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Optimized control of Induction Heating System

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Abstract - In this paper a simple power and frequency control scheme is proposed for high power/high frequency Induction heating for Typical Heavy Industrial Applications like Induction Welding & Annealing which require operating on 100 kW / 100 kHz. The Proposed PI controller controls the load parameter values of R and L and thereby controls the resonance frequency of the whole model.
The control scheme has the advantages of not only wide power regulation range but also ease of control output power.
Also, it can achieve the stable and efficient Zero-Voltage-Switching in whole load range. The proposed method is described in detail and its validity is verified through simulink model. The model achieves proper power control for load ranging from 80 kW to 100kw.

Keywords—Induction heating, power control, PI controller

1. Introduction

Recent development in the area of power semiconductor technology has introduced new devices working on high power and high frequencies such as power MOSFETS and IGBTs etc. [1]-[5]The various resonant inverters use power devices such as MOSFETs and IGBTs which offer reduced switching loss by technique of soft-switching and Pulse width modulation**.**

Full-bridge resonant inverter are used for high frequency induction heating application at output frequency from several kHz to several MHz, the load is the induction coil and is a part of the resonant circuit [1]. For heavy industrial and commercial induction heating applications, the voltage-fed inverter with series resonant load is widely used. The general method of output power regulation in voltage fed series resonant inverter is pulse frequency modulation. Frequency modulation means changing the operating Frequency of the inverter that has essentially some drawbacks for induction heating. Effective output power in Pulse frequency modulation control scheme is linearly proportional to square root of the inverter working frequency and hence inverter efficiency decreases significantly for light load. For output regulation there are two ways, either adjust the frequency of the inverter or to adjust the input DC voltage of the inverter. Adjusting the frequency of the inverter for regulating the output power is widely adopted because of its easy control and lower cost. Disadvantage of this method is the inverter works in inductance mode and power factor of the inverter is very low and the power losses are more. The method of adjusting the input DC voltage of the inverter for output power regulating can be used for both series and parallel resonant inverter since it exerts the characteristics of the inverter furthest in fixed output frequency and less switching losses and EMI and little dv/dt and di/dt *stress*. [6]-[9] Requirement of additional power regulation circuit is a concern. This paper uses a soft switching ZVS-PWM full bridge inverter. This kind of inverter regulates output by adjusting the width of out pulses and no power regulation circuit is need.

The power converter implemented in this paper is a series resonant converter due to their improved efficiency and lower size. The resonant circuit is connected between the inverter and the load; it can be assumed that the current harmonics in the series resonant circuit are very small which allows developing integrated appliances. The output voltage can be controlled by relative operating frequency f. Maximum voltage and power can be drawn at resonance. Output voltage can be controlled by increasing or reducing frequency. [4]-[6]Pulse width modulated dc to ac converter topology is used where switches are required to turn ON – OFF the complete load current during every zero crossing, these switches are subjected to high stress and power loss which increases linearly with switching frequency of PWM. The inverter topologies commonly used for induction heating are the series resonant full bridge, the series resonant half bridge Besides these, some derivations of these topologies are used to achieve multiple output converters and Improved Zero Voltage Switching (ZVS) operation

This paper presents simulink model of Inverter control and power control block which controls the values of R and L and thereby controls the resonance frequency of the whole model. Power is taken as input by sensing load voltage (V_r) and secondary current (I_{w2}) of the linear transformer, which is then given to comparator which computes the error from the reference power input(P_{ref}), this error is then given to PI controller which gives out the signal which corresponds to the desired values of R and L. The model achieves proper power control for load ranging from 80 kW to 100kw.

2. Induction Heating System

A 3 phase AC supply has to be used due to scale of the application, it is converted to DC by using rectifier and filter. The DC voltage thus obtained is given to inverter which converts DC to AC. The inverter output is given to a coil which is to be heated, also called as work-piece or work-coil in which the object to be heated is placed without any contact. A transformer is used for impedance matching to ensure maximum power is transferred to the load. The current in coil is measured and fed back to a decision making block called as power and frequency control circuit. This block generates the gate pulses for switching IGBT's of the inverter. Thus, by changing the width of gate pulses, the control block can change the frequency/phase of the inverter output. The feedback mechanism ensures that the actual frequency and phase difference is nearly equal to desired one. [1]-[3]

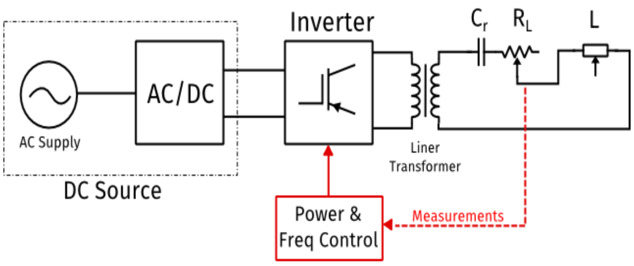

Fig 1 .Block Diagram of Induction Heating system

A. Series Resonant converter

Converters are used to reduce or eliminate switching losses. It consists of an LC resonant tank circuit. Converter switches can be switched at zero voltage or zero current. A series LC circuit is used in this case. Power flow to the load is controlled by resonant tank impedance, which in turn is controlled by switching frequency fs.

The resonant components *L* and *C have* a fixed value at the resonant frequency fr. Depending on the value of the frequency, the converter operates in the following three modes:

1. Below resonance mode (*fs* < *fr*) : current leads voltage , XC > XL , phase angle =+90degrees

2. Above resonance mode (*fs* > *fr*) : Voltage leads current, XL > Xc, phase angle = - 90degrees

3. At resonance mode (*fs* = *fr*) : both current & voltage in phase , XL=Xc

Consider a RLC circuit in which resistor, inductor and capacitor are connected in series across a voltage supply. This series RLC circuit has a distinguishing property of resonating at a specific frequency called resonant frequency.

Electrical resonance occurs in an electric circuit when the imaginary parts of impedances or admittances of circuit cancel out each other $X_L = X_c$.

$$F_r = \frac{1}{2\pi\sqrt{LC}}$$

$$\arctan = \frac{X_L - X_C}{R} = 0^\circ \quad \text{(All Real)}$$

$$Q = \frac{\omega_0 L_r}{R} = \frac{1}{\omega_0 C_r R} = \frac{Z_0}{R}$$

At resonance the impedance seen by the inverter is resistive. Both the inductive and capacitive impedances cancel each other. The output current or voltage of the converter is maximum. The inverter output current is in phase with the voltage. With this the inverter operates with ZCS. It is clear that the maximum output voltage, therefore, the maximum power is obtained at the resonance point. The output voltage can be controlled either by reducing the operating frequency or by increasing the operating frequency. [1]-[6]

Advantages of the Series Resonant Circuit:

The main advantage of the series resonant converter is its simplicity and its high efficiency from full-load to reduced-load.

B. DC Source

Power quality is getting higher and higher importance as power electronics penetrates into different fields of application and it has become increasingly difficult to maintain the "purity" of the supply due to the existence of cheap – ill-designed electronics component at the distribution level. And different steps are taken by suppliers and Distribution Companies (DISCOM) for keeping a check on the harmonics injection into the grid because of this the converter selection is of vital importance. Hence rectification part must consider following points:

- Current harmonics needs to be in limit while drawing nonlinear current at DC link

- Power factor needs to be maintained unity

Here in the model the DC supply is achieved from DC source directly but it can also be achieved from an AC source and rectification. The primary requirement of DC source is that it should have least possible ripple in DC link. It provides the necessary power to the DC-link to maintain the DC link voltage

C. Inverter

Here an IGBT based 2 arm (i.e. 4-IGBT's) converter is designed for developing the resonance converter. The PWM control pattern for maintaining the resonance is obtained from the power control block.
In this implementation series load resonance has been used.
Inverter is operated at variable frequency between ~80 kHz to 100 kHz.

D. Impedance Matching Transformer

It is primarily used for two purposes in our circuit:

- Impedance Matching
- Voltage step-down

A transformer can also be used as an inductor or to connect the load with different voltage level. Here it is used as impedance matching purpose and for adjusting current level. Linear-transformer block of Simulink / Sim Power System has been used.

E. Load Circuit : Variable R and Variable L

Variable R - Load circuit consists of a variable R. This is a self-developed block which implements the voltage to resistance relationship of V=I * R. This block receives Resistor value as input and a dependent voltage source, generates voltage on the basis of the I*R relation. Variable R is used for modeling the change in depth of skin effect due to frequency variation.

Variable L :This block is used to take into consideration the transformer action taking place due to the coil.

This is a self-developed block, which implements Faraday's law and it's following two equation:

$$V(t) = L(t)\frac{di(t)}{dt}$$

$$i(t) = \frac{1}{L(t)}\int v(t)\,dt$$

The implementation uses dependent current source, integrator and divider. Due to transformer action the impedance seen by the primary will be inversely proportional, i.e. L is inversely proportional to frequency, and Hence L reduces, with increase in Frequency.

3. Control Circuit

Control part of this does the following things 1) Stability Control, 2) Power Control and 3) Frequency Control.
The frequency control part eventually controls the resonance frequency of the circuit with thereby results in change of R & L value of the load model. Hence control circuit can be divided in to two fundamental parts:

1. Inverter Control
2. Power Control

1. INVERTER CONTROL

Inverter controller's primary function is to provide stability control. It takes transformer secondary side current (I_{W2}) as an input, detects phase of the signal and computes the frequency by comparing the simulation time and the time difference between two zero crossing. And then from phase detection PWM switching pulses are also obtained. Which are given to the inverter block. Complete overview of the working of the block can be seen from the following figure:

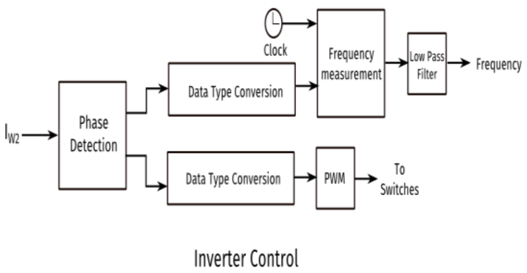

Fig 2. Inverter control model

A MATLAB Function block (from Simulink Library >> User-Defined Function Blocks) is used for writing a frequency measurement code. Output of which is passed through a low pass filter. Low Pass Filter (LPF) is used to remove the noise and the aliasing effect due to sampling and to get a nominal frequency signal. Transfer function of LPF is 1/1+Ts; where Ts = 10e-5.
Data conversion blocks are used for two purposes:
To convert Float to Boolean
To convert Real World value (RWV) to floor

2. POWER CONTROL

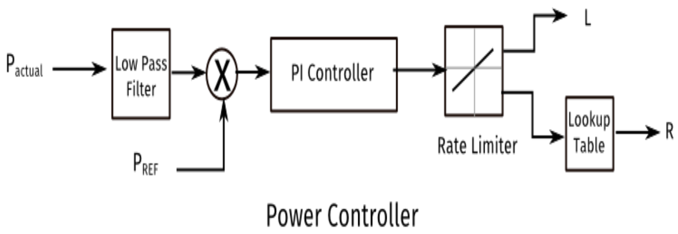

Fig 3. Power controller Block Diagram

This masked block controls the values of R and L and thereby controls the resonance frequency of the whole model. Power is taken as input by sensing load voltage (V_r)

and secondary current (I_{w2}) of the linear transformer, which is then given to comparator which computes the error from the reference power input (P_{ref}), this error is then given to PI controller which gives out the signal which corresponds to the desired values of R and L. Details of PI controller is given in the following table

Name	PID controller
Type	PI
Time Domain	Continuous
Saturation Limit	25e-6 to 40e-6

Table 1: PI controller parameters

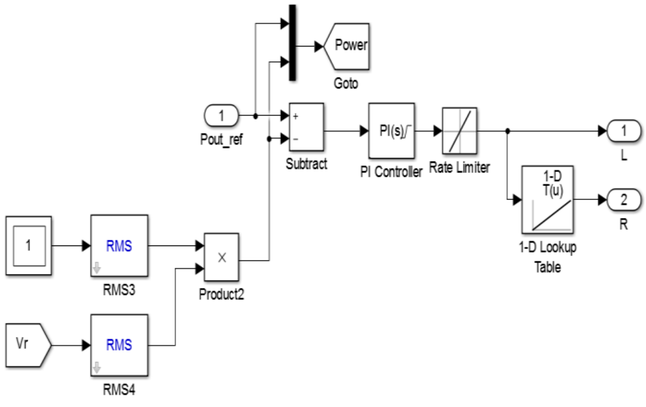

Fig -4 .Simulink Model for Power control

A **rate-limiter** is used for modeling the response time of real system. A real life induction heater would respond to the change in power value slowly, in the orders of magnitude in few milliseconds due to the physical inertia of the servo mechanism & winding.

This *slowed-down signal* is then given to the **look-up table** for computing R and it's directly given to the L.

1-D Lookup table implements an equation of line the details are given below:

Name	Lookup Table (n-D)
No. of Table dimensions	1
Table Data	[1.96,2.5]
Breakpoint 1	[24.6e-6,40e-6]

Table 2 – look up table parameters

PI Controller is a part of the feedback loop mechanism which continuously monitors the input or the error signal with the "reference set point" and tries to minimize the error. There are different controllers here in this a PI controller is used. Which is tuned for operating frequency of 80 kHz to 100 kHz and with reference power input of 80kW to 100kW.

This can be physically regarded as dashpot system with a spring. There are two parameters Kp which is a proportional gain which handles the present value error and Ki which is a integral coefficient which handles the accumulation of past errors. This is the reason which PI controller doesn't have steady state error if tuned properly.

It is a fairly challenging task to tune a controller if the plant under consideration is non-liner. There are different methods proposed for tuning of controller but nothing matches the manual tuning when a large nonlinear system is involved.

4. Result & Discussion

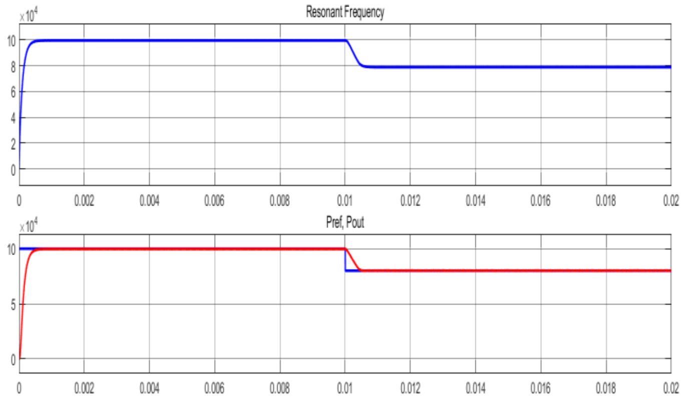

Fig 5a. output Waveforms – Resonance frequency
Fig 5b Power output and Reference power

Initial Power reference input P_{ref} = 100 kW and at 10 mSecP_{ref} = 80kW, this step change is show in Fig-6 above. Here in fig.-6(1) Shows the change in frequency with change in load power. Fig-6(2) shows the change in output power due to change in Pref it is seen that power reference (blue line) changes at 10e-3 Sec to 80 kW and actual converter output changes accordingly.

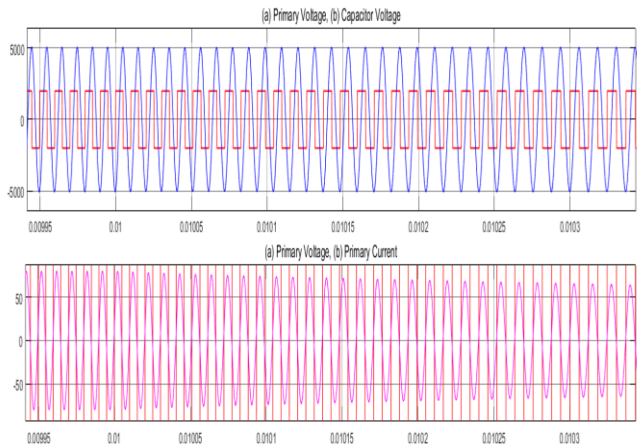

Fig 6 .Output waveform a) Primary voltage & capacitor voltage b) Primary voltage & Primary current

Here in above figure-6 it can be seen that, 1st plot is of primary voltage versus capacitor current and it has is 90 lagging phase shift. This is the primary stability condition. 2nd figure show the change in primary current with the change in load, at 10msec the load is reduced from 100kW to 80 kW and hence current also reduces accordingly.

Software Details:

MATLAB/Simulink's R2015B version has been used.

Packages used:

Simulink & SimPower Systems

Sr. No.	Parameter	Values
1	R @ 100kHz	2
2	R @ ~80kHz	2.5
3	L @ 100kHz	25e-6
4	L @ ~80kHz	100e-6
5	I_{Load} @ 100kHz	222
6	I_{Load} @ ~80kHz	177.8
7	C	2000 v
8	Vdc	IGBT
9	Switch Type	100e-6
10	LPF	

Table 3 – Simulink values in model

5. Conclusion

Induction heating has become popular in commercial and heavy industrial application due to its property of spot heating at a particular time instant, environmentally friendly and energy efficient system. Series resonant converter for Induction Heating application is modeled here and is able to provide (almost) "pure" sinusoidal output. An effort is made to develop a control model using PI controller tuned for operating frequency of 80 kHz to 100 kHz and with reference power input of 80kW to 100kW. PI controller controls the values of load R and L and thereby controls the resonance frequency of the whole model.

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