Electrical Circuit Modelling of Reversed Field Pinch (RFP) Plasma Discharge

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Master Thesis

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Abstract

Fusion power can be harnessed on earth if a perfect electrical circuit can be modelled to confine plasmas for long time. Toroidal and poloidal magnetic field enables plasma to be confined with the pressure exerted by magnetic field. A helical shape of electromagnetic field is the result of these two fields and plasma follows it. In this thesis a complete electrical circuit was modelled by Simscape (a Simulink tool) for both ohmic heating circuit and toroidal field circuit. The main attempt of the simulation was to generate exactly same experimental waveform to find out the circuit parameter. To do so all the circuit elements were chosen from Simscape block library and EXTRAP T2R (KTH experiment fusion reactor) data was used. It was ensured that capacitor voltage and the capacitance does not change during simulation because they are well known parameters during experiment. Mutual inductance is the crucial parameter to be extracted among all others. Parameters which were continuously changed during simulation are the resistance and inductances in the circuit to converge the experimental waveforms. First of all, mutual inductance was calculated using existing block coupling coefficient, primary coil inductance and secondary coil inductance. Then, simulation was done to produce the same waveform replacing block with customized block to realize the mathematics of mutual inductance which is dependent on circuit and reactor parameters. By using customised block, coupling coefficient cannot be obtained directly. In such case creation of same waveform like Simscape block confirms the same coupling coefficient for both simulations as all other parameter remained same. Experimental waveform was possible to create by simulation and a mutual inductance of 0.145 [μH] was calculated from simulation which corresponds to a coupling coefficient of 0.034 between poloidal and toroidal field circuit.

Keywords: Toroidal field circuit, poloidal field circuit, ohmic heating of plasma, Simscape, mutual inductance, plasma discharge, reversed field pinch.
Acknowledgement

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Finally, I would like to dedicate this thesis to my parents, without their immense love and financial support all my educational journey would have been impossible.

Md. Shahriar Jahan

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1 Introduction

Finding a new sustainable source of energy is unavoidable in near future due to depletion of fossil fuel and fissile element for controlled nuclear fission. Scientific research is being conducted all over the world to meet such requirement and it is well understood that an immense source of energy can be achieved if fusion, the energy source of the stars [1], on earth becomes reality. However, it is not a trivial task to accomplish. In sun plasma naturally occur and an immense gravitational force and temperature allows lighter nuclei to fuse together whereas both of these phenomenon is absent on earth. As a consequence, an environment must be created where it will be possible to experience fusion and extract electric power from it. A long term research concludes that magnetic confinement of plasma would be feasible to harness fusion energy.

1.1 Fusion: A potential energy source

1.1.1 Why fusion

Extremely radioactive waste products are produced in fission reactors which has to be stored tens of thousands years [2]. The only waste product that is produced in fusion cycle is helium gas which is neither toxic nor radioactive. Tritium, the element is going to be used as fuel is radioactive and its half-life is 12.3 years and it will be totally burnt in the reactor. So, it is evident that it is not going to harm us into future. The major safety feature is that radioactive fuels are not needed to be handled for long journey within countries. No carbon emission from fusion reactor which confirms total environment friendly technology for mankind. One of the biggest question posed for the fusion also is, having bad experience with fission, can fusion reactor explode? The answer is no because the fuel deuterium and tritium that are very small in amount, typically 1 gram, must be supplied and replaced in the reactor continuously, if replacement is not done reaction will be stopped. Fuel source is the key factor for extensive fusion research. The raw material lithium which breeds tritium and water from where deuterium can be extracted and among these two former one can energise us at least tens of thousands of years and the latter one is truly endless in amount. No country can monopolize fuel market share because they are almost evenly distributed around the globe.

1.1.2 Fusion energy content

The energy of tens of tons of coal, oil, or gas can be achieved from only a few grams of fusion fuel [3]. A calculation showed that it is possible to extract equivalent energy of 500 litres of petrol from the deuterium available in one litre of ordinary water [4].
1.2 Vital factors for fusion research

1.2.1 Lawson criteria
Energy confinement time \((\tau_E)\) has been introduced to realize a steady state plasma which is measured as the ratio of plasma energy content \((U)\) and the required input energy \((W)\) to maintain such steady state [5].

\[
\tau_E = \frac{U}{W}
\]

Equation 1.1

A plasma density of, \(n\), multiplied by \(\tau_E\), determines the requirement of fusion to occur. This multiplied parameter is known as Lawson parameter \((n\tau_E)\). Lawson criteria for DT are \(n\tau_E = 1.7 \times 10^{20} \text{ m}^{-3} \text{ s} [3]\).

1.2.2 Confinement \(Q\)
A controlled fusion reactor can sustain reaction on its own if produced fusion power is satisfactorily larger than the power needed to heat the plasma because 80% of produced energy is taken by escaping neutron. This state of the reactor is termed as ignition as no external power is needed to sustain the reaction.

\[
Q = \frac{\text{Fusion power produced}}{\text{Heating power supplied}}
\]

Equation 1.2

1.2.3 Safety factor
Magnetic line twist is measured by safety parameter \(q\). It is a number of the magnetic field line journey in the toroidal direction until it finds its starting point in the poloidal plane. A tightly wound helix is observed if \(q\) is small. Study result concludes that more stability can be obtained with high \(q\).

\[
q(r) = \frac{rB_T(r)}{R_0B_p(r)}
\]

Equation 1.3

1.2.4 Plasma beta
The magnetic efficiency of the confinement is measured by the parameter beta.

\[
\beta = \frac{\text{Plasma thermal energy}}{\text{Magnetic field energy}}
\]

Equation 1.4

Average plasma beta can be calculated with the following formula,

\[
\langle \beta \rangle = \frac{\langle p \rangle}{\langle B_p^2/2\mu_0 \rangle}
\]

Equation 1.5

Here, Numerator is average plasma pressure and denominator is magnetic pressure.
1.3 Physics of fusion energy

If we measure the mass of each proton and neutron of any nuclide individually it turns out that the sum of the mass of individual measurement is more than the mass of atomic nuclide itself as a whole. This mass defect is basically converted into energy according to Einstein’s law which is the core physics of extracting fusion energy. Therefore, it is evident that if we can fuse two atomic nuclei together, a fractional mass will be converted into energy [6]. Equation 1.6 and Equation 1.7 depicts all the energy conversion process.

\[ \Delta m = [Z_m m_p + (A-Z)m_n] - A m_z \]  

Equation 1.6

\[ E = \Delta mc^2 \]  

Equation 1.7

Where, \( A = \) Nucleon number, \( m_c = \) mass of the nucleon. \( Z = \) Proton number, \( \Delta m = \) Mass defect and \( c = \) velocity of light.

To fuse two positively charged nuclei, repulsive force between them, which is known as long range Coulomb force, has to be overcome so that short range attractive nuclear force prevails which is shown in Figure 1.1. Strong nuclear force activates at \( 5 \times 10^{-15} \) [m] for DT\(^{1}\) reaction which can be observed in Figure 1.2. To reach at this range a potential energy of 280 keV has to be overcome which corresponds to 3000 million°C. Thanks to quantum tunnelling, which can be observed from Figure 1.1, that allows the fusion reaction to take place below 150 million°C corresponding to a potential energy of 15 keV [3] [7].

---

\(^{1}\) Deuterium-Tritium fusion
Interesting reactions are listed according to primary fuel, their reaction type, total released energy and required energy to make this reaction possible is tabulated in Table 1.1 [6] [8]

<table>
<thead>
<tr>
<th>Reaction type</th>
<th>Total Energy release [MeV]</th>
<th>Threshold energy required [K]</th>
<th>[keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{D} + \text{T} \rightarrow \text{He}^4 (3.5 \text{ MeV}) + n (14.1 \text{ MeV})$</td>
<td>17.6</td>
<td>$4.5 \times 10^7$</td>
<td>4</td>
</tr>
<tr>
<td>$\text{D} + \text{D} \rightarrow \text{T} (1.01 \text{ MeV}) + p (3.02 \text{ MeV})$</td>
<td>4</td>
<td>$4.0 \times 10^{18}$</td>
<td>35</td>
</tr>
<tr>
<td>$\text{D} + \text{He}^3 \rightarrow \text{He}^4 (3.6 \text{ MeV}) + p (14.7 \text{ MeV})$</td>
<td>18.2</td>
<td>$3.5 \times 10^8$</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 1.1 Fusion reaction and corresponding energy release

Among these reactions the highest cross section\(^2\) for fusion at the lowest energy can be achieved for DT reaction which can be observed in Figure 1.3.

\(^2\) Cross section: The size of the potential energy hole.
Reaction rate can be maximized by controlling the temperature which peaks at certain temperature and then falls slowly. The reaction rate is higher for DT reaction with lower temperature (about 70 keV or 800 million K) which makes it the main choice of fusion fuel which can be observed in Figure 1.4. Obviously, the higher the cross sections the larger possibility of being fused in lower temperature.

![Figure 1.4 Reaction rate of different fusion reaction at different temperature](http://en.wikipedia.org/wiki/File:Fusion_rxnrate.svg)

1.4 Fusion to electricity production

In a fusion power plant fuel is injected in the core of the reactor which is burnt at a very high temperature. For example in case of DT fuelled fusion reactor, which can be seen from Figure 1.5, the fuel deuterium is injected from outside whereas tritium is created from lithium blanket on absorption of neutron that surrounds the plasma core.

![Figure 1.5 Schematic of a proposed fusion power plant](http://www.ipp.cas.cz/)
The created tritium is extracted from the blanket and is injected into the core following a cycle. Neutron, which is emitted as a result of fusion, takes 80\% of the energy released during fusion and is deposited in the surrounding lithium blanket. Here the concept of a conventional steam-generating plant is used to convert nuclear energy to electrical energy. He is taken away from the core as waste product.

### 1.5 Magnetic confinement physics

So far discussion has been done on the fuel of fusion, temperature requirement, fusion physics and also a plant demonstration. The biggest problem lies in the temperature because no element can sustain this enormous heat. As a consequence, reaction must be done in vacuum where plasmas will be confined. A lot of proposals were made and finally magnetic confinement was found to be in good agreement to reach breakeven even though there are other constraints, for example plasma instability, a reason why fusion reactors have stayed on paper until now. To experience an infinitely long magnetic field a torus shaped structure offers best arrangement. In this arrangement a copper coil is wounded around the torus to produce toroidal\(^3\) magnetic field and the poloidal\(^4\) magnetic field is created by the current flows through the plasma which is induced by a transformer [9]. Two magnetic fields are introduced to create a helical magnetic field around the torus. Plasmas follow the helical magnetic field as they are charged particles. Entire arrangement can be observed in Figure 1.6.

![Magnetic confinement](http://www.ipp.cas.cz/)

3 Toroidal: the direction around the torus  
4 Poloidal: the direction transverse to the toroidal direction.
2 Electrical modelling Basic

2.1 Transformer theory

A transformer is a device which comprise of two physically separated circuits where electric power from one circuit is transformed into another circuit through electromagnetic induction [10] [11]. It is used to raise or lower the level of voltage. If voltage is reduced with induction law, current will be raised in second circuit and vice versa.

![Transformer diagram]

Figure 2.1 Transformer

2.2 Ohmic heating

If a constant electric field is applied parallel to the magnetic field where plasmas are confined, electric energy will be converted into heat due to the resistivity of plasma [12] [13]. This process is known as ohmic heating. A finite plasma current density can be obtained in a defined magnetic field due to hydrodynamic instability proposed by Kruskal [14].

2.3 Mutual Inductance

Circuits which are electrically separated but are magnetically linked or share same magnetic flux created by any one of them will experience a rise of current in another circuit due to rise of electromotive force by Faradays law. This process is termed as mutual inductance.

If inductance in one circuit is L1 and the inductance in another circuit is L2 and their coupling coefficient is K; then mutual Inductance, M, can be calculated with following relation,

\[ M = K\sqrt{L1 \times L2} \]  

Equation 2.1
3 Theory of the modelled system

3.1 Basic principal of the model

The confinement of the plasma has entirely been modelled electrically as two ports [15] where one port represents the poloidal field and the other represents toroidal field as shown in Figure 3.1. In one port voltage $V_p$ and in another port $V_t$ has been introduced by three stage capacitor banks. Here, $I_p$ and $I_t$ stands for plasma current and the current in toroidal field windings. The circular cross section of RFP plasma is termed as minor radius $a$ and the major radius $R$ is taken from the axis of the torus which is large compare to $a$.

![Figure 3.1 Two port presentation of RFP plasma](image)

The toroidal-field current and voltages can be related to major radius $R$, minor radius $a$, toroidal field at the wall $B_{tw}$ and average toroidal field in the following way,

$$I_t = \frac{2\pi RB_{tw}}{\mu_0}$$  \hspace{1cm} \text{Equation 3.1}

$$V_t = \pi a^2 \frac{d\langle B_t \rangle}{dt}$$  \hspace{1cm} \text{Equation 3.2}

Where the average toroidal field can be found from the following formula,

$$\langle B_t \rangle = \frac{2}{a^2} \int_0^a r B_t dr$$  \hspace{1cm} \text{Equation 3.3}

Field reversal parameter $F$ and pinch parameter $\theta$ can be calculated from the following formulas,

$$F = \frac{B_{tw}}{\langle B_t \rangle} = \frac{\mu_0 I_t}{2\pi R \langle B_t \rangle}$$  \hspace{1cm} \text{Equation 3.4}

$$\theta = \frac{B_{pw}}{\langle B_t \rangle} = \frac{\mu_0 I_p}{2\pi a \langle B_t \rangle}$$  \hspace{1cm} \text{Equation 3.5}

Where, $B_{pw}$ is the toroidal field at the wall.
3.2 Coil model and the parameters

The modelling of plasma discharge depends on the coupling between the poloidal and toroidal field circuits [16]. A mutual inductance is developed between the poloidal and toroidal circuits when helical plasma current is activated. In this thesis it has been assumed that the flow of plasma current creates a constant mutual inductance which in reality is not true and plasma resistance has also been assumed constant.

3.2.1 TFC: Creation of toroidal field

The current circulates through the toroidal field coils (Figure 1.6) which is responsible for the toroidal magnetic field (Figure 1.6) that encircled the toroid [17] [18]. The toroidal field circuit (Figure 3.2) runs on two small, high voltage condenser banks and one large, low voltage condenser bank. All the data of condensers and the time of activation are tabulated in Extrap T2R chapter.

![Circuit diagram of OHC and TFC interaction](image)

Figure 3.2 Circuit diagram of OHC and TFC interaction

3.2.2 OHC: Creation of plasma current

A current is induced in the plasma by the transformer action where plasma acts as secondary coil (Figure 1.6). Ohmic heating of the plasma is responsible for the creation of plasma current [19]. The primary circuit of the transformer (Figure 3.2) runs on two small, high voltage condenser banks and one large, low voltage condenser bank. All the data of condensers and the time of activation are tabulated in Extrap T2R chapter. This current creates a poloidal magnetic field.

3.3 Mutual Inductance

A mutual inductance is developed between toroidal and poloidal currents due to the helicity of plasma current.
A constant mutual inductance emerges with the advent of plasma current. This mutual inductance can be obtained by solving the following coupled linear equations for the parameters of Figure 3.2 where $M_{pt}$ is the created mutual inductance between toroidal and poloidal circuits.

\[ V_t = R_t I_t + L_t \frac{dI_t}{dt} + \frac{d(M_{pt} I_p)}{dt} \quad \text{Equation 3.6} \]

\[ V_p = R_p I_p + L_p \frac{dI_p}{dt} + \frac{d(M_{pt} I_t)}{dt} \quad \text{Equation 3.7} \]

\[ I_t = -C_t \frac{dV_t}{dt} \quad \text{Equation 3.8} \]

\[ I_p = -C_p \frac{dV_p}{dt} \quad \text{Equation 3.9} \]

In the equation $I_p$ and $I_t$ is poloidal and toroidal current respectively, $V_p$ and $V_t$ is toroidal and poloidal field voltage. The resistance and self inductances are $R_p$, $R_t$ and $L_p$, $L_t$. $C_t$ is the equivalent field condenser of toroidal field circuit and $C_p$ is equivalent condenser of poloidal field circuit. To get an intuition one can have a look at Figure 3.2.
4 Validation of the software

An attempt was made to produce similar waveform as paper [16] and a good agreement was achieved which is shown in Figure 4.1 and Figure 4.2. The following data were taken from the paper during simulation.

Circuit parameter:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Toroidal field circuit</th>
<th>Poloidal field circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td>120 [uF]</td>
<td>70.5 [mF]</td>
</tr>
<tr>
<td>Voltage</td>
<td>-5000 [V]</td>
<td>-250 [V]</td>
</tr>
<tr>
<td>Time</td>
<td>2.30 [ms]</td>
<td>2.75 [ms]</td>
</tr>
<tr>
<td>Inductor</td>
<td>77 [uH]</td>
<td>2 [uH]</td>
</tr>
<tr>
<td>Resistance</td>
<td>0.193 [Ω]</td>
<td>0.01 [Ω]</td>
</tr>
</tbody>
</table>

Table 4.1 Circuit parameter

![Comparison](image)

Figure 4.1 Toroidal field, Toroidal and Poloidal field at wall
Figure 4.2 Toroidal and poloidal voltage
5 Extrap T2R data

Primary circuit of the transformer runs on two small, high voltage condenser banks and one large, low voltage condenser bank and each capacitor bank is discharged in different time with timed switch. All the values can be found in Table 5.1.

5.1 Ohmic heating circuit parameter

<table>
<thead>
<tr>
<th>OH Cap Bank</th>
<th>Parameter</th>
<th>Discharge time</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH1</td>
<td>R 0.5 [Ω]</td>
<td>0.5 [Ω]</td>
</tr>
<tr>
<td></td>
<td>L 150 [μH]</td>
<td>150 [μH]</td>
</tr>
<tr>
<td></td>
<td>C 4 [mF]</td>
<td>4 [mF]</td>
</tr>
<tr>
<td></td>
<td>V 5500 [V]</td>
<td>5500 [V]</td>
</tr>
<tr>
<td>OH2</td>
<td>R 0.02 [Ω]</td>
<td>0.05 [Ω]</td>
</tr>
<tr>
<td></td>
<td>L 20 [μH]</td>
<td>5 [μH]</td>
</tr>
<tr>
<td></td>
<td>C 72 [mF]</td>
<td>72 [mF]</td>
</tr>
<tr>
<td></td>
<td>V 600 [V]</td>
<td>600 [V]</td>
</tr>
<tr>
<td>OH4</td>
<td>R 0.002 [Ω]</td>
<td>0.029 [Ω]</td>
</tr>
<tr>
<td></td>
<td>L 10 [μH]</td>
<td>10 [μH]</td>
</tr>
<tr>
<td></td>
<td>C 9024 [mF]</td>
<td>9024 [mF]</td>
</tr>
<tr>
<td></td>
<td>V 320 [V]</td>
<td>320 [V]</td>
</tr>
<tr>
<td>Primary coil inductance</td>
<td>200 [μH]</td>
<td>2 [μH]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary circuit (plasma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner resistance</td>
</tr>
<tr>
<td>Plasma resistance</td>
</tr>
</tbody>
</table>

| Toroidal inductance 2 [μH] |

Table 5.1 Ohmic heating circuit parameter
Toroidal field circuit runs on two small, high voltage condenser banks and one large, low voltage condenser bank and each capacitor bank is discharged in different time with timed switch. All the values can be found in Table 5.2.

### 5.2 Toroidal Field circuit parameter

<table>
<thead>
<tr>
<th>TFC(^6) Capacitor bank</th>
<th>Parameter</th>
<th>Provided</th>
<th>Extracted from simulation</th>
<th>Discharge time</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4</td>
<td>R</td>
<td>5 [mΩ]</td>
<td>1 [mΩ]</td>
<td>-2.6 [ms]</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>30 [μH]</td>
<td>30 [μH]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>64 [mF]</td>
<td>64 [mF]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>500 [V]</td>
<td>500 [V]</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>R</td>
<td>30 [mΩ]</td>
<td>28 [mΩ]</td>
<td>0.25 [ms]</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>4 [μH]</td>
<td>4 [μH]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3 [F]</td>
<td>3 [F]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>210 [V]</td>
<td>210 [V]</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>R</td>
<td>20 [mΩ]</td>
<td>13 [mΩ]</td>
<td>0.2 [ms]</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>8 [μH]</td>
<td>9 [μH]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>16 [mF]</td>
<td>16 [mF]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>800 [V]</td>
<td>800 [V]</td>
<td></td>
</tr>
<tr>
<td>Toroidal field circuit resistance</td>
<td>2 [mΩ]</td>
<td>8 [mΩ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toroidal Field Circuit Inductance</td>
<td>10 [μH]</td>
<td>10 [μH]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 Toroidal field circuit parameter

---

\(^6\) Toroidal Field Circuit
6 Experimental result

In this thesis, experimental data has been taken from shot#24337, shot#24338, and shot#24346. In all cases toroidal field circuit was completely active.

![Experimental TFC current](image)

Figure 6.1 Experimental TFC current for all shots

The first shot (shot#24337) is carried out in vacuum chamber to understand the behaviour of the vacuum chamber and also the impact of liner resistance.

If we look at experimental toroidal field current, Figure 6.1, we can see that the behaviour of the current is similar in all shots before 0.2 [ms]. When plasma is injected at 0.2 [ms] a mutual inductance was developed which enabled the induction of more current in toroidal field circuit. The current of both plasma shot is of comparable size, Figure 6.1, with a slight difference in magnitude due to the presence of all OHC capacitor banks in the last plasma shot, Figure 6.1. The presence of plasma evidently proves the development of mutual inductance and can clearly be observed in Figure 6.1.

---

7 shot without plasma or vacuum shot
8 Shot with first OH circuit bank OH1
9 Shot with complete OH circuit bank
OHC current waveforms can be observed in Figure 6.2. In case of all shots; presence of current was unobserved before 0 [ms] because OHC\textsuperscript{10} was not activated before 0 [ms]. In the vacuum shot no capacitor bank was discharged, as a result presence of current was unnoticed in OHC primary coil of the transformer for total time frame. Capacitor bank OH1 of primary circuit of the transformer was discharged at 0 [ms] in second discharged, as a result presence of current was unnoticed in OHC primary coil of the transformer for total

\footnote{Ohmic Heating Circuit}
shot and all the capacitor bank was discharged in third shot with the initiation of plasma at 0.2 [ms] and instantly a rise in current was observed, Figure 6.2, which has the highest magnitude of 7.3 [KA] in case of second shot and 7.8 [KA] in case of third shot. Current in second shot shows a declined trend after 1.5 [ms] whereas current in third shot showed a stabilized trend in current because in case of third shot current was stabilized by using all capacitor banks in OHC.

Toroidal current was created by induction of transformer action where OHC represents the primary coil and plasma represents the secondary coil of the transformer. Deactivated OH circuit did not enabled toroidal current to rise before 0 [ms], see Figure 6.3, which is same for OHC primary current as well. In the vacuum shot no capacitor bank was discharged as well as absence of secondary coil or plasma is the main reason for zero current for total time frame. Capacitor bank OH1 of primary circuit of the transformer was discharged at 0 [ms] in second shot and all the capacitor bank was discharged in third shot with the initiation of plasma at 0.2 [ms] and with a winding ratio of 10 in the transformer a 10 times larger current was induced in plasma in compare to OHC current. The declined and stabilized trend in toroidal current after 1.5 [ms] holds the same reason for OHC current.

![Experimental OHC voltage](image)

**Figure 6.4 Experimental OHC voltage**
If we analyse experimental OHC voltage, Figure 6.4, we can see that the behaviour of the current is similar in all shots before 0 [ms]. In the vacuum shot no capacitor bank was discharged, as a result no presence of voltage can be observed in OHC primary coil of the transformer for total time frame. Capacitor bank OH1 of primary circuit of the transformer was discharged at 0 [ms] in second shot and all the capacitor bank was discharged in third shot with the initiation of plasma at 0.2 [ms] and instantly a rise in voltage was observed, Figure 6.4, which has the highest magnitude of 4.3 [KV] in case of second shot and 4.2 [KV] in case of third shot. The difference in magnitude of voltage is due to the activation of the all OHC capacitor banks in third shot.
7 Simulated result

7.1 Method
The main attempt of the simulation was to generate exactly same experimental waveform to find out the circuit parameter. To do so all the circuit elements were chosen from Simscape block library and EXTRAP T2R data was used. It was ensured that capacitor voltage and the capacitance does not change during simulation because they are well known parameters in experiment. Mutual inductance is the crucial parameter to be extracted among all others. Parameters which were continuously changed during simulation are the resistance and inductances in the circuit to converge the experimental waveforms. First of all, mutual inductance was calculated using existed block coupling coefficient, primary coil inductance and secondary coil inductance. Then, simulation was done to produce the same waveform replacing block with customized block to realize the mathematics of mutual inductance which is dependent on circuit and reactor parameters. By using customised block, coupling coefficient cannot be obtained directly. In such case creation of same waveform confirms the same coupling coefficient for both simulations as all other parameter remained same.

7.2 Simulated result with simscape block

![Simulated TFC current](image)

Figure 7.1 Simulated TFC current for all shots
Using all the parameters (Table 5.1 and Table 5.2) in the circuit almost exact waveform was possible to generate during simulation for TFC current (Figure 7.1), OHC current (Figure 7.2), toroidal current (Figure 7.3), and OHC voltage (Figure 7.4). To create experimental waveform changes was done on many resistance and inductance data. To mimic the generated mutual inductance in simulation, inductance in primary coil and secondary coil had to change in the mutual inductance block from the value which produced the vacuum waveform.

![Simulated OHC Current](image1)

**Figure 7.2** Simulated OHC current for all shots

![Simulated Toroidal Current](image2)

**Figure 7.3** Simulated toroidal current for all shots
Customized block enabled to write own equations which is dependent on circuit and reactor parameters. The equations were used from [16] which were developed for Extrap T1u reactor and modified in the customised block for Extrap T2R reactor simulation. Using the customised block it was possible to generate experimental waveforms for TFC current (Figure 7.5), OHC current (Figure 7.6), toroidal current (Figure 7.7) and OHC voltage (Figure 7.8) similar to existing mutual inductance block (figure).
Figure 7.6 Simulated OHC current with customised block

Figure 7.7 Simulated toroidal current with customised block
7.4 Simulation result comparison

Comparison of simulation result from existing mutual inductance block and customised mutual inductance block was necessary to confirm that the used equations (see sub chapter: Block equations) in the block. Obtaining same waveforms for TFC current (Figure 7.9), OHC current (Figure 7.10), toroidal current (Figure 7.11), OHC circuit voltage (Figure 7.12) confirms that the modified equations are well suited for Extrap T2R reactor.
Figure 7.9 TFC current Simscape block vs customised block

Figure 7.10 OHC current Simscape block vs customised block
Figure 7.11 Toroidal current simscape block vs customised block

Figure 7.12 OHC voltage simscape block vs customised block
7.5 Simulation and experimental waveform comparison

Comparison between experimental result and simulated result shows good agreement about the extracted power supply parameters. Similar waveform was possible to generate for TFC current (Figure 7.13), toroidal current (Figure 7.15), OHC current (Figure 7.14), OHC voltage (Figure 7.16). The little discrepancy in experimental and simulated waveforms occurred because plasma resistance was assumed
constant during simulation which in reality is not true. A time varying plasma resistance would allow us to align simulated waveform more precisely with experimental waveform.

Figure 7.15 toroidal current simulation vs experiment

Figure 7.16 OHC circuit voltage simulation vs experiment
7.6 Block equations

A customised block was created to realize the mathematics of mutual inductance which is dependent on circuit and reactor parameters. In reactor there is a flux loop to calculate the average toroidal field which is not part of this thesis. Only developed mutual inductance between poloidal field circuit, toroidal field circuit and flux loop was taken into consideration.

Voltages are related to self-inductance of both field $L_1$ and $L_2$, mutual inductance $M_{pt}$ and current $I_p$ and $I_t$ with following relationship.

\[
V_p = L_1 \frac{dl_p}{dt} + M \frac{dl_t}{dt} \quad \text{Equation 7.1}
\]
\[
V_t = L_2 \frac{dl_t}{dt} + M \frac{dl_p}{dt} \quad \text{Equation 7.2}
\]

The mutual inductance between the flux loop and the toroidal field circuit is denoted as $M_{lt}$. Correspondingly, $M_{pl}$, is the mutual inductance between the flux loop and the poloidal field circuit.

The inductance $M_{lt}$ and $M_{pl}$ is obtained from the following equations,

\[
M_{lt} = \frac{\mu_0 N_i a^2}{2R} \quad \text{Equation 7.3}
\]
\[
M_{pl} = 0.034M_{lt} \quad \text{Equation 7.4}
\]

And mutual Inductance between poloidal field circuit and toroidal field circuit is obtained from the following equation,
\[ M = M_{pt} = N_t M_{pl} \]  \hspace{1cm} \text{Equation 7.5}

Where, \( a \), denotes the radius of the coil.

In the block a constant mutual inductance was used. L1 and L2 were achieved by iterating the values in the block during simulation to produce experimental waveform as close as possible. The multiplication factor 0.034 in Equation 7.4 was also found iteratively to produce experimental waveform. The values of L1 (poloidal field inductance) and L2 (toroidal field inductance) mentioned here were found in good agreement for the production of experimental waveforms. In experimental reactor total number of toroidal field coil turns is 64 which are divided in 4 quadrant comprising 16 turns in each and all 4 are connected in parallel. In Simscape model 16 turns toroidal field coil was used to represent 4 parallel connected 16 turns coil, one for each quadrant of the torus. As a result 4 times current was achieved during simulation.

In the block the following values were used,
L1 = Poloidal field inductance = \( 3.3 \times 10^{-6} \) [H]
L2 = Toloidal field inductance = \( 5.6 \times 10^{-6} \) [H]
\( \mu_0 \) = Vacuum permeability = \( 1.2566 \times 10^{-6} \) [H/m]
R = Major radius = \( 1.24 \) [m]
a = Minor radius = \( 0.18 \) [m]
\( N_t \) = Number of turns in the toroidal coil =16

### 7.7 Mutual Inductance calculation

**Constant mutual inductance:**

By using mutual inductor block directly from library we obtain mutual inductance of 0.145 [\( \mu \text{H} \)] and 0.0156 [\( \mu \text{H} \)] for second and third shot respectively. The calculation has been shown below.

For calculation, toroidal and poloidal inductance was found directly from Simscape mutual inductor block L1 (poloidal inductance) and L2 (toroidal inductance).

**For second shot:**
Inductance in toroidal field: 3 [\( \mu \text{H} \)]
Inductance in poloidal field: 6 [\( \mu \text{H} \)]
Coupling coefficient: 0.034
Mutual inductance = \( 0.034 \sqrt{3} \times 6 = 0.145 \) [\( \mu \text{H} \)]

Using customised block:
Mutual inductance = \frac{1.256637 \times 10^{-6} \times 0.0345 \times 16^2 \times 0.18^2}{2 \times 1.24} = 0.146 \mu H$

For third shot:
Inductance in toroidal field: 3.8 [\mu H]
Inductance in poloidal field: 5.6 [\mu H]
Coupling coefficient: 0.034

Mutual inductance = 0.034 \sqrt{5.6 \times 3.8} = 0.156 [\mu H]

Using customised block:

Mutual inductance = \frac{1.256637 \times 10^{-6} \times 0.037 \times 16^2 \times 0.18^2}{2 \times 1.24} = 0.155 [\mu H]
8 Conclusion

- It was possible to generate waveforms with simulation which is in good agreement with Extrap T2R waveforms.
- It was possible to generate waveforms of Extrap t1u device as well (see validation of the software chapter) that approves that Simscape can be used to Simulate any fusion reactor.
- The entire capacitor banks were kept constant throughout the simulation as they are very well known parameters.
- Circuit parameters were successfully extracted from simulation.
- Equations underlying physical system was organised by Simscape library and solved automatically which enables a user to concentrate more on developing physical system.
- Simulating the reactor in Simscape allows a user to change parameters as many times as he wants which in reality cannot be possible for the complexity of the system as well as for not being cost efficient.
- Toroidal field circuit is powered by 4 parallel connected power supply which was modelled as a equivalent single power supply in Simscape.
- Simulation was carried out assuming that plasma resistance is constant that is in reality is not true which made a little discrepancy between experimental and simulated waveform.
- Good agreement between experimental and simulated waveform proclaims that calculated mutual inductance and obtained coupling coefficient is credible.
9 Future Work

- A time varying plasma resistance and time varying mutual inductor block can be developed using Simscape to produce exact experimental waveform which will provide more precise circuit parameters.
- The model can be used to optimise entire power system of the reactor.
- Toroidal field circuit can be modelled using 4 parallel power supply system to be closer to real reactor.
Bibliography


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Mutual Inductance</td>
</tr>
<tr>
<td>R</td>
<td>Major Radius</td>
</tr>
<tr>
<td>a</td>
<td>Minor Radius</td>
</tr>
<tr>
<td>I_P</td>
<td>Poloidal Current</td>
</tr>
<tr>
<td>I_t</td>
<td>Toroidal Current</td>
</tr>
<tr>
<td>I_{tw}</td>
<td>Toroidal Current at the wall</td>
</tr>
<tr>
<td>I_{pw}</td>
<td>Poloidal Current at the wall</td>
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<tr>
<td>F</td>
<td>Field reversal parameter</td>
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<tr>
<td>\theta</td>
<td>Pinch parameter</td>
</tr>
<tr>
<td>\langle{B_t}\rangle</td>
<td>Average toroidal magnetic field</td>
</tr>
<tr>
<td>N_t</td>
<td>Number of toroidal turns</td>
</tr>
<tr>
<td>c</td>
<td>Speed of light</td>
</tr>
<tr>
<td>D</td>
<td>Deuterium</td>
</tr>
<tr>
<td>T</td>
<td>Tritium</td>
</tr>
<tr>
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<td>Boltzmann’s constant</td>
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A Simscape

**Simulation software**
Simscape is a modelling tool developed by MathWorks and distributed as a toolbox which is supported by Simulink. Simscape is developed to simulate real physical system which is different from Simulink. Each Simulink block represents one type of mathematical operators and when they are connected together they represent exact mathematical model of the system. On the contrary, each Simscape block is designed on the basis of Physical Network approach of the components that interact with each other by exchanging energy through their ports. Once the connections of the blocks are done, they mimic the real physical system layout.

The connection ports are bidirectional. Energy flow direction and information flow need not to be specified during the connection of Simscape blocks. Each block has an underlying code where all the variables and directionality is written with through and across variables which is solved by existed library functions.

The number of connection ports for each element is determined by the number of energy flows it exchanges with other elements in the system.

**Variable type and domain**
Variables in Simscape are declared on the basis of their energy flow characteristics. Energy is transferred from one port to another with two variables, one through and one across and products of them are energy flow in watts. These are very basic variables. For example, current and voltage are basic variables for electrical system which falls in electrical domain.

**Through variable**
Series connection of a gauge with any element measures through variable. In electrical system, this is how current is measured.

**Across variable**
Parallel connection of a gauge with any element measures across variable. In electrical system, this is how voltage is measured.

**Physical domain**
Physical domain corresponds to real world interaction of the variables. Electrical is the domain where current and voltage are interacting to each other.
<table>
<thead>
<tr>
<th>Physical Domain</th>
<th>Across Variable</th>
<th>Through Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>Pressure</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetomotive force(mmf)</td>
<td>Flux</td>
</tr>
<tr>
<td>Mechanical Rotational</td>
<td>Angular velocity</td>
<td>Torque</td>
</tr>
<tr>
<td>Mechanical translational</td>
<td>Translational velocity</td>
<td>Force</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>Pressure and temperature</td>
<td>Mass flow rate and heat flow</td>
</tr>
<tr>
<td>Thermal</td>
<td>Temperature</td>
<td>Heat flow</td>
</tr>
</tbody>
</table>

Figure 1: Physical domains, Across and Through variable declared in Simscape

**Direction of variables**

Direction of any variable is based on their magnitude and sign [20]. Depending on the polarity of measurement gauge orientation a variable can turn out to be positive and negative. The same rule must be applied through entire network to ensure credibility of measurement data. If any element is designed such a way that it’s through variable will be transferred to port B from port A then through variable will be attributed as positive if it flows from A to B whereas across variable is calculated on node potential of A(PA) and on node potential of B(PB) as $AV = PA - PB$.

![Direction of variables](image)

Figure 2: Direction of variables

Having positive and negative node in the approach allows determining energy flow direction and as a consequence, energy consumption of the element refers to positive energy and negative if energy is delivered to the system.

**Connector ports and connection lines**

Basically two types of connection ports are used in Simscape.

- Physical Conserving ports
- Physical Signal ports

**Physical Conserving ports**

Conserving ports are designed to connect with physical connection lines which have no inherent directionality and characterize the interchange of energy flows on the basis of Physical Network approach applied on that port. Conserving port can only be connected to other conserving port of same type to carry
same physical variable, thus they are not suitable to be connected to any Simulink ports or to Physical signal port. Moreover, each physical conserving port characterizes a physical modelling domain.

Figure 3: Physical Conserving ports

**Physical Signal ports**

Physical signal ports carry signals between Simscape blocks. Associated unit can be carried with physical signals, contrary to Simulink signal which is unitless. Simscape software takes the responsibility of unit conversion if they are specified in the block.

Figure 4: Physical Signal ports

**Simscape Library**

Simscape block library comprised of Foundation library and Utilities library. Foundation library does functional operation and Utility library creates Physical Network model. Fundamental elements of different domain have already been created and ready to use. They can be modified and added together to create a physical system or subsystem.

Figure 5: Foundation library of electrical elements

**Simscape language**

Simscape language is textual language [21] which is based on MATLAB programming language. A completely new component can be written down as textual file with parameterization, physical connections, and equations represented as acausal implicit differential algebraic equations (DAEs). It allows a user to use existed physical domain and also to create users own physical domain. Having facilities of textual environment, it is possible to share the components as well after creation throughout the organization. Besides, It is possible to maintain confidentiality of the component text as well. The following example of a resistor can clarify how Simscape language works:
\[ V = I \times R \]

Equation 0.1 is the voltage-current (V-I) relationship of a linear resistor where \( R \) is the constant resistance in ohms. Simscape textual language is basically divided into five segments such as component name, nodes, parameters, function setup and equations.

The component name is declared in the first line. It is better to write a distinct name so that Matlab does not find a file of same name in its path. Thus, it is possible to avoid possible conflict of having same name. For example, if we want to create a resistor, it can be started by naming it first.

```matlab
component resistor

A description of the component and its working principle can be written as Matlab script comment after initializing the name and this part will appear in the customized box for a user to understand it well. However, this part can be avoided. In this part, all the description of relationship among parameters, variables can be described.

```matlab
% Resistor
% The voltage-current (V-I) relationship for a linear resistor is V=I*R,
% where R is the constant resistance in ohms.
```

Next segment of the code describes number of node that will be used in the block and their domain. In this illustration, the box will have two nodes with electrical domain. Here, there is no code regarding electrical domain because it is an existed domain of Simscape. It is possible to create a totally new domain on user’s choice by writing a text and keep it on Matlab path and how this can be done has been elaborated in [20].

```matlab
nodes
    p = foundation.electrical.electrical; % +:left
    n = foundation.electrical.electrical; % -:right
end
```

In the following section of the code, the main parameters of the system are declared with their unit. This parameter will be available to component box as variable and user will be allowed to change their value each time before the simulation as long as it does not exceed the error requirement.

```matlab
parameters
    R = { 1, 'Ohm' }; % Resistance
end
```

In the function setup section, through and across variable are declared and also an error message is created to prevent the user from providing unsuited input to mimic real physical system. For example, In our example, in reality electrical resistance cannot be negative.
function setup
    through( il, pl.i, n1.i );
    across( vl, pl.v, n1.v );
    if R < 0
        pm_error('simscape:GreaterThanOrEqualToZero','Resistance')
    end
end

The most crucial part of the text is equation section where relation between all the parameter and variables are written.

equations
    v == R*i;
end

Simscape data handling

Logging data from simscape to matlab workspace:
Simscape simulation data is not logged automatically in matlab workspace. To do it manually follow the following instruction.

1. From the top manu bar, select Simulation > Model Configuration Parameters.
2. In the Configuration Parameters dialog box, in the left pane, select Simscape.
3. In the pane Log simulation data option is set to none by default and from the dropdown list by selecting all data logging will be initiated.
4. After completion of simulation a workspace variable with name simlog is created and this can be changed in Model configuration parameter to get all the data set for different model.

If we would like to plot our expected data, we need to have an understanding of data tree of simscape and also how it logs the data in its path.
Once data are logged in workspace, it is easy to plot them using conventional matlab operation.

Depth level
Data can be extracted and plotted simultaneously by using command only. To do so, it is necessary to know the data tree in matlab path. To get the data tree of current model, for example: paper1(model), write the command in matlab command prompt.

er1.print
    e1
    + Capacitor
    | +i
    | +n
    | | +v
    | +p
Here, for convenience, only data tree associated with capacitor has been given. Each data tree have different depth level. In the data tree of capacitor the first level is Capacitor and rest each line corresponds to a single level. The same applies for other component in the model.

**Data Plotting**

If it was possible to find data tree and to understand depth level we can plot all the parameters to each depth level. Plot currents of all the blocks in the model:

```matlab
plot(paper1, 'units', 'A', 'depth', 2)
```

This command will plot all the currents until depth two, although there is data of current in other levels as well and they will not be plotted.

```matlab
plot(paper1, 'units', 'A', 'depth', 3)
```

Now plotting will be done to all current until depth 3.

```matlab
plot(paper1.mutual_inductor,'depth', 1)
```

Here we can see there is no units are mentioned. In this circumstance, all the parameters that have been declared in mutual inductor will be plotted in same window.

**Plot two series against each other**

The following command will plot series associated with two node objects against each other.

```matlab
plotxy(paper1.mutual_inductor.i1, paper1.mutual_inductor.v1, 'xunits', 'A', 'yunits', 'V')
```

Data can be plotted within a time range with the following command

**Examples**

Plot all currents (series that are commensurate with units of A) units, for the top-level model node (with the workspace variable name, paper1), within the time range between .0025 and .0035 seconds:

```matlab
h = simscape.logging.plot(paper1, 'units', {'A'}, 'time', [.0025 .0035], 'depth', 2);
```

**Compare data from two simulation runs**

The following command will allow us to compare data from two simulations.

```matlab
simscape.logging.plot([paper1.mutual_inductor.i1 paper.Current_Sensor2.I], 'names', {'Run1' 'Run2'});
```

**Simulation time and values extraction**

**Time**

The following command returns simulation time data for the mutual inductor,
t1 = paper1.mutual_inductor.i1.series.time

**Values**
The following command returns simulation current data for the mutual inductor,

t2 = paper1.mutual_inductor.i1.series.values

**Trouble Shooting**

**General troubles**
There are several reasons why simulation could be stopped before producing the result. In Simscape, wrong connection between the blocks, mismatch in polarity and using wrong units could be the main reason. Creating subsystem is a good approach to reduce the complexity of the system. There are other crucial error that is encountered if following are missing.

- Missing Solver Configuration Block: Each Simscape system requires one Solver Configuration Block to mathematically solve the underlying mathematics.
- Missing Reference Block: A reference block is necessary for conserving ports. For example, an entire electrical circuit requires at least one Electrical Reference Block.
- Basic Errors in Physical System Representation: Through variable has to be declared in series and across variable has to be declared in parallel. If they are not done logically, simulation will encounter error.
B Block code

component mutual_inductor_custom

% Mutual Inductor
% If winding 1 has voltage V1 across it and
% current I1 flowing into its + terminal, and winding 2 has voltage V2
% across it and current I2 flowing into its + terminal, then
% %
% V1 = L1*dI1/dt + M*dI2/dt
% %
% V2 = L2*dI2/dt + M*dI1/dt
% %
% where parameters L1 and L2 are the winding self-inductances, and
% % M is the mutual inductance. M is defined in terms of major radius, minor
% % radius and number of poloidal turns with the equation
% %
% % M_Lt = meu_0*N_t^2*a^2/(2*R); M_pL = 0.034*M_Lt
% %
% M = N_t*M_pL
% %So finally, M = 0.034*meu_o*(N_t^2/(2*R))

nodes
    p1 = foundation.electrical.electrical; % +:left
    n1 = foundation.electrical.electrical; % -:left
    p2 = foundation.electrical.electrical; % +:right
    n2 = foundation.electrical.electrical; % -:right
end

parameters
    L1 = { 5.6e-6, 'H' }; % Toroidal inductance
    L2 = { 3.8e-6, 'H' }; % Poloidal inductance
    meu_0 = { 1.256637*10^-6, 'H/m' }; % Vacuum permeability
    N_t = 16; % Number of toroidal coil turns
    R = { 1.24, 'm' }; % Major radius
    a = { 0.18, 'm' }; % Minor radius
    i10 = { 0, 'A' }; % Winding 1 initial current
    i20 = { 0, 'A' }; % Winding 2 initial current
end

variables
    i1 = { 0, 'A' };
    v1 = { 0, 'V' };
    i2 = { 0, 'A' };
    v2 = { 0, 'V' };
end

function setup
    through( i1, p1.i, n1.i );
    across( v1, p1.v, n1.v );
    through( i2, p2.i, n2.i );
    across( v2, p2.v, n2.v );
    if R <= 0
        pm_error('simscape:GreaterThanZero', 'Major radius R')
    end
end
if a <= 0
  pm_error('simscape:GreaterThanZero','Minor radius a')
end
if N_t <= 0
  pm_error('simscape:GreaterThanZero','Number of toroidal coil turns N_t')
end
i1 = i10; % Initialize current for winding 1
i2 = i20; % Initialize current for winding 2
end

equations
  let
    k = meu_0*0.034;
    z = N_t^2*a^2;
    q = 2*R;
    M = k*z/q
  in
    v1 == L1*i1.der + M*i2.der;
    v2 == L2*i2.der + M*i1.der;
  end
end
data extraction code to workspace with Simscapeblock:
format short g

%Current value in [KA] and [KV]
%==============================for shot 24337
%=================================
ohc_curr_sim_2437=paper24337.Ohmic_heating_primary.Current_Sensor.i1.series.values*10^-3;
ohc_volt_sim_24337=paper24337.Ohmic_heating_primary.Voltage_Sensor.v1.series.values*10^-3;
tfc_curr_sim_24337=paper24337.Toroidal_Field_Coil.Current_Sensor.i1.series.values*10^-3;
%Current and voltage time values [ms]
%=========================for shot 24338
%=================================
ohc_curr_sim_tm_24337=paper24337.Ohmic_heating_primary.Current_Sensor.i1.series.time*10^3;
ohc_volt_sim_tm_24337=paper24337.Ohmic_heating_primary.Voltage_Sensor.v1.series.time*10^3;
tfc_curr_sim_tm_24337=paper24337.Toroidal_Field_Coil.Current_Sensor.i1.series.time*10^3;
ohc_curr_sim_24338=paper24338.Ohmic_heating_primary.Current_Sensor.i1.series.values*10^-3;
ohc_volt_sim_24338=paper24338.Ohmic_heating_primary.Voltage_Sensor.v1.series.values*10^-3;
tfc_curr_sim_24338=paper24338.Toroidal_Field_Coil.Current_Sensor.i1.series.values*10^-3;
%Current and voltage time values [ms]
ohc_curr_sim_tm_24338=paper24338.Ohmic_heating_primary.Current_Sensor.i1.series.time*10^3;
ohc_volt_sim_tm_24338=paper24338.Ohmic_heating_primary.Voltage_Sensor.v1.series.time*10^3;
tfc_curr_sim_tm_24338=paper24338.Toroidal_Field_Coil.Current_Sensor.i1.series.time*10^3;

%=======================================
%==============for shot 24346
%=======================================
ohc_curr_sim_24346=paper24346.Ohmic_heating_primary.Current_Sensor.i1.series.values*10^-3;
ohc_volt_sim_24346=paper24346.Ohmic_heating_primary.Voltage_Sensor.v1.series.values*10^-3;
tfc_curr_sim_24346=paper24346.Toroidal_Field_Coil.Current_Sensor.i1.series.values*10^-3;
%Current and voltage time values [ms]
ohc_curr_sim_tm_24346=paper24346.Ohmic_heating_primary.Current_Sensor.i1.series.time*10^3;
ohc_volt_sim_tm_24346=paper24346.Ohmic_heating_primary.Voltage_Sensor.v1.series.time*10^3;
tfc_curr_sim_tm_24346=paper24346.Toroidal_Field_Coil.Current_Sensor.i1.series.time*10^3;

Data extraction code to workspace with Customised block:

format short g
%Current value in [KA] and [KV]
%==============================
%===========for shot 24337
%=======================================
ohc_curr_sim_24337_b=paper24337.Ohmic_heating_primary.Current_Sensor.i1.series.values*10^-3;
ohc_volt_sim_24337_b=paper24337.Ohmic_heating_primary.Voltage_Sensor.v1.series.values*10^-3;
tfc_curr_sim_24337_b=paper24337.Toroidal_Field_Coil.Current_Sensor.i1.series.values*10^-3;
%Current and voltage time values [ms]
ohc_curr_sim_tm_24337_b=paper24337.Ohmic_heating_primary.Current_Sensor.i1.series.time*10^3;
ohc_volt_sim_tm_24337_b=paper24337.Ohmic_heating_primary.Voltage_Sensor.v1.series.time*10^3;
tfc_curr_sim_tm_24337_b=paper24337.Toroidal_Field_Coil.Current_Sensor.i1.series.time*10^3;

%=================================
%==========for shot 24338
%=================================

ohc_curr_sim_24338_b=paper24338.Ohmic_heating_primary.Current_Sensor.i1.series.values*10^-3;
ohc_volt_sim_24338_b=paper24338.Ohmic_heating_primary.Voltage_Sensor.v1.series.values*10^-3;
tfc_curr_sim_24338_b=paper24338.Toroidal_Field_Coil.Current_Sensor.i1.series.values*10^-3;
%Current and voltage time values [ms]

%=================================
%==========for shot 24346
%=================================

%Current and voltage time values [ms]
C Physical System

Physical system represented as subsystem in Simscape:
Physical system for Ohmic heating circuit in Simscape:

Physical system for TFC in Simscape: