Induction Motor Equivalent Circuit Parameters

Problem Definition

The induction generator has 6-phase asymmetric windings as shown in Figure 1.

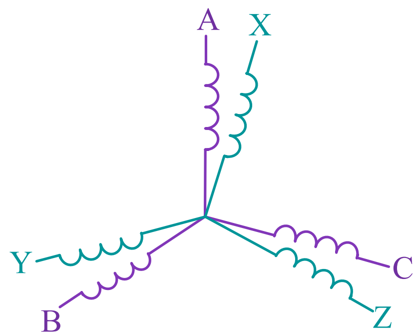


Figure 1 6-phase Induction Machine

In this winding configuration, it can be figured out that there are two separate three phase motors in the same lamination. These separate motors have inherently 30-degree phase difference in their induced voltage. We can find the speed-torque characteristics of the induction motor using parametric sweep in transient model of Maxwell, but it does not give the equivalent circuit parameters. Since the deduction of the equivalent circuit parameters from the torque speed characteristics is difficult in transient model, we can use "rmxprt" model that gives directly these circuit parameters. However, these models are only valid for 3-phase induction machines. Therefore, we can convert our six-phase induction machine to combined three-phase induction machines. Firstly, we can divide our machine into two windings sequences that are ABC and XYZ, and then we can connect these two motors' in parallel or series, as shown in Figure 2 and Figure 3.

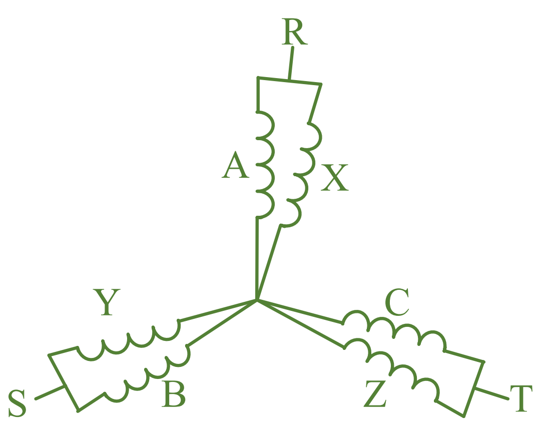


Figure 2 Combined parallel connected 3-phase IM

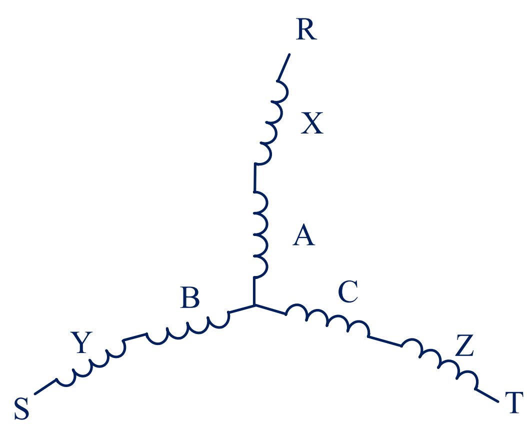


Figure 3 Figure 2 Combined series connected 3-phase IM

Assume that these ABC and XYZ machines have no phase difference at their induced voltage. Since we have two machines in series or parallel, we can calculate different equivalent circuit parameters. While, in series connection, we achieve twice of ABC or XYZ parameters in the combined three-phase machine, in parallel connection, we obtain the half of ABC or XYZ parameters.

Further, converting 6-phase motor to 3-phase motor changes some circuit parameters because we have actually 30-deree phase difference at the induced voltage. It means that actually distribution factor become involved. The equivalent circuit diagram of a phase of an induction motor is shown in Figure 4.

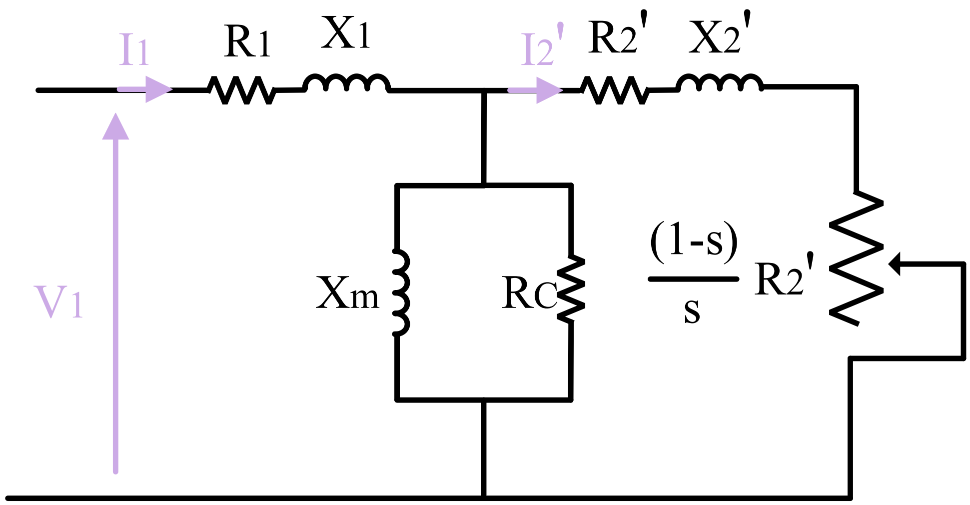


Figure 4 The equivalent circuit of IMs

where,

R_1= Stator winding resistance

X_1 = Stator winding leakage reactance

R_C = Resistance-representing core losses

X_m= Magnetizing reactance

R_2'= Rotor winding resistance referred to the primary

X_2'= Rotor winding reactance referred to the primary

Resistance Calculation in Induction Motor

Winding resistances can be calculated by $R = L\frac{\rho}{A}$ where, L is length, A is area, and ρ is resistivity which changes with temperature $\rho_2 = \rho_1\ (1 + \alpha(T_2 - T_1))$.

Since mean length of the windings become twice in series connection, which means that we achieve twice of the phase resistance. Besides, in parallel connection, the copper is become twice, which means that we achieve half of the phase resistance.

Combined 3-phase series model (Per phase equivalent)	Combined 3-phase parallel model (Per phase equivalent)	Six-phase model (Per phase equivalent)
$2R_1$	$\frac{R_1}{2}$	R_1
$2R_1$	$\frac{R_1}{2}$	R_1

Stator Rotor Turns Ratio

$$Turns\ ratio = \frac{N_r}{N_s}\frac{k_{wr}}{k_{ws}}$$

k_{ws} and k_{wr} are winding factors for the stator and rotor respectively. In the combined three-phase and six-phase models, k_{ws} and k_{wr} changes via 30-degree distribution factor.

$k_w = k_d k_p = \frac{sin\left(\frac{q\lambda}{2}\right)}{qsin\left(\frac{\lambda}{2}\right)}\ \cos(\frac{\alpha}{2})$ where q is the number of slots, λ is angular slot pitch, and α is pole pitch.

In our case, winding factor changes with correction factor 0.9659 of k_d. $\left(\frac{sin\left(\frac{2x30}{2}\right)}{2xsin\left(\frac{30}{2}\right)}\right)$

Combined 3-phase series model (Per phase equivalent)	Combined 3-phase parallel model (Per phase equivalent)	Six-phase model (Per phase equivalent)
0.9659 k_{ws}	0.9659 k_{ws}	k_{ws}
k_{wr}	k_{wr}	k_{wr}

.

Cage Rotor Parameters

A cage rotor is equivalent to a secondary winding having Q_2 conductors or bars connected in pairs a pole pitch apart so that there are Q_2/p phases.

$$i_2 = \frac{m_s k_{ws} N_s}{m_r k_{wr} N_r} i_2'$$

where i_2' is the rotor phase current referred to primary (stator), m is # of phase

The current per bar is

$$i_b = \frac{N_s k_{ws} m_s}{\frac{p}{2}\frac{Q_2}{p}} i_2' = \frac{2N_s k_{ws} m_s}{Q_2} i_2'$$

In deriving this equation, the rotor is assumed to have Q_2/p phases each with p/2 turns and the pitch factor is taken as unity. Let R_{ber} = resistance of one bar including the end ring. Then,

$$Q_2 i_b^2 R_{bar} = m_s i_2' R_2'$$

$$R_2' = \frac{Q_2 i_b^2 R_{bar}}{m_s i_2^2} = \frac{4m_s (N_s k_{ws})^2}{Q_2} R_{bar}$$

So, the rotor resistance referred in primary side changes with k_{ws}.

Combined 3-phase series model (Per phase equivalent)	Combined 3-phase parallel model (Per phase equivalent)	Six-phase model (Per phase equivalent)
$(k_{ws}^2)2R_2' = 0.933x2xR_2'$	$\frac{(k_{ws}^2)R_2'}{2} = 0.933\frac{R_2'}{2}$	R_2'

Leakage Reactance

For a coil of N turns surrounding a magnetic circuit of reluctance R, the flux per ampere is

$$\Phi = \frac{Ni}{R} = Ni\,\Lambda$$

where Λ is the permeance of the flux path. Now $\Lambda = \frac{\mu_0 A}{L}$

where A is the effective area and L is the length of the flux path. The leakage inductance of the coil is

$L = Ni\,\frac{\mu_0 A}{\Phi}$ Henries

Then, for the combined system leakage reactance's are the same. However, rotor reactance referred to primary side changes with k_{ws}.

Combined 3-phase series model (Per phase equivalent)	Combined 3-phase parallel model (Per phase equivalent)	Six-phase model (Per phase equivalent)
$(k_{ws}^2)2X_2' = 0.933x2xX_2'$	$\frac{(k_{ws}^2)X_2'}{2} = 0.933\frac{X_2'}{2}$	X_2'

Magnetizing Reactance

This reactance in the equivalent circuit determines the current that is drawn by the motor to establish the pole flux φ in the magnetic circuit.

$$X_m = \frac{V_p}{I_m}$$

We have already shown that for a 3-phase winding of N_{ph} turns per phase and p-poles, the amplitude of the resultant MMF is

$$F_R = \frac{3}{2}\frac{4}{\pi}\frac{Ni}{p}\left(\sqrt{2}\right) = 2.7\frac{N_{ph}k_w}{p}i$$

where, i is the rms current.

Combined 3-phase series model (Per phase equivalent)	Combined 3-phase parallel model (Per phase equivalent)	Six-phase model (Per phase equivalent)
$k_{ws}2R_2' = 0.9659x2xX_m'$	$\frac{k_{ws}X_m'}{2} = 0.9659\frac{X_m'}{2}$	X_m'

Solidity of the Equivalent Circuit Parameters

The equivalent circuit of IMs actually changes with respect to slip, but IMs are working the slip near "s=0". Rmxprt model gives the stator leakage reactance, rotor resistance, and rotor leakage reactance with respect to varying slip as can be seen in Figure 5.

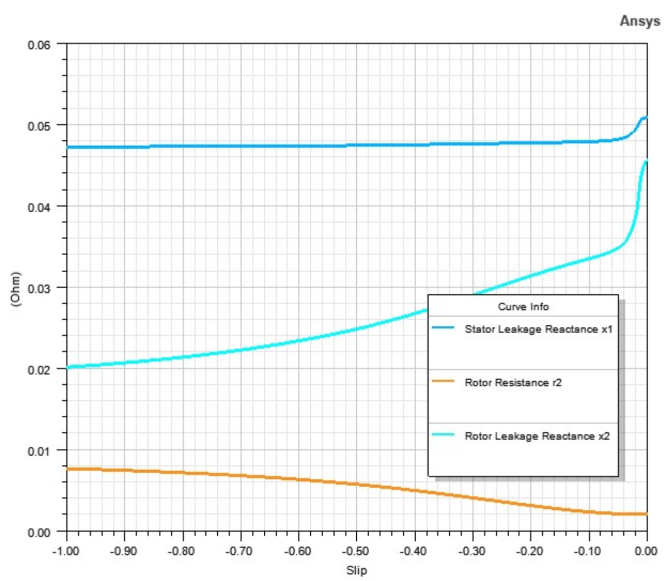


Figure 5 Rmxprt results of equivalent circuit parameters

However, using only the equivalent circuit parameters in "s=0" gives a realistic torque values the slip close to 0. The comparison of varying (Rmxprt model) and constant (equivalent circuit model) equivalent circuit parameters are given Figure 6. The values are separated by moving away from "s=0", but these operations are already not expected. Therefore, equivalent circuit model can be used in modelling of IMs.

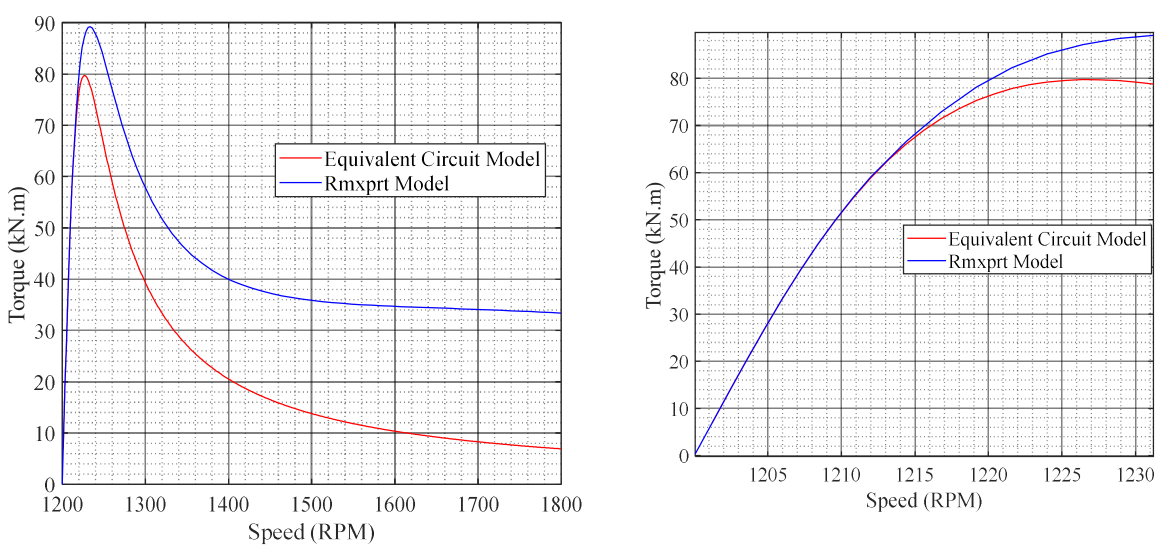


Figure 6 Comparison of Torque for equivalent circuit parameters and Rmxprt model

Comparison of 6-phase Transient Model and 3-phase Combined Rmxprt Model

In 3-phase combined Rmxprt model, we can connect two 3-phase IMs in parallel or series, but we cannot excite them separately. Therefore, we have some differences in Torque-slip characteristics as can be seen in Figure 7.

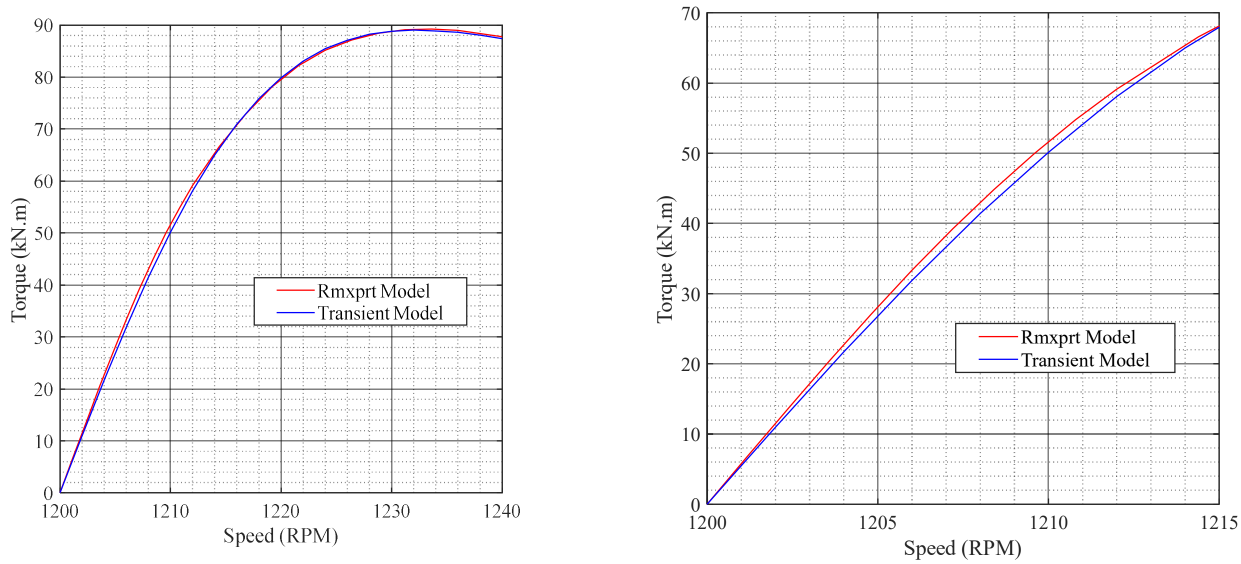


Figure 7 Comparison of Torque Characteristics for Transient and Rmxprt model

While Rmxprt model gives the rated torque at 1206.25 RPM, Transient model gives it at 1206.55.

Enhanced Equivalent Circuit Parameters

The equivalent circuit parameters are updated by considering the electrical 30^{o} differences between the phases. The comparison of torque characteristics of all models is given in Figure 8.

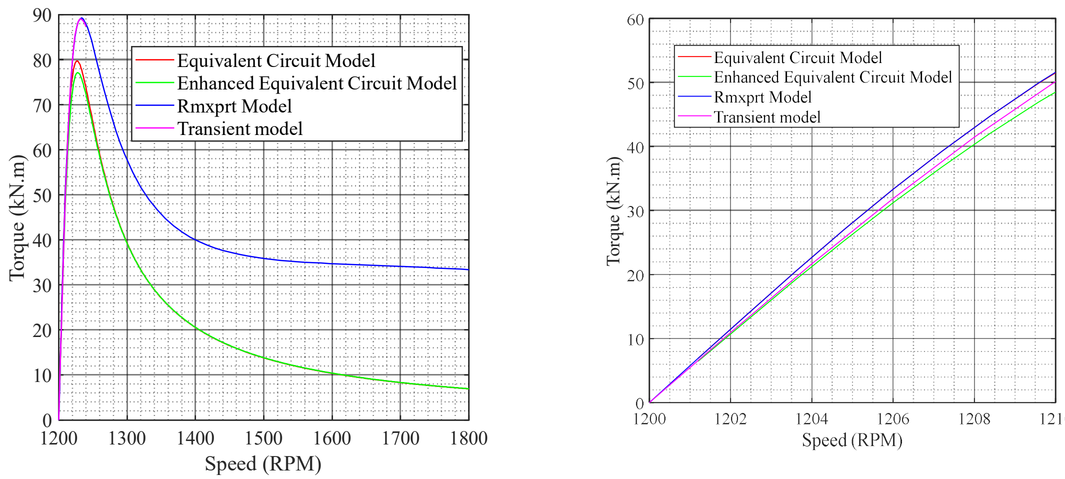


Figure 8 Comparison of Torque Characteristics for all models

While Transient model gives the rated torque at 1206.55, enhanced equivalent circuit model gives it 1206.7.

Circuit Parameters

Parameter	**3-Phase Combined Parallel Model (for combined two IMs)**	**3-Phase Enhanced Model (for single IM)**
R_1	$0.789831\ m\Omega$	$1.579662\ m\Omega$
X_1	$12.6978\ m\Omega$	$25.3956\ m\Omega$
R_2'	$0.52717\ m\Omega$	$1.13005\ m\Omega$
X_2'	$11.2829\ m\Omega$	$24.18628\ m\Omega$
R_C	$22.2\ \Omega$	$45.9676\ \Omega$
X_m	$0.3597\ \Omega$	$0.7447893\ \Omega$
Stator Phase Current	$4066\ A$	**2016A**
Magnetizing Current	$1070\ A$	-
Core Loss Current	$17.35\ A$	**10.15A**
Power Factor	0.8778	0.8781
Slip	-0.005264	-0.0055779
Shaft Speed	$1206.32\ RPM$	1206.6935 RPM
Number of Poles	6	6
Inertia	242.28 kg.m^2	$121.14\ kg.m^2$

Simulink Model

In the Simulink, built-in induction motor model exists, and it takes the equivalent circuit parameters except core loss resistance. Therefore, we can update our equivalent circuit as given in Figure 9.

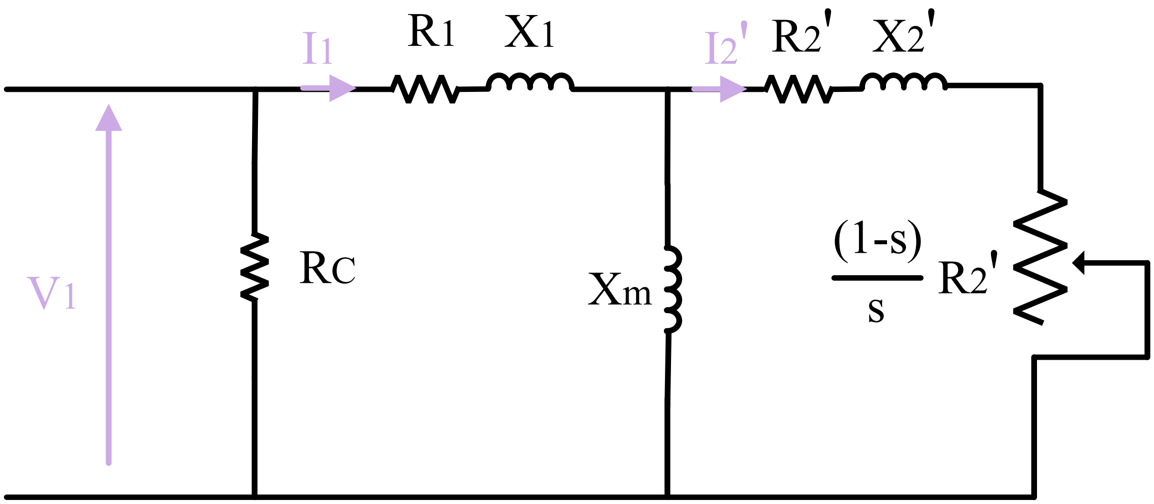


Figure 9 Updated equivalent circuit of IMs

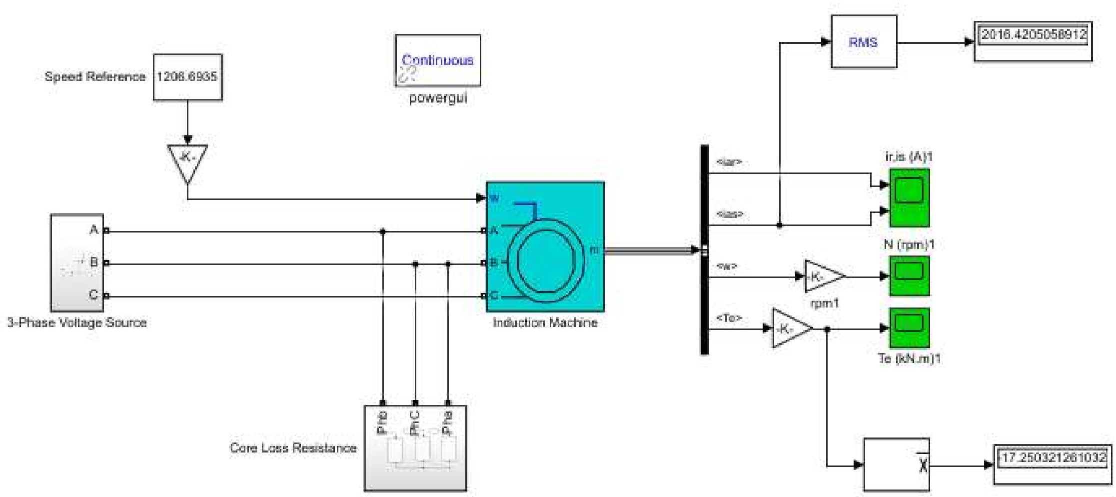
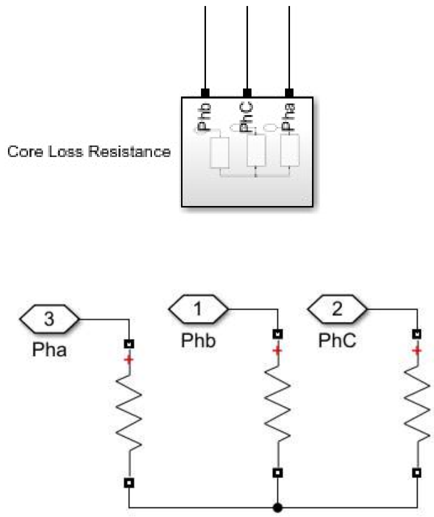
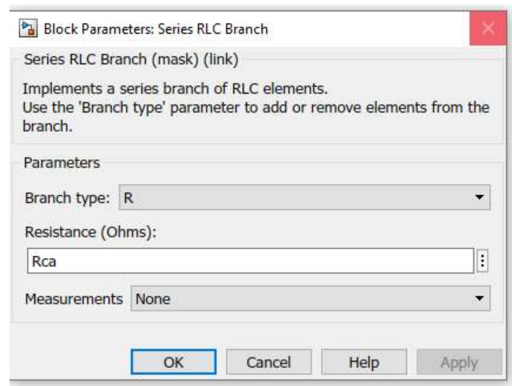


Figure 10 Simulink Model Of the IM

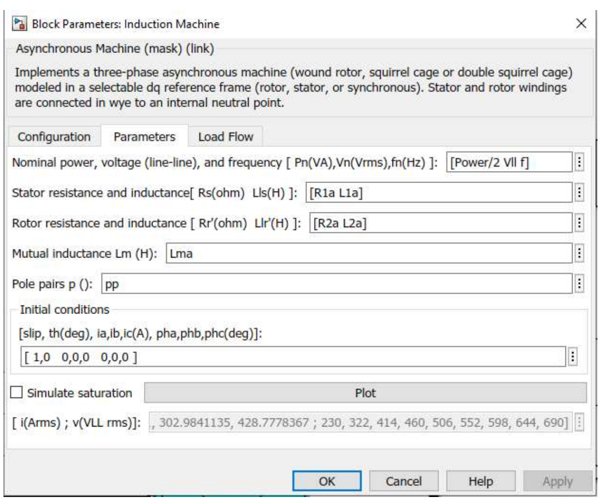
Blocks and Parameters in the Simulink

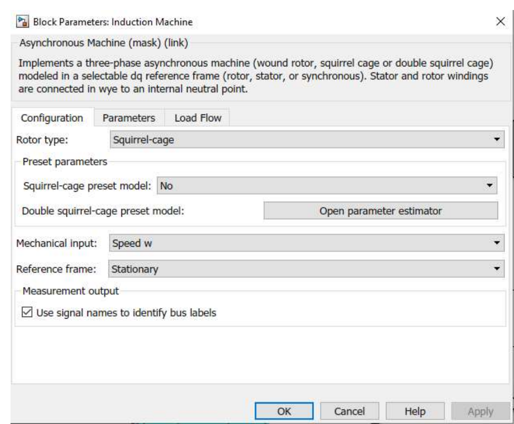
Core Losses

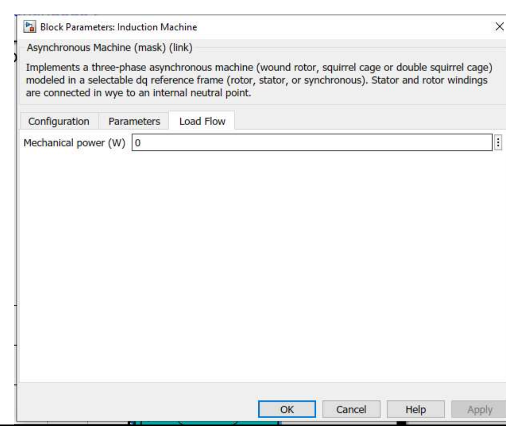


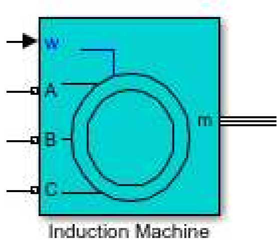


Induction Machine

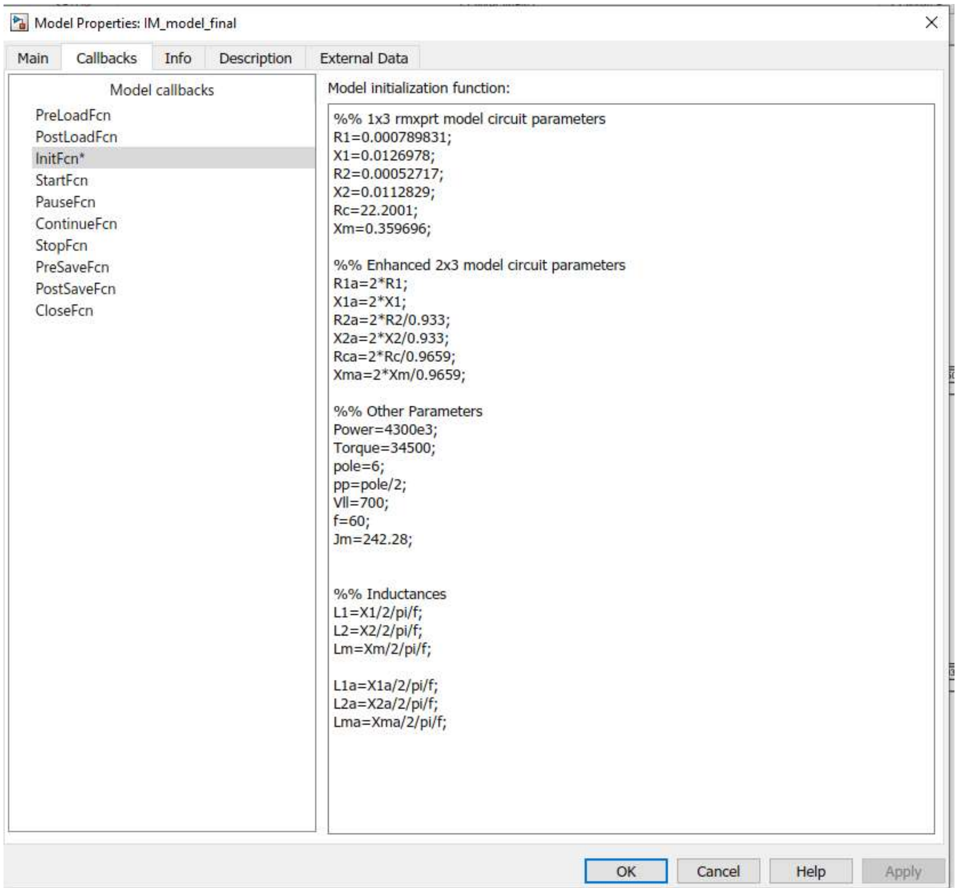








System Parameters




```
%% 1x3 rmxprt model circuit parameters
R1=0.000789831;
X1=0.0126978;
R2=0.00052717;
X2=0.0112829;
Rc=22.2001;
Xm=0.359696;

%% Enhanced 2x3 model circuit parameters
R1a=2*R1;
X1a=2*X1;
R2a=2*R2/0.933;
X2a=2*X2/0.933;
Rca=2*Rc/0.9659;
Xma=2*Xm/0.9659;

%% Other Parameters
Power=4300e3;
Torque=34500;
pole=6;
pp=pole/2;
Vll=700;
f=60;
Jm=242.28;


%% Inductances
L1=X1/2/pi/f;
L2=X2/2/pi/f;
Lm=Xm/2/pi/f;

L1a=X1a/2/pi/f;
L2a=X2a/2/pi/f;
Lma=Xma/2/pi/f;
```

DlgSilent Model