CHAPTER 5
RECONFIGURABLE INDUCTION HEATING SYSTEM

5.1 PID Controller
5.2 PI Control
5.3 Snubber circuit
5.4 Zero voltage / Zero current switching
5.5 Series load resonant converter
5.6 Reconfigurable Induction Heating System
5.6.1 Power Circuit Design
5.6.2 Control Circuit Design
5.7 Results and Discussion

RECONFIGURABLE INDUCTION HEATING SYSTEM

Induction heating has become popular in recent times due to its improved performance in comparison with the old heat treatment methods and its numerous advantages like smoke free, noise free environmentally clean process with high energy efficiency covering an entire range of products in metal, nonmetallic heat treatment industries.
Gas and resistive heating techniques were prevalent in the past they are totally replaced by this quick heat treatment method which makes no contact with material to be heated does not pollute the atmosphere, no emission of any harmful gases etc. Since there is no physical contact to heating devices all unpleasant electrical hazards or accidents are avoided. High energy density and spot heating is achieved by generating required heat energy in a short instant of time.

The Induction Heaters used in heavy Industries work on 3 phase supply which is rectified and filtered to give nearly pure DC of the order of few volts to few thousand volts. Extracting such high voltages without any ripple is a huge task, generating smooth DC is a challenging and costly. Rectification, filtering using heavy Industrial components adds to the system cost, further need of Step Up – Step Down and Impedance matching transformers with a water cooling system is a must.

The work coil needs to be designed as per specification; rigid calculations for the core; thickness of windings and no of turns etc. should be analyzed properly. Where and how the work piece can be placed, type of work piece required, working frequency of the system depends on penetration depth, skin losses etc. are required to be considered.

Soft switching power devices have to be used for switching which work comfortably at such frequency and power rating. Power MOSFETS, SITs or IGBTs have to be used. Frequency locking, stability, over voltage protection, closed loop feedback control system etc. all adds to cost of the system.

The objective is this thesis is to develop a model for Induction Heating system which can be used for a range of load RLC values at high power and high frequencies of the order of 100KW / 100 KHz where the software (code) or model parameters can be altered to adapt to the changes in load values without changing the Hardware involved.

A reconfigurable Induction Heating system is modeled in MATLAB /Simulink, in this chapter which has the following parameters:

- Control system - Close loop control system.
- Control Element – PI controller
This chapter deals in detail with the close loop control system, brief theory of PID controller is mentioned. The system designed here does not require the derivative part for the control action hence PI controller is the chosen control approach. To reduce the di/dt stress - Snubber circuit is used which are discussed in detail with the switching characteristics. The switching action of the switching elements (IGBT chosen here for high frequency operation) should be done when voltage across device or current through it is zero to avoid switching losses; the method used is ZVS, discussed in detail. Complete inverter design is presented in chapter 4, Voltage source Inverter with IGBT as the switching element is the choice due to its capability to work high frequency around 100KHz. Series load resonant converter is used in the model which is discussed in detail here. Once all the design elements and their choice is justified the block diagram of the entire Induction heating system is modeled and all the Simulink blocks are discussed analyzed in detail with the tables of the actual values and components used in the model. Later all output graphs are presented and discussed in detail.

5.1 PID Controller:
The PID controller calculates an error value continuously which is difference of the desired reference value or set point and the quantity to be measured or the process variable. By continuously adjusting the control variable which may be in the form of control valve or a damper or may be power supplied to an element for heating, to get a new value the PID controller tries to minimize the error at its output.

The present values of error is represented by P in the model. E.g. the output is similar if error is large and positive. Past values of error is represented by “I”. The error might accumulate if current output is not strong and the controller will reply with a stronger action. Future values of error is represented by D, based on current analysis.
PID controller does not rely on any information coming from underlying process; it only depends on measured process variable. Specific process requirements can be accomplished by tuning all the parameters of the model.

The response of controller depends on how it responds to error, the amount of change it makes with reference value or set point and oscillations. The PID control system does not guarantee optimized system control or its stability.

Applications might not always require all three terms for control action; the term which is not required can be set to zero. In such case the controller can be called PI control by setting D term to zero, Only P or I control by setting remaining two terms to zero, or PD control.[67][68]

PID controller can be designed in MATLAB by directly using its transfer function. e.g.
Kp=1;
Ki=1;
Kd=1;
S=tf('s');
C = Kp + Ki/s + Kd*s
C = s^2 + s + 1 / s using continuous time transfer function.
MATLAB's PID controller object could also be used to generate continuous-time controller for e.g. c = pid (Kc, Kd, Ki )
C = Kp+ Ki * 1/s + Kd *s with Kp=1, Ki=1, Kd=1 for PID controller in parallel form in continuous time analysis.

The effects of Kp , Kd and Ki on a close loop system are mentioned below:

<table>
<thead>
<tr>
<th>CL response</th>
<th>Rise time</th>
<th>Overshoor</th>
<th>Settling time</th>
<th>S-S error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kp</td>
<td>Decrease</td>
<td>Increase</td>
<td>Small Change</td>
<td>Decrease</td>
</tr>
<tr>
<td>Ki</td>
<td>Decrease</td>
<td>Increase</td>
<td>Increase</td>
<td>Eliminate</td>
</tr>
<tr>
<td>Kd</td>
<td>Small Change</td>
<td>Decrease</td>
<td>Decrease</td>
<td>No Change</td>
</tr>
</tbody>
</table>
**History of PID:**

The History of PID is interesting, the first PID controller was developed in 1911 for controlling the automatic steering systems of the US based Navy ship by Elmer Sperry, depending on the analysis and observations done by helmsman, the ship was controlled based on the current error and past error along with the current rate of change, this was later mathematically modeled by Russian American engineer Nicolas Minorsky in 1922.

In olden days for automatic process controlling, PID was implemented as a mechanical device using lever, spring and mass which was energized by compressed air, this was Industry standard then. Later Electronic was used; analog controllers were made from solid state devices, tube amplifiers and passive components.

Programmable logic controllers with coding techniques and digital design logic are used in present PID controllers in Industry. Software implementations make the system relatively cheaper and more flexible. PID temperature controllers find application in industrial high temperature ovens, packaging industry, plastic machinery for dye injection, hot-stamping molding machinery.

**Control Loop Theory:**

The sensed position is PV i.e. processed variable. The set point (SP) is the desired position. The PID controller output is input to the process (which can be the electric current in the motor). It is called control variable (CV) or the manipulated variable (MV). The error (e) is the difference between the present position and the set point.

The position (PV) is subtracted from the set point (SP), to find the error (e). How much electric current has to be supplied to the motor depends on error (e). The most common method is proportional control: the motor current is set in proportion to the existing error (e). A complex control method may include another term which is the derivative term. How quickly the error approaches zero is decided by electric current supply. The position of the mechanical arm is set out too low or too high depending on accumulated position error in the past and to set the electrical current in relation to the error and the time for which it has persisted, all this is set by third term.

Overshoot will result if too much impetus is added when the error is too small and is reducing. After overshoot, if the controller applies a large correction in the opposite direction, the output would oscillate around the set point in a constant, growing, or decaying sinusoid.
The system becomes unstable, if the amplitude of the oscillations increases with time. If amplitude decreases with time then the system is stable. The system is marginally stable if the oscillations remain at a constant magnitude. The controlled system has to be critically damped in order to achieve controlled arrival at desired position in time and should be accurate. The required current to the motor can be applied by a well-tuned Position control system in order to push and pulls arm to resist external forces trying to move it away from the set position. The set point itself can be generated by an external system, like the PLC or computer system.

To control a process with a measurable output (PV) controller is used; a known ideal value for output (SP) and input to the process (MV) will affect the relevant PV. To regulate temperature, feed, force, flow, speed, flow rate, pressure, position and weight practically every other variable for which a measurement exists controllers are widely used in industry.

- **Process variable (PV)** indicates sensed position.
- **Desired position** is called set point (SP)
- **Output of PID controller** is the input to the process, called as manipulated variable (MV) or control variable (CV)
- **Error (E)** is difference between present position and set point
- **Kp** - is the proportional gain, which is a tuning parameter
- **Ki** - is the integral gain, which is also a tuning parameter
- **Kd** - is the derivative gain, which is also a tuning parameter
- **E** - Is the error, (PV) - (SP) = E

**Proportional Term: Kp**
Fig. 5.2 is a graph of Proportional term (PV) v/s time, kp has 3 values ranging from 0.5, 1.1 and 1.6, three graphs of Kp are plotted for this with respect to a common reference point. Kd and ki are the constant terms in the graph.

Output produced by Proportional term (PV) is proportional to the current error (E) value. Multiplying the error (E) by a constant Kp, which is called the proportional gain constant proportional response is adjusted.

Large change in output for a given change in the error is result of having higher value of Kp. The system becomes unstable if proportional gain Kp is too high. If Kp is too low, the control action would be very small, when reacting to system disturbances. The theory of tuning along with industrial practice suggest that the proportional term should contribute to the maximum output change.

Making corrections when error is too small and is diminishing might lead to overshoot and now if large correction is applied in opposite direction the oscillations near the set point can be seen in the output in the form of a increasing or reducing sinusoid. If amplitude increases with time then system loses stability, if amplitude reduces with increase in time then system gains stability. If oscillations have constant magnitude then the system is in marginally stable state.
Integral term – Ki

Fig. 5.3: Plot of PV v/s time, for three values of Ki (Kp and Kd held constant)

Fig. 5.3 is a graph of Proportional term (PV) v/s time, ki has 3 values ranging from 0.5, 1 and 2, and three graphs of Ki are plotted for this with respect to a common reference point. Kp and Kd are the constant terms in the graph.

The integral term Ki is proportional to magnitude and duration of the error. The accumulated offset along with sum of instantaneous error for a time period is used for deriving value of Ki, which should have been corrected earlier. The output of controller is the accumulated error and is multiplied by Ki. The integral term makes the movement rapid to get the set point faster and the residual steady-state error is nearly zero which would have occurred with a pure proportional controller. The integral term is dependent on errors accumulated in the past and might cause the current value to exceed the set point value.

Derivative term – Kd
Fig. 5.4 is a graph of Proportional term (PV) v/s time, kd has 3 values ranging from 0.5, 1 and 2, and three graphs of Kd are plotted for this with respect to a common reference point. Ki and Kp are the constant terms in the graph.

Improvement in settling time and stability of the system and system behavior is predicted by derivative action. Low-pass filtering is used to implement the derivative term for PID controllers in order to limit the gain at high-frequency and noise. Since the derivative action has variable impact on system stability hence for real-world applications the derivative action is used in practice for 25% of deployed controllers.

For calculating process errors the slope of the error over a time period and then this rate of change is multiplied by the derivative gain $K_d$. The contribution of the derivative term magnitude to the overall controller is termed the derivative gain, $K_d$.

**Guidelines for designing a PID control system:**
Following steps should be taken while designing PID to get a desirable response.

- The first step is to generate an open loop response and then think on improvising it.
- In order to improve the rise time a proportional control is required.
- In order to improve the overshoot a derivative control is required.
In order to improve the steady state error an integral control is required.

Kp, Kd and Ki are adjusted for getting desired response.

If all type of control are not required, it is not mandatory to implement all three, the system could be PID or a PI controller depending on the requirement.

The controller must be as simple as per specification requirement.

Tuning the Loop

Tuning is meant by the adjustment of control parameters like Gain, band width, integral/derivative gain, reset etc. It has to be done for setting optimum values for the desired control action. The basic requirement is Stability, no oscillations. Every system might have different requirement.

There are number of Tuning methods for a PID loop. After developing the process model the P, I and D are chosen, this is the best method. For systems with long loops manual methods if used would be extremely time consuming.

The loop can be taken for “offline” tuning, on the response time or cannot be taken depends on the method selected for tuning.

Some common tuning methods are:

- Manual
- Ziegler-Nichols
- Tyreus Luyben

MATLAB has provided tools for tuning automatically by choice of PID loop gains which use the trial and error procedure. Pidtune command is used for the tuning algorithm or a graphical user interface (GUI) called pidtool can be used. The algorithms by MATLAB for automated tuning use PID gains for better performance in the form of bandwidth, response time, robustness, stability margins etc. These algorithm have a 60 degree phase margin set as default parameter.[67][68]

The PI control loop in this research work uses the Manual tuning method.

5.2 PI Control:
All Applications might not always require all three terms P, I and D for control action; the term which is not required can be set to zero. In such case the controller can be called PI control by setting D term to zero, Only P or I control by setting remaining two terms to zero, or PD control. The Induction Heating control system discussed in this research work does not require the derivative term for control action hence D term is set to zero.

The definition of proportional feedback control is

\[ U = K_p e(t) \]

Where

\( e = \) is the "error"

\( K_p = \) Proportional gain

The definition of the integral feedback is

\[ U = K_i \int e(t) dt \]  \hspace{1cm} (2)

Where \( K_i \) is the integral gain factor.

![Fig. 5.5: Basic block of a PI controller](image)

Fig. 5.5 shows blocks for the PI Controller (proportional -integral controller) which is a special form of the PID controller where the derivative (D) is not used. The fig.5.5 shows the summation of the two terms SP and PV which are given to two blocks the P – Proportional and I – Integral block.

Since the derivative term is absent the system becomes steadier in the steady state even in presence of noise or with noisy data. Since derivative action is more sensitive to higher-frequency terms in the inputs. PI controllers are quite common, derivative action is sensitive to noise; if integral term is absent it would prevent the system from reaching its target value.
Controllers are most commonly used in industry for regulation of Pressure, Flow, Temperature, Force, Position, Speed etc. and are practically used where any variable is to be used for measurement. [66]

5.3 Snubber circuit:
The switching frequencies in KHz and MHz range reduce the size and weight of transformer and components used for filter and also the cost of converter reduces. If switching stress and losses and EMI is reduced then only frequencies can be increased to higher values.
The switching stress can be reduced by using diodes and passive components in series and parallel with switch in converters as shown in Fig. 5.6(a) below. This dissipative snubbers circuit shift switching power loss from switch to snubber, but this logic does not provide complete elimination of losses. Fig. 5.6(b) is a graph with on Voltage on x-axis and current on Y-axis. It represents turn ON and Turn OFF of switching transistors or IGBT’s implemented in the circuit, modeled here in fig. 5.6(a) by switches.

5.4 Zero voltage / Zero current switching:
Snubber circuit will not eliminate switching losses completely, instead of using dissipative snubbers the switching losses, stress and EMI can be overcome by selecting proper combination of switching strategy and converter topology. These losses will be eliminated if switch voltage or current is made zero during switching transition. This is called Zero voltage or Zero current switching as shown in Fig.5.7.

5.5 Series load resonant converter:
In all DC to AC converters discussed in chapter 4, the control switches are expected to turn ON or turn OFF the complete load current in each switching cycle. They are operated in a switch mode. The switching stress and loss increases linearly with switching frequency of the Pulse width modulator all the switching devices suffer due to this loss. EMI is produced due to large di/dt stress and dv/dt stress caused due to the switch mode operation this is a major drawback of the switch mode operation.
To reduce the size and weight of converter, and to increase the power density the switching frequency is increased, in such case the losses of switch-mode converter further increases. 

Each switch of the converter must change state when voltage across it or current through it is zero during the time of switching then the shortcomings in switch-mode converter is reduced. Most of the topologies require some kind of LC resonance and such converters are called “Resonant Converters”.

Classification of Resonant converters:
All resonant converters are defined by combination of converter topology and switching strategy resulting in ZVS/ZCS.

- Load –resonant
- Resonant switch
- Resonant –dc link
- High-frequency integral half cycle

Load resonant converters:
They have a LC resonant tank circuit. Converter switches are switched at ZVS/ZCS. Series LC or parallel LC circuit can be used. Power flow to load is controlled by resonant tank impedance – Z, which is controlled by switching frequency fs.
These DC to AC converters are further classified as:

- Voltage Source Series resonant converters – further classified as : SLR – Series load resonant converters , PLR- parallel load resonant converters and Hybrid load resonant converters
- Current source parallel resonant converters
- Class E and Sub class E resonant converters

The Reconfigurable system modeled in the research work uses the Load resonant converter which are sub classified as SLR which stands for a Series load resonant converter which is dealt in detail below.

Series resonant circuit:
Fig. 5.8(a) shows an undamped series resonant circuit where $V_d$ is the input voltage at time $t_0$. 5.8 (b) shows normalized waveforms for $I_L$ and $V_c$. $I_L$ is Inductor current and $V_c$ is capacitor voltage are the state variables then the circuit equations are:

$$L_C \frac{di_L}{dt} + v_c = V_d$$  \hspace{1cm}  \text{Equation 3}$$

$$C_r \frac{dv_c}{dt} = i_L$$  \hspace{1cm}  \text{Equation 4}$$

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}}$$  \hspace{1cm}  \text{Equation 5}$$

$\omega_0$ is angular resonance frequency

$$Z_0 = \sqrt{\frac{L_r}{C_r}} \ \Omega$$  \hspace{1cm}  \text{Equation 5}$$

$Z_0$ is characteristic Impedance

Fig. 5.8 (a) Undamped Series Resonant circuit, (b) normalized waveforms for $I_L$ and $V_c$[65]

**Frequency characteristics of Series resonant circuit:**

$\omega_0$ is angular resonance frequency and $Z_0$ is characteristic Impedance are defined above in equation 2 and 3, In presence of load resistance $R$ another quantity can be defined as Quality Factor Q.
Fig. 5.9 (a) Series resonant Circuit

5.9(b) Graph of magnitude $Z_s$ v/s frequency

Fig. 5.9 (a) represents series resonant circuit with series connected LC elements with load resistance $R$.

Fig 5.9 b shows magnitude $Z_s$ of the circuit impedance on Y axis v/s frequency $\omega_s$ on x axis with $Q$ as a parameter, when $R$ is constant. $Z_s$ is pure resistance equal to $R$ at $\omega_s = \omega_0$ and is very sensitive to frequency change from $\omega_0$ to higher values of $Q$.

5.9 (c) current phase angle as function of frequency
A resonant circuit involves L and that is how the process continues. In case of R LC 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 resonant frequency.

The series resonance has an RLC circuit comprising a resistance inductance and capacitance connected in series across a voltage supply. This series RLC circuit resonates at a specific frequency which is called resonant frequency. Electrical resonance occurs in an electric circuit when the imaginary parts of impedances or admittances of circuit cancel out each other, Inductive reactance is XL and Capacitive reactance is Xc, when XL = XC resonance occurs, at this instant the transfer function of the circuit is close to one.

5.6 Reconfigurable Induction Heating System
The Reconfigurable Induction Heating System Block Diagram in Fig. 5.10 consists of AC mains supply an AC to DC converter which generates 2000V from the main line is given to the DC to AC converter block (IGBT Inverter) output of it is fed to Primary of transformer. The secondary winding of transformer has a load resonant converter circuit (Voltage Source Series resonant converters). The Digital controller design which is the main block for this research is broken into two parts i) power circuit design, ii) Control circuit design both design blocks are explained below in detail with the Simulink design block of each and design parameters.

As it is apparent from the figure 5.10 that the Digital Control Design block is divided into 2 parts:

- Power control circuit
- Control Circuit

**Power Control is made up of following blocks:**

- DC Source
- Inverter
- Impedance Matching Transformer
- Voltage step down Transformer
- Series Load Resonant converter circuit – variable R and variable L

**Control Circuit is further classified in 2 parts:**

- Frequency Control
- Power Control

**Design Tool for Reconfigurable IH system:**

The entire Reconfigurable system is modelled using MATLAB’s Simulink tool which is explained in detail with the common MATLAB commands and Simulink windows in chapter 4. In order to model some specific blocks of electrical systems and Power systems a separate
tool box called Simscape power system is required. It was referred to as Simpower systems earlier.

This box has libraries for all components and tools for analysis in order to simulate and model electrical power components for example 3 phase machines, electrical motor drives, Flexible AC transmission systems, renewable energy components required to calculate the total harmonic distortion, flow in load models, analysis of harmonics, automation of electrical systems and performance analysis and investigation using Simscape power systems. Model parameters can be set by writing code in MATLAB and use Simulink and Simscape both for the blocks to be designed.

Thermal, mechanical and Hydraulic and other physical systems in the model can be integrated by Simscape product family. The models can be deployed to other Simulation environment like hardware –in-the-loop systems etc. C- Code generation is also supported by SimScape. It was developed to collaborate with Hydro-Quebec of Montreal. [46]

**Features of Simscape Power system:**

- Used to build specific models for a particular application. E.g. AC and DC drives, systems using renewable energy resources.
- For faster execution discrete modeling can be done or phasor simulation.
- Ideal switching devices should be considered for faster simulation.
- Computing machine flow and State space representation by analysis method.
- For developing electrical technology basic models are available.
- Creation of custom component model in MATLAB based on Simscape.
- C-code generation supported by a Simulink coder.

**Power System Libraries blocks in Simscape:**

It contains libraries for representing two top level blocks for representing two technologies.

**Simscape Component Library:**

Simscape component library is a part of Simscape power systems tool box for working with multiphase electrical systems. It has Simscape foundation areas and a 3 phase electric systems area which can be utilized to build custom made 3 phase blocks by Simscape.
language. Many machine sources as well as transformer blocks can be viewed and customized as per requirement. Pe_lib is the main Simscape library for components which contains three phase and single phase blocks for electrical ports along with blocks for translation ports and mechanical rotation. The blocks can be taken from the sub libraries built as per their functioning. The blocks from sub libraries can be connected to blocks from Simscape library directly or connected with foundation library or any other add on product library. To support single line diagrams three phase ports blocks are collapsed. They can be expanded to inject line to ground faults etc.

**Components used in Simscape**

Electrical components for power systems are used in Simscape as under:

- Basic modeling components have model construction technique and best practices
- Type of connections may be grounding, neutral, phase splitting, multiplexing
- Passive devices like Resistive load, capacitive load or RLC branches and transmission lines.
- Semiconductor switching devices like converters, rectifiers, diodes and thyristors.
- Voltage, line, phase and current sensors.
- Single phase and 3 phase voltage and current sources.
- 3 phase switch and circuit breakers, single phase switch and circuit breakers
- Pulse generators for supplying triggering pulses.
- Simulation Tools for improving performance, graphically analyzing facts and implementation techniques.

**Simscape’s Specialized Technology Library:**

Models for the major power equipment like the Transformers, lines, machines, and power electronic components are available in the Simscape Power Systems Technological library. The Power Systems Testing and Simulation Laboratory of Hydro-Québec which is a large North America based organization placed in Canada which validates the systems, based on their experience and actual models which are taken from standard text and reference books. The experience of École de Technologies Supérieure and University Laval is also taken into consideration.
The electrical system modelling capabilities of Simscape Power Systems software are illustrated in sample example files. Self-learning case studies are available for users wanting to refresh their knowledge on theory of power system.

Simscape power systems_ST is the main Specialized Technology library. Sub libraries of blocks are organized according to their behavior in the main library. Powertgui block is found in the sub library called Fundamental Blocks. The steady-state analysis for electrical circuit’s tools are available in the powertgui block. [46]

**Specialized Technology has following libraries:**

Specialized components and algorithms are required to Model electrical power systems all such special components are mentioned below.

- **Electrical Sources** have all AC and DC sources, circuit breakers, all type of transformer blocks, series and parallel RLC branch elements and load elements and transmission lines.
- **Motors:** Asynchronous and synchronous machines, AC and DC motors, AC - DC Generators and excitation systems.
- **Power Electronics switching devices like** Thyristors, power diodes, AC bridges, **Sensors for Measurements of** Current, voltage, and impedance sensors and specialized measurement blocks.
- Block for signal generation and control blocks - Pulse generators, filters, and signal conversion blocks.
- **Electric Drives for** AC - DC drives, shafts and speed controllers, batteries, fuel cells and **Renewable Energy equipment’s like AC flexible** Transmission Systems and wind turbine models under renewable energy systems.
- Blocks to connect Simscape power systems and Interface it to Simscape electrical circuits for doing further simulation and analysis.
- Tools to analyze simulation performance and techniques used.

**The Simulink Library Browser is used to access the libraries and blocks.**

The Simscape Power Systems libraries can be accessed through the Simulink Library Browser. In order to display the Simulink Library Browser using the MATLAB command
prompt, the `slLibraryBrowser` command should be entered on the MATLAB command prompt. From the left pane of the library browser one needs to scroll down to the Simscape node. On expanding the Simscape node and then expanding the Power Systems node the window shown below will open.

![Simulink Library Browser](image)

**Fig. 5.11 Simulink Library Browser**

Fig. 5.11 shows the Simulink library browser and method to open the Simscape and the power components library in Simulink is mentioned above. The figure shows Simscape component block and Simscape Specialized technology block on the right side of the window. Left hand side displays all general library blocks available under Simscape for example the foundation block, driveline, fluids etc.

The library browser can be used to access the Simscape Power Systems library from a Simulink model window by clicking Library Browser button in the toolbar of the model window.

The Command Prompt can also be used to access the Library blocks. In order to access the required libraries mentioned in table below the relevant command should be entered at the MATLAB command prompt.
Table 5.2: Simscape Library with Description of block and commands

<table>
<thead>
<tr>
<th>Library to be used</th>
<th>Description of block</th>
<th>Simscape power systems / Simscape and Simulink library Commands to be used for the required work.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simscape Power Systems</td>
<td>Top-level libraries in Simscape Power Systems</td>
<td>Simscapepowersystems</td>
</tr>
<tr>
<td>Simscape Components library under Simscape power systems</td>
<td>Simscape Components blocks</td>
<td>pe_lib</td>
</tr>
<tr>
<td>Specialized Technology library under Simscape Power Systems</td>
<td>Specialized Technology blocks</td>
<td>Simscapepowersystems_ST</td>
</tr>
<tr>
<td>Specialized Technology under Simscape Power Systems with the Fundamental Blocks</td>
<td>Powergui block with the interface elements, and other fundamental blocks for Specialized Technology</td>
<td>powerlib</td>
</tr>
<tr>
<td>General Simscape</td>
<td>Under general Simscape utility blocks: single-phase electrical sources, sensors, and other Foundation library blocks</td>
<td>simscape</td>
</tr>
<tr>
<td>Simulink</td>
<td>Generic Simulink blocks</td>
<td>slLibraryBrowser</td>
</tr>
</tbody>
</table>

Methods used for Simulation by Simscape power systems:

Three methods are used to simulate the models by Simscape power systems:

- Continuous
- Discrete
- Phasor

Highly accurate simulations for power system models can be done in Continuous domain by varying the step size to capture the system dynamics. Precision of simulation can be
controlled by selecting the time step size with discrete methods. The differential equations are replaced by representing the network by a set of algebraic equations at a fixed frequency by doing transient stability analysis of systems with multiple machines in phasor simulation method. Out of the three methods that best method can be selected depending on the needs. This research work uses the continuous time approach simulation method.

The Simscape Power Systems has an algorithm called ideal switching algorithm which can be used for quick and accurate simulation for systems having power electronic devices used as switches which are assumed to work ideally. The algorithm avoids use of snubbers which are numerically stiff high-impedance devices for modeling the power electronic switches. The method has great flexibility in selecting a solver which results in shorter simulation time.

Fig. 5.12 shows how to use the ideal switching algorithm which speeds up simulation time by avoiding snubbers. Left side of figure shows the selected type of simulation method i.e. continuous. Then tick the unwanted elements in simulating i.e. use ideal devices, disable snubbers, disable on resistance in switch device etc. Right side shows the application of

![Fig. 5.12 Ideal Switching Algorithm](image)
algorithm to the component selected in this example i.e. GTO and its speedy simulation graph with larger steps for simulation.

SimScape power system supports some more tools for analysis of loads and power quality which are explained below:

**Load Flow Analysis**
The tool is used for initializing model and finding out the steady-state response is the load flow tool by Simscape power systems. Depending on the steady state condition the tool finds out the initial current, internal flux, and rotor positions for synchronous and asynchronous machines. The required values are entered automatically into the model and are put down in report.

**Analysis of Power Quality**
The power quality of design can be analyzed along with overall harmonic distortion evaluation and it could be compared with set limits, distortion filtering parameters could be found out by this Simscape power systems tool. *MATLAB* functions and graphical tools enable you to analyze you’re the system can be analyzed under various conditions with summary reports and graphical plots.

**Simscape Power Systems - Power Gui block for Specialized Technology models:**
The powergui block has number of circuit solving methods, the user can choose depending on his requirement.

- Continuous has a variable step size method adopted from Simulink for analysis.
- Ideal switching algorithm where ideal conditions are assumed for switches for speedy results.
- The Electrical system can be discretized by giving a fixed step size.
- Phasor method for analysis

The powergui is also used for advanced parameter design and steady-state result analysis. The powergui block is required to simulate any Simulink model which contains Simscape Power Systems tools for Specialized Technology. The state-space equations of the model are stored in an equivalent Simulink circuit.

If one powergui block is used in a model, then it should be placed in the top-level of the diagram for optimized performance. The blocks must use the name powergui. During
updating of model this block is disabled, the link of library should not be restored for proper execution of model. Multiple blocks for powergui can be used for two or more impendent circuits which can be solved by simulating with separate solvers. In one circuit the upper block can be solved by continuous mode and lower block by discrete mode and simulations can be compared later.

In this research the entire reconfigurable IH system is simulated by Simulink and some part of power components are simulated in Simscape power systems, a small MATLAB code is written for frequency measurement block for the inverter. The Simulated model uses continuous domain and power Gui block is used which requires following parameters

**PowerGui Configuration for Reconfigurable IH heating circuit simulation.**
- Simulation Type: Continuous
- Ideal Switching Device: Enable
- Disable snubbers in switching devices: Enable
- Disable ON resistance in switching devices: Disabled
- Disable Forward voltage in switching devices: Enabled

**MatLab / Simulink Model of Reconfigurable Induction heating System:**
Fig. 5.13 below represents Simulink Model of Reconfigurable Induction heating System, the main blocks in the model comprise of a 2 leg IGBT inverter which requires DC voltage of the order of 2000Volts at its input, this block converters DC to AC. Output of Voltage fed inverter block is AC voltage of 500 V, sinusoidal waveform is expected at output of inverter. The IGBT’s are triggered by the PWM pulses by employing zero voltage switching (ZVS) scheme. Inverter is operated at a variable frequency between ~80 KHz to 100 KHz.

The PWM control pattern for maintaining the resonance is obtained from the power control block. Output of inverter is fed to primary of a linear-transformer block (Simulink / Simscape PowerSystem block is used) which has 1414 Volts RMS at primary winding and 353 Volts RMS at secondary winding, idealized parameters are used. Idealization is taken to simplify the modeling and to remove the nonlinear magnetization effect on the control circuit.

The impedance matching Transformer is used for two purposes, for impedance matching purpose and for adjusting the current level. It can also be used as an inductor or to connect the load with different voltage levels. Here it is used for impedance matching purpose and for
adjusting the current level. It also acts as a step down transformer to convert RMS voltage of 1414V at primary to 353V at secondary.

**Fig. 5.13 MATLAB / Simulink Model of Reconfigurable Induction heating System.**

Control part of this model has three type of control procedures i.e. Stability Control, Power Control and Frequency Control. The frequency control part controls the resonance frequency of the circuit which thereby results in change of R and L values in the load model. Inverter controller’s primary functions are 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. 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 $L$. 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. PI controller is tuned for operating frequency of 80 kHz to 100 kHz, with reference power input of 80KW to 100KW.

5.6.1 Power Circuit Design

Fig. 5.14 is the power circuit, it comprises of a DC source, and a voltage fed IGBT Inverter, Impedance Matching Transformer and Voltage step down Transformer, Series Load Resonant converter circuit with variable $R$ and variable $L$.

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 further rectified and filtered.
- The primary requirement of DC source is that it should have least possible ripple in DC link.
- It should provide the necessary power to the DC-link to maintain the DC link voltage.

In the Simulink model designed the parameters of DC source are chosen as per table 5.3 below: Description: Simulink Model Parameter: DC Source Voltage

<table>
<thead>
<tr>
<th>Table 5.3 DC Source Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Measurement</td>
</tr>
</tbody>
</table>

**Inverter**

Here an IGBT based 2 arm (i.e. 4-IGBT) converter is designed for developing the resonance converter. The PWM control pattern for maintaining the resonance is obtained from the power control block.

In the Simulink model designed the parameters of IGBT 2 Leg - Inverter are chosen as per Table 5.4 below:

<table>
<thead>
<tr>
<th>Table 5.4: Inverter parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name:</td>
</tr>
<tr>
<td>Switch Type/No.</td>
</tr>
<tr>
<td>Ron</td>
</tr>
<tr>
<td>Measurement</td>
</tr>
</tbody>
</table>
Table 5.4 presents common parameters of inverter block which are set as per Simscape power systems library, detailed explanation of all parameters is given below:

- **Ron** - Internal Resistance
  Ron is the internal resistance of IGBT and is given in ohms (Ω)
- **Rs** – Snubber Resistance
  Snubber resistance Rs is given in ohms (Ω). The parameter is disabled for speedy simulation results and eliminated from the model.
- **Cs** – Snubber capacitance
  Snubber capacitance Cs is in farads (F). Parameter is set to zero to eliminate the snubber Ron is in ohms (Ω). This parameter cannot be set to zero when the Inductance Lon parameter is set to 0. Lon is internal inductance given in henry (H). Normally Lon is set to zero.
- **Vf** - Forward Voltage
  Vf is the forward voltage of the IGBT device, in volts (V).
- **Tf** – current fall time
  Tf is the current fall time given in seconds. Tf parameter is not modeled when the ideal switching devices parameter is enabled and the Powergui block is selected, Tf parameter is not modeled.
- **Tt** - Current tail time
  Tt is the current tail time given in seconds. Tt is not modeled when the Enable use of ideal switching devices parameter of the Powergui block is selected.

- **Ic** – Initial current
  Initial current Ic flowing in the IGBT is usually set to 0. If Ic parameter is more than 0 then the steady-state analysis considers that the IGBT is closed. Power electronic converters all states initialization is a complex task, hence this option is only useful for simple circuits.
  - In this implementation series load resonance has been used.
  - Inverter is operated at variable frequency between ~80 KHz to 100 KHz.
  - Impedance Matching Transformer: It is primarily used here for two purposes in this circuit: i) Impedance Matching and ii) Voltage step-down
A transformer can also be used as an inductor or to connect the load with different voltage levels. Here it is used for impedance matching purpose and for adjusting the current level.

**Linear Transformer**

A linear-transformer block of Simulink/Simscape PowerSystem has been used whose parameters are as follow:

1414 Volts RMS at primary winding / 353 Volts RMS secondary winding, 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.

**Table 5.5 Linear transformer Block**

<table>
<thead>
<tr>
<th>Name</th>
<th>Linear Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power and Frequency</td>
<td>[100e3 100e3]</td>
</tr>
<tr>
<td>[Pn: power (VA) fn: frequency (Hz)]:</td>
<td></td>
</tr>
<tr>
<td>Winding 1 parameter [V1(Vrms), R1(pu), L1(pu)]:</td>
<td>[1414.21 0 0]</td>
</tr>
<tr>
<td>Winding 2 parameter [V2(Vrms), R2(pu), L2(pu)]:</td>
<td>[353.55 0 0]</td>
</tr>
<tr>
<td>Magnetization</td>
<td>None</td>
</tr>
</tbody>
</table>

**Modelling parameters for an Ideal Transformer in Simulink:**

- The winding resistances and inductances are set to zero for implementing ideal transformer.
- The Rm- magnetization resistance and Lm - Inductance are set to inf.
- The units used to enter the parameters for Linear Transformer block should be set properly by selecting pu for per unit and selecting SI in order to use SI units.
- Unit parameters can be changed from SI to PU or vice versa, this will convert the displayed parameters automatically in the block mask.
- The pu conversion is dependent on the frequency fn in Hz, transformer power Pn in VA and the winding voltage Vn in Vrms.

**Nominal power**
The nominal power rating Pn is given in volt-amperes (VA) and frequency fn, in hertz (Hz) for the transformer. If the Units parameter is set to SI then the nominal parameters have no impact on the transformer model.

**Parameters for Winding 1**
The Primary winding 1 has V1 Rms voltage, resistance R1 value in per unit (pu) or ohms, and leakage inductance L1 in per unit (pu) or henries. The pu values are based on the nominal power Pn and on V1Rms. For ideal winding the winding resistances and inductances are set to 0.

**Parameters for Winding 2**
The secondary winding 2 has V2 Rms voltage, resistance R2 value in per unit (pu) or ohms, and leakage inductance L2 in per unit (pu) or henries. The pu values are based on the nominal power Pn and on V1Rms. For ideal winding the winding resistances and inductances are set to 0.

**Load Circuit: Variable R**

![Model for Variable R](image)

**Fig. 5.15: Model for 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*R) relation. Variable R is used for modeling the change in depth of skin effect due to frequency variation.
Load Circuit: 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. \( L \propto \frac{1}{f} \), Hence L reduces, with increase in frequency.

5.6.2 Control Circuit Design

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

- Inverter Control
Inverter Control

Fig 5.17 shows the blocks inside the inverter control. Fig. 5.18 represents Simulink model for 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. 5.17: Inverter Control Block](image)

- 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 $\frac{1}{1+Ts}$; 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

![Fig. 5.18 Inverter control Simulink Model](image)

The Simulink model for inverter control shows input taken from transformer secondary winding $I_w2$, a zero cross detector for showing phase difference of the signal and the frequency computed by MATLAB code. PWM pulses are obtained after phase detection and given to inverter block as trigger pulses. First order LPF removes noise to get a nominal frequency signal.

**Frequency Measurement Code used in inverter control block:**

```matlab
function fout = fcn(u,t)
persistent x t0 u0 f
if (isempty(x))
```

\[ x = 1; \]
\[ t0 = 0; \]
\[ u0 = 0; \]
\[ f=50e3; \]
end
if ((u-u0)>0)
\[ f=1/(t-t0); \]
\[ t0=t; \]
end
fout=f;
u0=u;
end

**Power Control:**

![Power Control Block Diagram](image)

**Fig. 5.19: Power Control Block**

- Fig. 5.19 shows the power control block and 5.20 represents Simulink model of the same. 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. The output of PI controller is not directly processed to give R and L but the speed of actual servo
mechanism is very slow and will take more time for the output power to change depending on the load values, hence some block for modeling this delay has to be part of the model.

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

Details of PI controller is given in the following table 5.6

<table>
<thead>
<tr>
<th>Name</th>
<th>PID controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>PI</td>
</tr>
<tr>
<td>Time Domain</td>
<td>Continuous</td>
</tr>
<tr>
<td>Saturation Limit</td>
<td>25e-6 to 40e-6</td>
</tr>
</tbody>
</table>

The PID controller block parameters are shown above. The basics of design say that the controller must be simple; if a particular term or proportionality constant is not required it should be eliminated. In this case the derivative term is not required and hence it is eliminated. The Simscape tools continuous time domain tool is selected for modeling by defining a saturation limit.

<table>
<thead>
<tr>
<th>Name</th>
<th>Lookup Table (n-D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Table dimensions</td>
<td>1</td>
</tr>
</tbody>
</table>
1-D Lookup table implements an equation of line, the details are given below in table 5.7 above. The delayed response generated by rate limiter is not given directly as load block R but through this 1D: Look up table.

### Table Data

<table>
<thead>
<tr>
<th>Table Data</th>
<th>[1.96,2.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakpoint 1</td>
<td>[24.6e-6,40e-6]</td>
</tr>
</tbody>
</table>

- 5.20: Power control Simulink Model

The RMS block in figure 5.20 computes the true root mean square (RMS) value of the input reference signal and the feedback signal. The true Root mean square value of the power reference signal is calculated over a running average window of one cycle and compared with feedback signal output of this block is given to Simulink product block.

This 3x3 block for Cross Product computes vector product or cross product of two vectors fed at its input, by generating a third in a direction normal to the plane containing the two vectors with magnitude equal to the product of the lengths of the two vectors which are multiplied by
the sine of the angle between them. The output of this cross product block is fed to the PI controller.

**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 research a PI controller is used. PI controller is tuned for operating frequency of 80 KHz to 100 KHz, with reference power input of 80KW to 100KW. This can be physically regarded as dashpot system with a spring. There are two parameters $K_p$ - which is a proportional gain which handles the present value error and $K_i$ - which is an integral coefficient which handles the accumulation of past errors. This is the reason why a 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.

### 5.7 Results and Discussion

![Graph showing change in frequency with change in load power](image)

**Fig. 5.21:** Change in frequency with change in load power.

Fig. 5.21 is a graph of time in microseconds on X axis and Power in KW on y axis at resonance. Initial Power reference input $P_{ref} = 100$ KW from time 0sec upto10msec, after
10msec up to 20 msec - Pref = 80KW, this step change is shown in Fig.:5.21 above. With change in frequency load power changes from 100 KW to 80 KW.

**Fig.: 5.22 change in output power due to change in Pref**

Fig.: 5.22 is a graph of Pref – reference power indicated by blue line and converter power indicated by red line on y axis v/s time on x axis. The graph shows the change in output power due to change in Pref, it is seen that power reference (blue line) changes at 10msec from 100KW to 80 KW and actual converter output (red line) follows the reference value and changes accordingly.

**Fig. 5.23: primary voltage and capacitor current**
Fig. 5.23 is a graph of Primary voltage $V_{pri}$ (represented in red) which is a square waveform and capacitor current $V_c$ (represented in blue) sinusoidal waveform on y-axis v/s time in microseconds on x-axis which shows current 90 degrees lagging w.r.t voltage.

![Graph of Primary voltage and capacitor current](image)

**Fig. 5.24: change in primary current with the change in load**

Fig. 5.24 is a graph of primary voltage $V_{pri}$ (represented in red) square waveform and primary current $I_{pri}$ (represented in pink) sinusoidal on y-axis v/s time on x-axis, when load value is changed, output power changes, hence current changes which can be clearly seen in fig. 5.22 in terms of reduced magnitude of Primary current. Upto 10 msec, the power is 100 KW later the power is reduced to represent reconfigurable working of the model to 80 KW, with reduction in power the primary current $I_{pri}$ also reduces.

Here from above figure-5.23 it can be seen that, 1st waveform is of primary voltage versus capacitor current and it is 90 degrees lagging phase shift. This is the primary stability condition for a series resonant load circuit.

2nd waveform fig. 5.24 show the change in primary current with the change in load, at 10 msec the load reduces from 100 KW to 80 KW and hence current also reduces accordingly. Two load conditions are analyzed to show how system responds to change in load. From waveform it is clear that with change in load value the primary current changes. Since the circuit is not a hardware implementation but has software modeling, by minor change in circuit parameters the change in current can be seen in order to confirm that the induction heating system is reconfigurable. The analysis can be done for all load values in the 20 to 100 KW range and output observed.
Fig. 5.25: stability plot - phase difference between primary voltage and capacitor voltage

Figure-5.25: is a stability plot, it shows two major things:
1) The phase difference between primary and capacitor voltage.
2) The pure sinusoidal profile – without any distortion
Fig. 5.26: (a) shows change in secondary current w.r.t change in load.

(b) Shows secondary voltage

(c) Shows load voltage

In figure 5.26 waveform (a) shows constant secondary current for a load value of 100KW, at time t= 10msec onwards the load value changes from 100KW to 80 KW at this time the output current decreases, hence it can be concluded that the output current changes with change in load value. Number of load conditions can be analyzed easily since it is not a fixed-hardware implementation but a software modeling / coding. With minor changes in model / code the same circuit can be used at multiple loads making the system reconfigurable.
Fig. 5.26 (b) represents voltage taken at secondary side of the impedance matching transformer, which is a square waveform with constant voltage of 500V.

Fig. 5.26 (c) represents load voltage which is later fed via voltage transducer to the closed loop feedback PI controller loop, it is in the form of a sine waveform with constant voltage above 500V.