ICSE 2009

PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE ON SCIENCE AND ENGINEERING

Volume - 1

Electronics
Electrical Power
Information Technology
Engineering Physics

Sedona Hotel, Yangon, Myanmar
December 4-5, 2009

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Organized by
Ministry of Science and Technology

DECEMBER 4-5, 2009

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ELECTRONIC ENGINEERING

Design and Construction of Induction Hardening Machine (Controlled Rectifier Module)

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Abstract—**When surface hardening is done by means of induction heating, the method is known as induction hardening. This method involves heating the component by an induced current to very high temperature and then quenching it to get required level of hardness. The advantage of the induction over the conventional methods is mainly the rapid heating of the surface of the component without an appreciable rise in the temperature of the core. This condition makes it possible to case harden components in a few seconds with very little distortion. In induction hardening process, a single phase ac power source is converted to a pulsating dc supply and filtered. Then, the adjustable dc output of the filter is fed to a single phase bridge inverter circuit. At the last process, the medium frequency output current from the inverter is applied to the induction coil which also acts as heating coil. In this paper, design calculation and test results for converter section of prototype model 5kW, 4kHz induction hardening machine is described. The bridge type rectifier circuit for induction hardening machine is designed and constructed by using SCRs as controlled elements. Thyristor gate triggering control circuit is also constructed to get the controlled range between** 0° **and** 180° **.**

Keywords— **controlled range, induction hardening, quenching, thyristor gate triggering control circuit**

I. INTRODUCTION

Induction heating may be defined as the raising of the temperature of any material by electromagnetic generation of heat within the material itself. The two methods by which heat is produced in induction heating are (1) Eddy Current loss (2) Hysteresis Loss. Eddy current or induced current due to the flux changes give rise to differences of potential within the material and eddy current loss can be expressed by the equation,

$$W_e = Kf^2 B_m^2 V \quad (1)$$

Where W_e = the heat generated by eddy current loss (J)
K = eddy current coefficient varying with the characteristics of material
V = the volume of material (m^3)
B_m = maximum flux density (W_b/m^2)
F = applied frequency.

Hysteresis loss is related to the field strength and the frequency of the alternating magnetic field in which the material is placed. This loss is caused due to the friction of molecules which generates heat within the material as follows:

$$W_h = hfB_m^{1.6} V \quad (2)$$

Where W_h = the heat generated by hysteresis loss(J)
h = hysteresis constant for the materal
B_m = maximum flux density (Wb/m^2)

So, the applied frequency governs both eddy current lost and hysteresis loss in induction heating. In industrial practice of induction heating, a very wide range of frequencies is used for carrying out various production process operations.

Table I enumerates the main sources of alternating current for supplying induction heating equipment and shows the fields of their industrial application.

TABLE I
BASIC CHARACTERISTICS OF AC SOURCES USED IN INDUCTION HEATING PLANT

Types of Generator	Range of Working Frequency (c/s)	Limits of Output Employe kW	Efficiency %	Characteristic of objects heated
Mains Frequency Supply System	50	50-4000 and over	70-90	Through heating of heavy billets: Layer thickness of 8-10 mm
Motor Generator	500-10,000	15-1000	70-85	Machine Components, camshafts and crank-shafts, ammunition: Layer Thickness not less than 1-3 mm
Cyclo inverter extractron converter	500-3000	250-1000	90-95	Heavy objects of cylindrical shape, flat plates: Layer thickness not less than 5-8 mm
Spark-Gap Generator	50,000 - 500,000	5-35	30-40	Small Machine Components: Layer thickness from 1mm
Valve Oscillator	70,000-1000000	5-500	50-75	Articles of complex shape: Layer thickness from fractions of a millimeter.
Silicon Controll Rectifier	40,000 (max)	200 (max)	90	Machine Components, camshafts and crank-shafts, ammunition

At the present time, the solid state semiconductor devices are widely used for induction heating system as they have major advantages such as fast response, long duration and reliability.

In this paper, thyristorised induction hardening machine is designed for the output power of 5kW and operating frequency 4 kHz. The main contribution of this paper is to design and construct the single phase fully-controlled rectifier section for induction hardening machine. Thyristor gate triggering control circuit is also constructed to get the control range between 0° and 180°.

II. Design Criteria Of Controlled Rectifier In Induction Hardening Machine

For the prototype model 5 kW, 4 kHz Induction Hardening Machine, 50Hz single phase line ac source is used as a power supply because single phase converter circuits are adequate for low power, below 20kW. For high power above 20kW, three-phase circuits are used. Firstly, this single phase ac passes through fully-controlled bridge rectifier circuit. Then, the output of the rectifier is fed to the current limiting inductor. After being filtered by this inductive filter the adjustable dc supply is inverted to an alternating current and voltage by feeding through a single phase bridge inverter. Finally, this medium frequency range ac supply is passed through an induction coil which acts as heating coil. The complete circuit diagram for an induction gardening system is shown in Fig. 1.

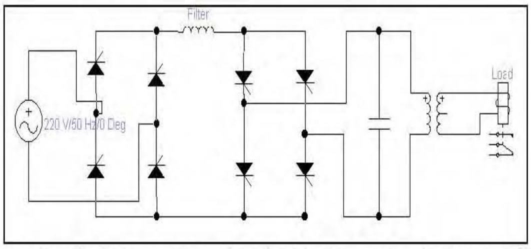


Fig. 1 Circuit diagram of thyristorised induction hardening machine

A. Selection of Converter Circuit

When power flow can be controlled by adjusting the RMS value of the ac voltage applied to the load with means of thyristor switch connected between ac supply and the load, this type of power circuitry is known as a converter. They can be classified into three classes: uncontrolled, fully-controlled and half-controlled. The converter type depends on the power to be handled and how much voltage ripple will be tolerated. The following points should be considered in designing the correct type of a converter circuit.

(1) The higher the pulse number, the lower the magnitude of ripple voltage and current in the load circuit and the ac supply

(2) Fully controlled circuits are capable of inversion and, therefore, regeneration, half-controlled circuits are not

(3) Half-wave circuits require higher-voltage thyristors than bridge-circuits for producing the same output dc voltage.

(4) Bridge circuits require twice more thyristors than half-wave circuits to carry the same current.

Although half-wave circuits require minimum no: of thyristors, they tend to be used for low-voltage, high current application. So, single phase fully-controlled bridge type rectifier is chosen for converter section of induction hardening machine. Since the output terminal of rectification circuit is connected to a filter reactor in series, the rectification works the condition of large inductive load. The circuit diagram of this rectifier circuit is shown in Fig.2.

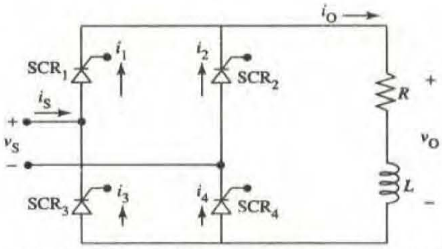


Fig. 2 Full-wave bridge rectifier circuit with inductive load

Depending on the shape and size of work-piece, the value of load impedance may vary. For 5 kW, 4 kHz prototype model induction hardening machine, total impedance of load coil is assumed to be 5 Ω.

Input line voltage =220 V

Input line frequency =50Hz

When $\alpha = 0$, the average load voltage,

$$V_{0(avg)} = \frac{2}{\pi} V_m \cos\alpha \qquad (3)$$

$$= \frac{2}{\pi}(\sqrt{2} * 220)\cos 0° = 198.06V.$$

The average ,load current, $I_{0(avg)} = V_{0(avg)}/R$ (4)

= 198.06/5

=39.6A.

So, maximum load current = average load current =39.6A, RMS Load current =average load current =39.6A.

Since the SCRs in bridge conduct in alternate half-cycles,

The average SCR current=1/2 $I_{0(avg)}$=39.6/2=19.8 Am

Power applied to the load $=I^2_{RMS}R=39.6^2*5=7.841$kW

Form factor, FF= $V_{0(RMS)}/V_{0(avg)}$=220/198.06=1.11

Ripple Factor, RF=$\sqrt{FF-1} = \sqrt{1.11^2 - 1} = 0.48$

Rectifier efficiency $=V_{0(avg)}/V_{0(RMS)}$=198.06/220=90.02%

For various value of controlled angle α, the above parameters can be calculated and listed in Table II.

TABLE II
OUTPUT RESULTS FOR VARIOUS VALUES OF α

Firing angle	0	15°	30°	60°	90°
Average load vtg(v)	198.06	171.53	171.53	99.03	0
average load current(A)	39.6	38.26	34.3	19.8	-
average SCR current(A)	19.8	19.13	17.15	9.9	-
power applied to the load(kW)	7.84	7.31	5.88	1.96	-

The highest value of output voltage occurs at $\alpha = 0$ and the average dc output voltage decreases as α increases. At $\alpha = 90°$, load voltage contains equal positive and negative areas, giving zero output voltage. For $\alpha > 90°$, the dc voltage becomes negative and power is now being delivered from dc side of the converter to the ac side and the circuit operates as an inverter. At $\alpha = 180°$, the negative voltage is maximum. As rectification and conversion are obtained from one converterthe process is called two-quadrant operation and the converter is called a full converter.

III. Design Criteria of Thyristor Gate Triggering Control Circuit

In this paper, triggering control circuit for single phase fully-controlled bridge rectifier circuit is designed and constructed. This controlled circuit contain seven sections.They are Zero Crossing Detector, Integrator, Level shifter, Comparator, Monostable Multivibrator, Power Amplifier and Pulse Transformer.

A. Zero Crossing Detector

ZCD determine whether the input signal is greater or less than zero. The input synchronizing signal of 3 V_{rms} is derived from the same supply from which the thyristor power circuit is fed. This signal is given to ZCD IC.This IC develops a square wave with 180 phase-shift because of using inverting input.TL 074 JFET op-amp is chosen for ZCD because of lower noise and distortion for ac input source. To calculate the output voltage of zero crossing detector circuit, TL 074IC op-amp with the following characteristic is considered.

Open loop voltage gain, $A_{ol} = 100{,}000$

Differential voltage between the two inputs, $V_{in} = 0.25$ mV

Open loop voltage gain, $A_{ol} = V_o / V_{in}$ (5)

Output voltage, $V_o = A_{ol}\, V_{in}$

$= 100{,}000 \times 0.25 \times 10^{-3}$

$= 25$ V.

But most op-amps have output voltage limitations of less than ± 15 V because of their dc supply voltages, the device would be driven into situation. Because of the dc supply voltage ±15 V for this op-amp IC, the output voltage of the zero crossing detector circuit is positive peak value of +15V and negative peak value of -15V.ZCD circuit and test result output waveform for this zero crossing detector circuit are shown in Fig.3 and Fig. 4.

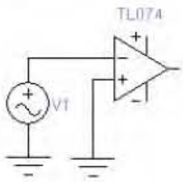


Fig. 3 Zero crossing detector circuit

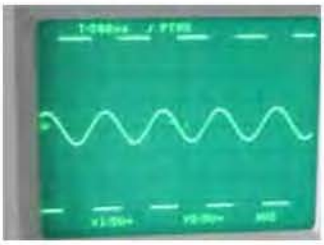


Fig. 4 The photo showing the output waveform of zero crossing detector circuit compared with input 3 V_{rms} voltage waveform

B. Integrator

The output of ZCD is square wave and this signal is fed to the integrator circuit. In this circuit, choose the value of feedback resistor R_F so that $R_F = 10\ R_i$.In this way, the input signal will be integrated properly and both the stability and low frequency roll-off problems can be corrected.

Choose $R_F = 10\text{k}\Omega$ and $R_i = 100\text{k}\Omega$.

If C_F is greater than $0.1\,\mu$F the possible failure of the amplifier input stage in integrator will occur. so, $C_F = 0.1\,\mu$F is chosen. The compensating resistor, R_c, is also added to compensate the effect of bias current. This resistance value can be obtained by the parallel combination of input resistance R_i and feedback resistance R_F.

$$R_c = \frac{R_i \times R_F}{R_i + R_F} = \frac{10\times10^3 \times 100\times10^3}{10\times10^3 + 100\times10^3} = 9.1k\Omega$$

In fact, the input signal will be integrated properly if the time period of the signal is larger than or equal to $R_F C_F$.That is, $T \geq R_F C_F$. The time period of the signal,

$T = 1/f = 1/50 = 0.02$ sec.

$R_F\, C_F = 100 \times 10^3 \times 0.1 \times 10^{-6}$

$= 0.01$ sec.

Thus, $T \geq R_F C_F$.

The design values of this integrator circuit and test results are located in Fig.5 and Fig.6.

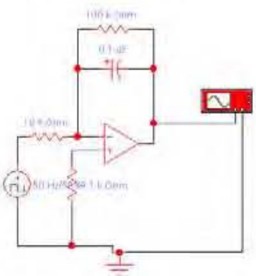


Fig. 5 The Integrator circuit with selected component values

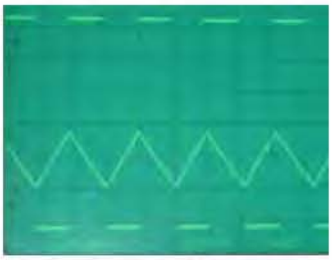


Fig. 6 The photo showing the input and output waveforms of Integrator circuit

C. Level Shifter

Since the level of output waveform of the integrator circuit is low, the level shifter circuit is used to raise the level of this waveform. In fact, inverting amplifier circuit can be used as the level shifter. The voltage gain of the inverting amplifier circuit is

$$A_v = -\frac{R_F}{R_i} \tag{6}$$

where

A_v = the closed loop gain of the inverting amplifier,

R_F = feedback resistor,

R_i = Input resistor.

The value of voltage gain can be adjusted by setting the ratio of R_F/R_i into the desired value.In this triggering circuit, the value of R_i is chosen as 4.7 kΩ.To get the variable range of voltage gain, the value of R_F is chosen into 100 kΩ variable resistor. These designed values are located in Fig.7 and test result waveforms are shown in Fig.8.

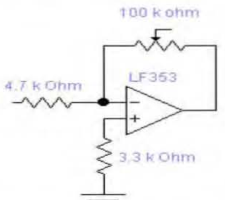


Fig.7 Inverting amplifier used as level shifter circuit

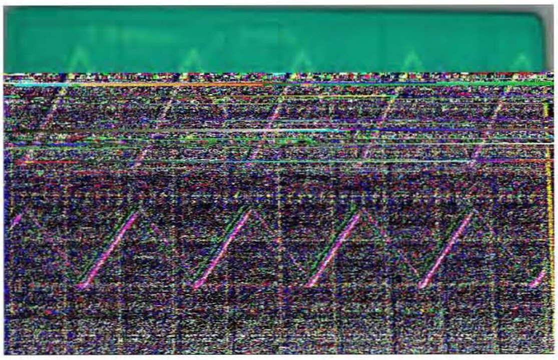


Fig. 8 The photo showing the input and output waveforms of level shifter circuit

D. Comparator Circuit

The output of the level shifter circuit is fed to the one input terminal of the comparator circuit. Another input terminal is connected with a fixed d.c reference voltage. The reference voltage can be set to any level by the potentiometer. When the two voltages at the comparator are equal, a rapid change in voltage level is produced at the output. This stage, therefore, produces pulses at a frequency of twice the fundamental frequency with a mark-space ratio which can be varied according to the d.c level of the input. The control angle α can also be varied by varying the d.c reference voltage. In this thesis, the range of d.c reference voltage is -15 V to +15 V. For single phase circuit, the minimum firing angle is zero. On the other hand, with transformer leakage reactance, triggering very close to 180° became uncertain because of the overlap angle during which
both the SCRs are in conduction to avoid misfiring and commutation failure, the permissible range of firing angle is from 0° to 180°.The output waveform of the comparator circuit is limited by a zener as shown in Fig.9 and hence the signal is compatible with TTL circuit.

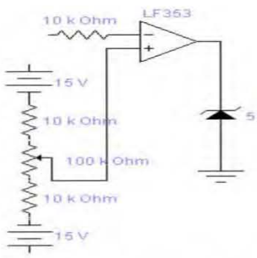


Fig. 9 Comparator circuit

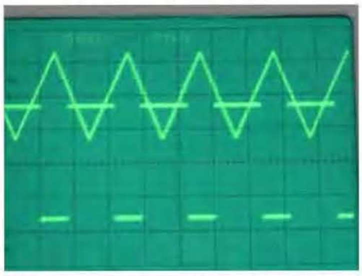


Fig. 10 The photo showing the input and output waveforms of comparator circuit

E. 74LS123 Monostable Multivibrator Circuit

The output of the zener is fed to the monostable multivibrator to get the triggering pulse with controllable pulse width. The DM74LS123 is a dual retriggerable monostable multivibrator capable of generating output pulses from a few nanoseconds to extremely long duration up to 100% duty cycle. The basic output pulse width is determined by selection of an external resistor (R_{ext}) and capacitor (C_{ext}). For values of $C_{ext} \geq$ 1000nF, the output pulse at V_{cc} = 5V and V_{Rc} = 5V is given by

$$t_W = R_{ext} C_{ext} \tag{7}$$

The C_{ext} terminal is an internal connected to ground, however for the best system performance C_{ext} should be hard-wired to ground. Care should be taken to keep R_{ext} and C_{ext} as close to the monostable as possible with a minimum amount of inductance between R_{ext}/C_{ext} junction and the R_{ext}/C_{ext} pin. As long as C_{ext} >1000 pF and 5K< R_{ext}< 260K, the change in K with respect to R_{ext} is negligible. Good ground plane and adequate bypassing should be designed into system for optimum performance to insure that no false triggering occurs. Fig.11 shows pin diagram of 74LS 123 including complete internal circuit block diagram. Its functional feature is also, shown in Table III.

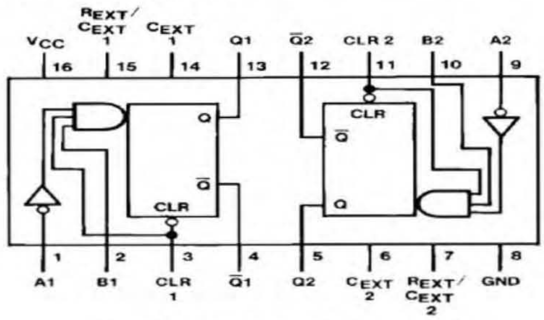


Fig. 11 Functional diagram of 74LS123 IC

TABLE III
FUNCTIONAL TABLE OF 74LS123 IC

Inputs			Outputs	
CLEAR	A	B	Q	$\overline{Q}$
L	X	X	L	H
X	H	X	L	H
X	X	L	L	H
H	L	↑	⎍	⊔
H	↓	H	⎍	⊔
↑	L	H	⎍	⊔

F. Power Amplifier

The power level of the output triggering pulse from the monostable multivibrator circuit is not sufficient to trigger the thyristor.Hence the power level is raised using Darlington pair as shown in Fig.12.

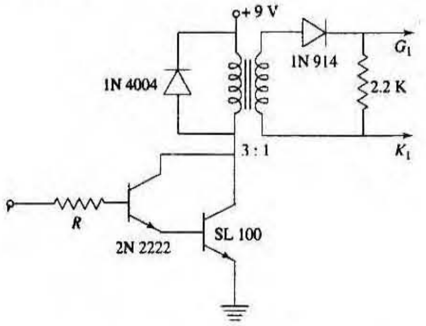


Fig. 12. Power amplifier circuit

G. Pulse Transformer

To get the electrical isolation between the gate triggering control circuit and thyristor, pulse transformer is used as an electrical isolator. In this paper, 1:1 two winding pulse transformer is constructed. Test result waveform to trigger SCR is shown in Fig.13.

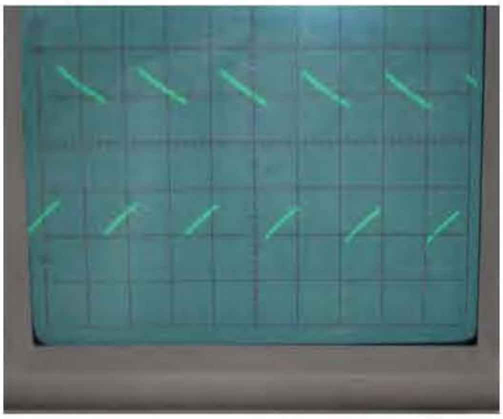
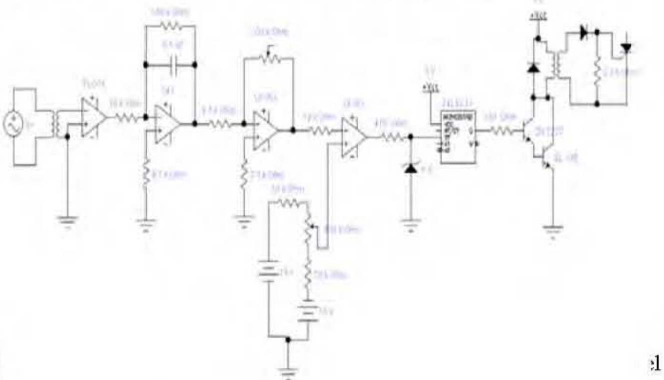


Fig. 13 the photo showing the output waveforms of 1:1 pulse transformer circuit

The complete circuit diagram of gate triggering control circuit for single phase converter is shown in Fig. 14.



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IV. CONCLUSION

In this paper, The concept of basic principle of induction heating is initially carried out. The various types of devices used for feeding induction heating equipment are also mentioned. When surface hardening is done by means of induction heating, the process is known as induction hardening. In this process, there is a known, calculable relationship between frequency and alternating current and the depth to which it penetrates in the work piece. The lower the alternating current frequency, the deeper the penetration and conversely the higher the frequency, the shallower the penetration. So, ranges of frequency from 50 hertz to several kilohertz can be generated by using various types of ac sources. In this project, thyristorized model is chosen for the prototype model medium frequency induction hardening machine. For the portion of converter design, type of converter depends on the power to be handled and how much voltage ripple will be tolerated. Single-phase fully-controlled bridge converter is chossen as single phase circuits are adequate for low powers, below 20kW.Since only a correctly designed firing circuit to supply the gate currents to thyristors will enable the full potential of both thyristors and equipment, the proper gate triggering circuit for thyristors is also designed.

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