SERIES LOAD RESONANT CONVERTOR FOR INDUCTION HEATING APPLICATION

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Abstract- Induction heating Applications have become immensely popular in today’s world due to its contactless, energy efficient, no smoke and environmentally clean heat treating methods. Typical Heavy Industrial Applications like Induction Welding & Annealing require operating on High power and High frequencies of the order of 100kwatt / 100 kHz. This Paper Proposes a voltage source series resonant convertor for high power (100kw) Induction heating application. It uses soft switching for the two-leg IGBT based Inverter which switches at variable frequency between 80 KHz to 100 KHz. A model is considered with Ron =1μ Ohm with Ton & Toff = 0 Sec. The model achieves proper power control for load ranging from 80 kW to 100kw.

Keywords- Induction heating, Series Resonant convertor, Inverter.

1. INTRODUCTION

Induction heating has acquired tremendous popularity due to its advantages like contactless heating without any smoke-ash emissions, energy efficiency and environment cleanliness for a wide range of applications in metal heat treatment industries. Common applications under High Power domain include Surface hardening, Welding, Melting liquid (molten metal), Annealing, Brazing and Soldering. [1] [3]

Conventional metal heating methods like gas heating and resistive heating techniques are being replaced by the well-researched non-contact type and energy efficient induction heating technique. The advances in manufacturing high power semiconductor switches like SITs, power MOSFETS, IGBTs and the developments in circuit integration have given a tremendous boost to its use. The demand for better quality, very short heating time, safe and less energy consuming products is rising for that reason Induction heating has become a popular area of research. [2]

The power convertor implemented in this paper is a series resonant convertor 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 controlling relative operating frequency f. Maximum voltage and power can be drawn at resonance. [3]

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. Another disadvantage of switch mode operation is the EMI produced due to large di/dt and dv/dt.[1] The switching losses are minimized at high frequency if the converter changes its status from on to off and vice versa when voltage across it and current through it is zero at switching instant; this strategy is modeled in this paper.

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 [4][5]

The modulation strategies commonly used to control output power are based on modifying switching frequency or duty cycle in order to achieve the desired output power.

The full bridge topology can offer higher output power and control flexibility; its efficiency can be improved by proper control strategy, only Disadvantage is its higher cost, hence not used in domestic low power – low budget applications. The half bridge series resonant inverter is the most used topology due to its appropriate balance between performance, complexity and cost. It can be applied to design converters up to 3.5 kW output power.[6]

This paper models full bridge topology due to high power, High frequency heavy Industry application under consideration.

A. Model Discription

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. [3]

B. Series Resonant Converter

Conversers 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 $f_s$.

One method of controlling the output voltage in resonant converters is to control the switching frequency of the full-bridge inverter. This method is called ‘variable frequency control’. In this type of control, the switching frequency ($f_s$) controls the impedance of the resonant components connected between the inverter and the load. This in-turn controls the power flow from the input to the output and, therefore, the output voltage. The resonant components L and C have a fixed value at the resonant frequency $f_r$. Depending upon the value of the frequency, the converter operates in the following three modes:

1. Below resonance mode ($f_s < f_r$) : current leads voltage, $X_C > X_L$, phase angle $= +90^\circ$

2. Above resonance mode ($f_s > f_r$) : Voltage leads current, $X_L > X_C$, phase angle $= -90^\circ$

3. At resonance mode ($f_s = f_r$) : both current & voltage in phase, $X_L=X_C$, Phase angle $= 0^\circ$

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 $X_L=X_C$. At this instant the transfer function of the circuit is close to one. A resonant circuit involves L-C or RLC tank circuit. In case of LC circuit, when circuit is in steady state, the collapsing of magnetic field generates current in the circuit which charges the capacitor, when capacitor eventually discharges it builds up a magnetic field in inductor and that is how the process continues. In case of RLC circuit the principal remains the same except that the oscillations decay eventually, if they are not passed through a source. Thus resonance circuit form a harmonic oscillator. This oscillator operates at

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

$$\arctan \frac{X_L-X_C}{R} = 0^\circ$$

(All Real)

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R} = \frac{Z_0}{R}$$

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]

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.

II. SIMULINK MODEL
a) 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 rectified. 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.

Table 1 : DC source Simulink circuit values

<table>
<thead>
<tr>
<th>Name</th>
<th>DC Voltage Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>2000</td>
</tr>
<tr>
<td>Measurement</td>
<td>Voltage</td>
</tr>
</tbody>
</table>

b) 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. The parameter of the inverter bridge is as follows:

Table 2 : Inverter Simulink circuit values

<table>
<thead>
<tr>
<th>Name</th>
<th>Universal Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Type/No.</td>
<td>IGBT/4</td>
</tr>
<tr>
<td>Ron</td>
<td>1e-6</td>
</tr>
<tr>
<td>Measurement</td>
<td>None</td>
</tr>
<tr>
<td>Ton &amp; Toff</td>
<td>0 Sec</td>
</tr>
</tbody>
</table>

In this implementation series load resonance has been used.
Inverter is operated at variable frequency between ~80 kHz to 100 kHz.

c) 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 whose parameters are as follow:

Table 3 : Linear Transformer Simulink circuit values

<table>
<thead>
<tr>
<th>Name</th>
<th>Linear Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power Frequency</td>
<td>[100e3 100e3]</td>
</tr>
<tr>
<td>Winding 1 parameter</td>
<td>[1.4142 0 0]</td>
</tr>
<tr>
<td>Winding 2 parameter</td>
<td>[353.55 0 0]</td>
</tr>
<tr>
<td>Magnetization</td>
<td>None</td>
</tr>
</tbody>
</table>

1414/353 Volts, idealized parameter is used. Idealization is taken to simplify the modeling and to remove the nonlinear magnetization effect on the control part, and it is observed that this simplification affects the accuracy of the result very little but simplifies the implementation greatly.

d) Load Circuit Variable R
Load circuit consists of a variable R. This is a self-developed block which implements the voltage to resistance relationship of \( V=I \times R \). This block receives Resistor value as input and a dependent voltage source, generates voltage on the basis of the \( I\times R \) 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 its 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.
**e) 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 5 : Simulink Model of Inverter*

- 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 \(Ts = 10^{-5}\)

- **Data conversion** blocks are used for two purposes
  - To convert Float to Boolean
  - To convert Real World value (RWV) to floor

**f) PI Controller**

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 why PI controller does not have steady state error if tuned properly.

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

### III. RESULT & DISCUSSION

Initial Power at reference input \(P_{ref} = 100\ kW\) and at 10 mSec then \(P_{ref} = 80\ kW\), 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 \(10^{-3}\) Sec to 80 kW and actual converter output changes accordingly.

*Fig 6 output Waveforms - Resonance frequency & Power*

Here in above figure-7 it can be seen that, 1st plot is of primary voltage versus capacitor current and it has 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.

*Fig 7 Output waveform a) Primary voltage & capacitor voltage b) Primary voltage & Primary current*

**CONCLUSION**

Induction heating has gained lot of popularity in industry due to cleanliness, control and convenience and is being adopted rapidly. Series resonant converter for Induction Heating application modeled here is able to provide (almost) “pure” sinusoidal output. Hence resonant converter is also gaining lot
of attraction. An effort is made to develop a Simulink model of practically possible reconfigurable Induction Heating converter and its controller which can operate on a wider frequency range of the order of 100 kilo-hertz and power can be as high as 100kW.

To derive high power, high frequency induction heating following points are considered in the model:

- In case of switched mode power converters, Power electronic switches (IGBTs) will increase its switching losses proportionally.
- To limit such switching losses, IGBTs or diodes need to switch at either zero current or zero voltage values i.e. ZCS or ZVS operation.
- Hence resonant converter is used.
- But resonance is natural phenomenon i.e. system needs to be maintained at marginally stable state with poles on imaginary axis.
- Finally, controller needs to act for stability and power i.e. over current protection or current regulation (during transient state).

REFERENCES

[1] Ned Mohan, Tore M. Undeland; Power Electronics: Converter, applications, and design, Wiley publication


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