVT] or resonant-transition) circuits. High-frequency converters powered from high source voltage show substantialadvances when operated with soft switching. These developments of soft switching are given by 1) reduction of switching losses, which permits high switching frequency and size reduction of reactive components, 2) reduction of EMI/RFI noise, 3) no need for complex and expensive snubbers, and 4) manipulation of the parasitic circuit elements to help the resonant transition. Zerovoltage-switching operations are currently used in power electronics, and especially in telecom power systems. MOSFET is one of the most common choicesfor controlled switching purposes in the zero-voltage-switching full-bridge converter. MOSFET is capable of very fast commutations and its intrinsic body diode serves as an additional external component that is necessary to clamp the switch voltage to the input supply voltage. The internal body diodeand the output capacitance of the MOSFET switch become essential components for the resonant transition. In zero-voltage-switching, the MOSFET operates well inside its safe operating area and its body diode is never subjected to hard turn-off, but somefailures do happen, due to the unavoidable usage of the intrinsic body-diode. This paper analyses the

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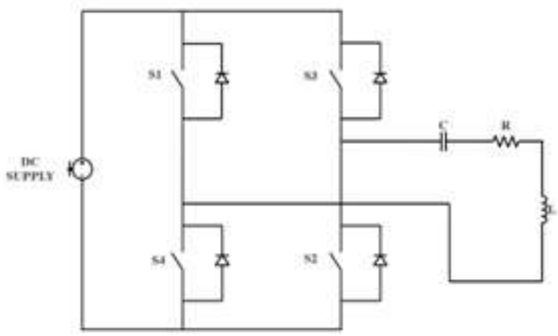
MOSFET's behaviour in highpower and high-input-voltage ZVS converters, and presents an original theory of the MOSFET breakdown. Some of the new technical solutions to improve the ruggedness of the device andthe reliability of the equipment has been proposed.

Francois Forestpresentedthe induction heating applications used for cooking which generally comprises two or four inductors and a converter is connected to each inductor. The objective of this paper is to proposeadesign of a multi-load or single converter system, based on the use of a voltage fed series-resonant ZVS inverter, supplying several resonant loads. The principle can be probably extended to different applications such as dc-to-dc converters, high power induction heating applicationsbut it has been restricted to a low power induction heating system. Therefore, a number of different electrical inductor models, from the basic - equivalent circuit to a representation taking into account and eddy currents effects, have been presented. The second part describes the multi-load operating principle with respecting ZVS conditions, by the analysis of an - inductor model. Finally, the third part completes this work with simulations, including a more realistic model of the inductors and the associated experimental justification. These emphasize the interest of this original system that is currently being assessed for an industrial application.

III. CONVERTERS USED FOR INDUCTION HEATING

In induction heating system, the heat is generated by eddy currents which are originated by a varying magnetic field that is obtained by means of a varying current circulating in an inductor. To have a high varying current in the inductoran oscillatory circuit is formed by an inductor and a capacitor in series or in parallel. This oscillatory circuitalso known as resonant tank, is usually fed by a converter, whose characteristics depend on the frequency, the power and the type of resonant tank. The commutation process occurring at resonant frequency allows more efficient operation in theequipment, which may be essential in high frequency applications, even though the main reason is for permitting higher currents in the inductor. One common criterion in classifying the converters according to the type of resonant tank, where the most basic topologies are based on series and parallel tanks. The converters which arerelatedwith these tanks are the current fed series resonant inverters (CFSRI) and the voltage fed parallel resonant inverters (VFPRI).For the sake of simplicity, the inductor and the workpiece system are modelled by a constant resistance and inductance in series.



3.1. VOLTAGE FED SERIES RESONANT INVERTERS

In series resonant tanks, the inductor is connected in series with the capacitor. In such a case, the tank will behave as a current source and the inverter is voltagefed inverter, which means that the inverter is fed from a constant voltage source. This indicates that the inverter is fed by a capacitor with a high capacitance value that sustains the voltage constant. In most of the applications the H-bridge inverter topology is widely used. This topology is used because allows transmitting the same power with less current for a given voltage.

In voltagefed series resonant inverters, two switches of the identical inverter leg cannot be turnedon at the same time, otherwise shortcircuit condition occurs. The time between the turning-off of one of these switches and the turning-on of the other is called dead-time. In this topology, antiparallel diodes are necessary to allow inductor's current conduction when the opposite switches are turned-off.There are two basic switching mechanisms with regards to softswitching: zero voltage switching (ZVS) and

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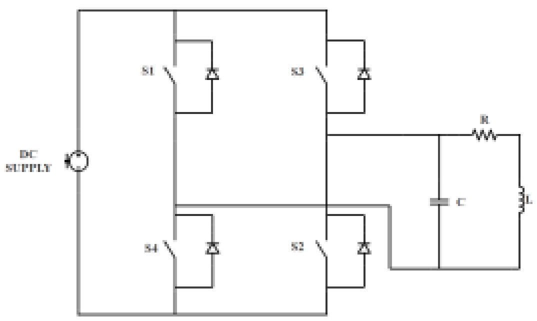
zero current switching (ZCS). ZVS is associated to the turn-on of the switch, that is realized with zero voltage, while ZCS is associated to the turn-off of the semiconductor, that occurs without current.

That resonant frequency is the point where the maximum power is given to the workpiece, was explained in previous sections. It was also explained that, at this frequency, the commutation occurs when the current is close to zero, diminishing the commutation losses. However, in real systems is almost impossible be at perfect resonance, due to small changes in the load or just because there are small inaccuracies in the control system. Therefore, during normal operation the converter is most of time slightly above or under resonance. These different commutation circumstances are studied in this section. The aim of this study is to understand the various sequence of events that are occurring during the process of commutationin the converter.

3.2. CURRENT FED PARALLEL RESONANT INVERTERS

In case of parallel tanks, the inductor is connected in parallel with the capacitor. Contrarily to a series connection, the tank behaves like a voltage source and the inverters used are current-fed. This implies that the inverteris fed with a high inductance that maintains the current and behaves as a constant current source.In case of current-fed inverters, the current path cannot be opened and switches from the same inverter leg have to overlap. Switches have to be unidirectional in current but bidirectional in voltage.Current fed parallel resonant invertershavevarious ways of controlling the power.In case of current fed parallel resonant inverters, the parallel tank acts as a tuned filter circuit at resonant frequency.The conclusion was that inductive switching improves the operation of the inverter because avoids the reverse recovery currents of diodes, but this fact changes when the parasitic inductances and the overlapping-time are taken into consideration.

In case of current fed parallel resonant inverter, the parallel tank will act as a tuned filter at resonant frequency.Thus, the only component of the tank voltage is due to the first harmonic of the current square wave. In this case, the current will be a square waveform and the voltage will be sinusoidal.



IV. CONCLUSION

The design of a Resonant High Frequency inverter has been presented. Extensive revision of the main converter topologies and their associated tanks used in IH field are summarized in this research paper. The workpiece of conductive materials has to be heated until it was red hot, using the inverter. From the analysis it can be seen that forworkpiece with small diameters the frequency of the varying electromagnetic field in which the workpiece is placed, must be high. If the diameter of the workpiece increases the frequency of the varying electromagnetic field decreases. This is obvious because at low frequency more eddy currents penetrate the cylinder that is the skin depth increases with the decrease in frequency and hence more eddy current losses are produced inside the workpiece.

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