ELEC 5564M

POWER GENERATION BY RENEWABLE SOURCES

Report on

INDUCTION GENERATOR MODELLING USING SPACE VECTOR EQUATIONS

Dagogo Godwin Orifama

201177661

MSc Electronics and Electrical Engineering

University of Leeds

January 2017

Introduction

This report is on the modelling of an induction motor using space vector equation of three-phase variables. The structure of an induction motor basically, consists of a cylindrical rotor that contains the distributed three-phase winding of rotating speed Ω_r. This speed can be determined by the mechanical torque that turns the shaft connected to the rotor. Similarly, the stator of the induction generator has also set of three phase winding which is magnetically connected to the rotor winding. The computation of the synchronous speed in radian per second and in revolution per minute, and the slip, s of the motor is shown subsequently.

$$\Omega_s = \frac{120 f_s}{p(poles)}(rev/\min)$$

$$w_s = \frac{4\pi f_s}{p(poles)}(rad/\sec)$$

$$s = \frac{\Omega_s - \Omega_r}{\Omega_s}$$

The value of the slip is positive for motoring mode an negative for generating mode.

Aim of the experiment

The aim of this laboratory simulation exercise was model the dynamic behaviour of an induction generator driven by a wind turbine

Objective of the experiment

The objectives of this exercise were to:

- Study and apply the phasor representation of three phase variables
- Study an apply the Clarke Transformation and reverse Clarke Transformation for voltage and current from the ABC plan to the d-q plane and vice versa
- Produce the state space equations that express the dynamic changes of an induction generator in terms of its stator and rotor current, flux linkage and speed.
- Study and understand the method of driving an induction machine by a wind turbine from start for generating electricity.
- Evaluate and analyse values for electric torque, power factor, output power and the efficiency of the induction generator using simulation results and comparing it with standard values.

Induction Machine Equivalent Circuit Model Using space vector

The equivalent circuit for the induction generator in a stationary reference frame for both the stator and rotor is shown in figure 1 and the corresponding model equations are shown subsequently.

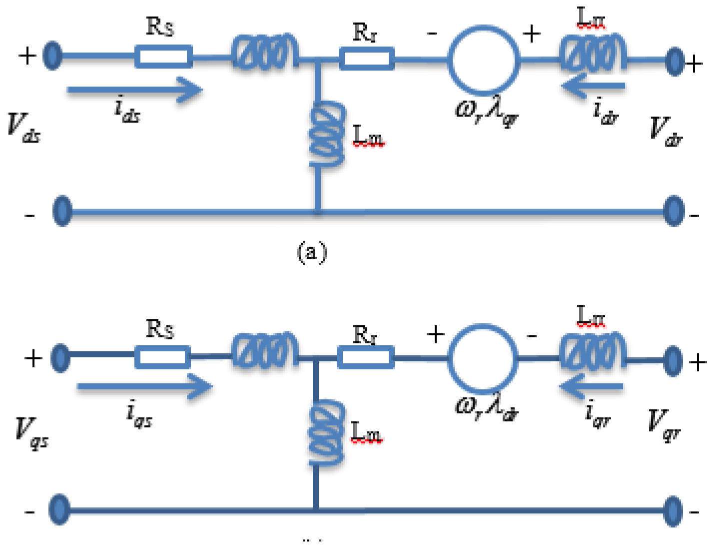


Figure 1: stationary equivalent circuit model for Rotor and Stator

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{2}$$

$$V_{qr} = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} - \omega_r \lambda_{dr} \tag{3}$$

$$V_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} + \omega_r \lambda_{qr} \tag{4}$$

Re-arranging the equations (1) – (4) gives the following

$$\frac{d\lambda_{qs}}{dt} = V_{qs} - R_s i_{qs} \tag{5}$$

$$\frac{d\lambda_{ds}}{dt} = V_{ds} - R_s i_{ds} \tag{6}$$

$$\frac{d\lambda_{qr}}{dt} = V_{qr} - R_r i_{qr} + \omega_r \lambda_{dr} \tag{7}$$

$$\frac{d\lambda_{dr}}{dt} = V_{dr} - R_r i_{dr} - \omega_r \lambda_{qr} \tag{8}$$

Where

$$\lambda_{qr} = L_r L_{qr} + L_m L_{qs} \tag{9}$$

$$\lambda_{dr} = L_r L_{dr} + L_m L_{ds} \tag{10}$$

$$L_s = L_{ss} + L_m \tag{11}$$

$$L_r = L_{rr} + L_m \tag{12}$$

State Space Representations

The equations from (13) – (16) are representation of the d-q current values in terms of flux linkages and inductance (mutual and self) values

$$i_{qs} = a(L_r\lambda_{qs} - L_m\lambda_{qr}) \tag{13}$$

$$i_{qr} = a(L_s\lambda_{qr} - L_m\lambda_{qs}) \tag{14}$$

$$i_{ds} = a(L_r\lambda_{ds} - L_m\lambda_{dr}) \tag{15}$$

$$i_{dr} = a(L_s\lambda_{dr} - L_m\lambda_{ds}) \tag{16}$$

Where

$$a = \frac{1}{L_s L_r - L_m^2} \tag{17}$$

The state space equation for the squirrel cage (induction generator) in terms of state variable (flux linkages) and d-q values (voltages) is shown below

$$\frac{d\lambda_{qs}}{dt} = V_{qs} - aR_s L_r \lambda_{qs} + aR_s L_m \lambda_{qr} \tag{18}$$

$$\frac{d\lambda_{ds}}{dt} = V_{ds} - aR_s L_r \lambda_{ds} + aR_s L_m \lambda_{dr} \tag{19}$$

$$\frac{d\lambda_{qr}}{dt} = V_{qr} - aR_r L_s \lambda_{qr} + aR_r L_m \lambda_{qs} + \omega_r \lambda_{dr} \tag{20}$$

$$\frac{d\lambda_{dr}}{dt} = V_{dr} - aR_r L_s \lambda_{dr} + aR_r L_m \lambda_{ds} - \omega_r \lambda_{qr} \tag{21}$$

The state space model of equation (16) – (19) is shown below

$$\begin{bmatrix} \frac{d\lambda_{qs}}{dt} \\ \frac{d\lambda_{ds}}{dt} \\ \frac{d\lambda_{qr}}{dt} \\ \frac{d\lambda_{dr}}{dt} \end{bmatrix} = \begin{bmatrix} -aR_sL_r & 0 & aR_sL_m & 0 \\ 0 & -aR_sL_r & 0 & aR_sL_m \\ aR_rL_m & 0 & -aR_rL_s & \omega_r \\ 0 & aR_rL_m & -\omega_r & -aR_rL_s \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{qr} \\ \lambda_{dr} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} \tag{22}$$

Also, we have

$$T_e = \frac{3}{2} * \frac{P}{2} * L_m * (i_{qs} * i_{dr} - i_{ds} * i_{qr}) \tag{23}$$

$$\frac{d\omega_r}{dt} = \frac{1}{J} * \frac{P}{2} * (T_m - T_e - (B\omega_r * \frac{P}{2})) \tag{24}$$

For a squirrel cage induction machine $V_{qr} = V_{dr} = 0$. Shown subsequently is the Clarke Transformation from the abc plan to the dq axis

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{25}$$

For a stationary reference plane (SRF) the value of θ is taken to be zero.

Similarly, the transformation into the abc plane from the d-q axis using reverse Clarke Transformation is shown below

$$V_A = V_{qs} \tag{26}$$

$$V_B = \frac{1}{2} V_{qs} - \frac{\sqrt{3}}{2} V_{ds} \tag{27}$$

$$V_C = \frac{1}{2} V_{qs} + \frac{\sqrt{3}}{2} V_{ds} \tag{28}$$

Where

$$V_A = V_m \sin \omega t \tag{29}$$

$$V_B = V_m \sin(\omega t - 120^o) \tag{30}$$

$$V_C = V_m \sin(\omega t + 120^o) \tag{31}$$

The flow chart for performing the modelling of the squirrel cage induction machine is shown in figure 2. The explanation of the flow chart is in Table 1

Algorithm 1: Flow chart description
Start Initialize all constant variable like J, B, HP, P, F, Lrr, Lr, Lm, Lss etc Initialize starting values Va, Vb, Vc, vqs, cds, Ia,Ib,Ic,iqs,ids,iqr,idr $\lambda_{qs}, \lambda_{ds}, \lambda_{qr}, \lambda_{d}$ and ω_r Evaluate the slip, period etc First loop: For total simulation time Generate a null or empty matrixes or vds,vqs $\lambda_{qs}, \lambda_{ds}, \lambda_{qr}, \lambda_{d}$ and ω_r Second loop: for every period, as subset of the first loop Using Clarke Transformation generate updates for vds and vqs Using 4^{th} order runge-kutta method update $\lambda_{qs}, \lambda_{ds}, \lambda_{qr}, \lambda_{d}$ and ω_r Generate the following ids,iqs,idr and iqr Update Te Using reverse Clarke Transformation update Va, Vb,Vc,Ia,Ib and Ic Update matrix ω_r End of first Loop Plot vital graphs Va, Vb,Vc,Ia,Ib, Ic, $\lambda_{qs}, \lambda_{ds}, \lambda_{qr}, \lambda_{d}$ and ω_r against simulation time **End**

Table1: Algorithm of program

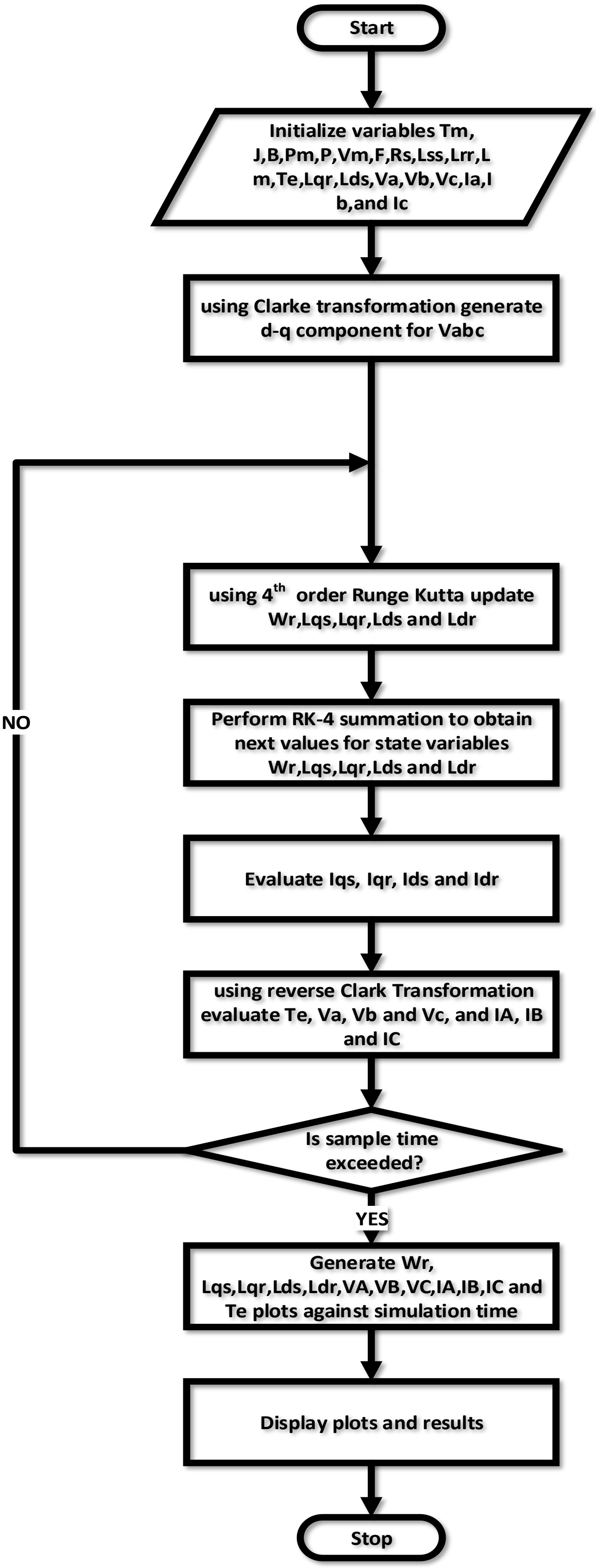


Figure 2: Flowchart for the squirrel cage induction generator modelling using state space vector

The Modelling Information and Parameters

The squirrel case wind turbine induction generator modelling was done using the MatLab software. The program code was written using the generated state space equations in equation (22) to (24) along with some other supporting equations. The coding was done in a MATLAB M-file script, this was to allow for repeated operations and adjustments. The completed and the fully commented code is shown in the appendix. The workstation used for this exercise is a 64-bit 500GB Hard disk HP computer with 4GB RAM with a CPU speed of 1.90GHz. The values used as the machine parameters for the exercise is shown below

Parameters	**Symbols**	**Values**
Machine inertia	J	0.025284Kg-m2/s
Machine friction	B	0.005Nms
Machine rated power	HP	5hp or 5*746.15W
Poles	P	4
Supply line-to-line voltage	Vl	230V (rms)
Supply phase voltage	Vph	230/sqrt(3) V (rms) (star)
Supply frequency	F	50Hz
Stator resistance	Rs	0.5673
Rotor resistance	Rr	0.7091
Stator leakage inductance	Lss	0.00301H
Rotor leakage inductance	Lrr	0.00301H
Mutual inductance	Lm	0.075239H
Stator self-inductance	Ls	Lss + Lm
Rotor self-inductance	Lr	Lrr + Lm

Table 2: Machine parameters for the wind turbine induction generator modelling

Results and Discussions

Synchronous mode startup

The wind turbine is said to operate in the synchronous mode when the rotor speed is equal to the synchronous speed. Similarly, synchronous mode startup for the wind turbine squirrel cage induction generator involves selecting a mechanical torque that generates a rotor speed value that is equal to the synchronous speed of the induction generator. Figure 3a indicates the response of the rotor speed of the induction generator for a mechanical torque Tm of -1. Similarly, the electrical torque response is shown in figure 3b

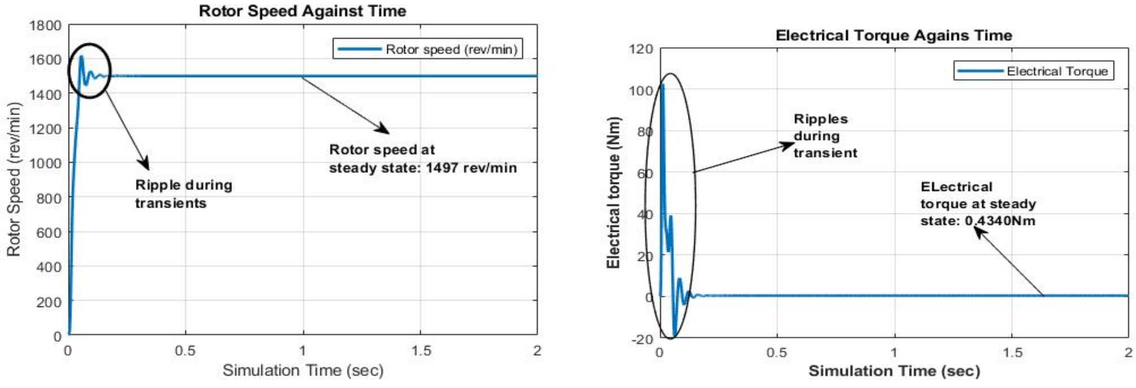
Discussion and Observation

From figure 3a, it can be observed that the rotor speed is 1497 and the corresponding slip produce is

$$s = \frac{\Omega_s - \Omega_r}{\Omega_s} = \frac{1500 - 1497}{1500} = 0.003 \approx 0$$

$$\Rightarrow \Omega_s \approx \Omega_r$$

Also, it can be seen from figure 3b that the electrical torque $T_e = 0.4340Nm \approx 0$ at steady state, this shows that no electrical power is currently being drawn by the grid from the wind turbine induction generator as it has not been connected. Figure 3c shows the phase current plot (3-phase)



(a) (b)

Figure 3: (a) Rotor speed plot (b) Electrical torque against simulation time

Figure 3c shows that the 3-phase current varies between $\pm 7.60A$ at steady state and are spaced from each other electrically by 120^0. Similarly, figure 3d shows the 3-phase voltage, where it is seen to vary between $\pm 188V$ and are electrically spaced by 120^0 from each other. The stator and rotor combined plot of the d-q flux linkages (mutual and self) is indicated in figure 3e

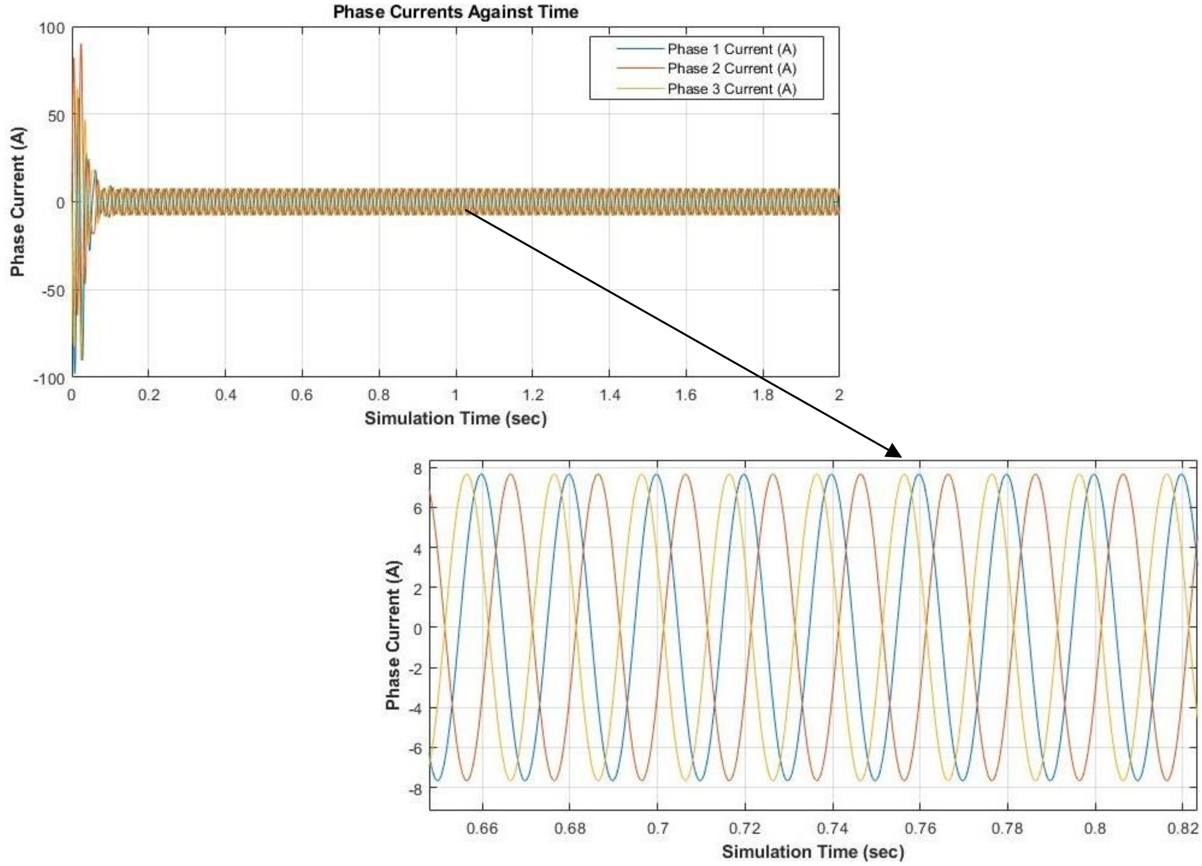


Figure 3c: Phase current plot for $T_m = -1Nm$

Similarly, the 3-phase voltage plot and the d-q flux linkage plot for the rotor and stator are indicated in figure 3d and 3e

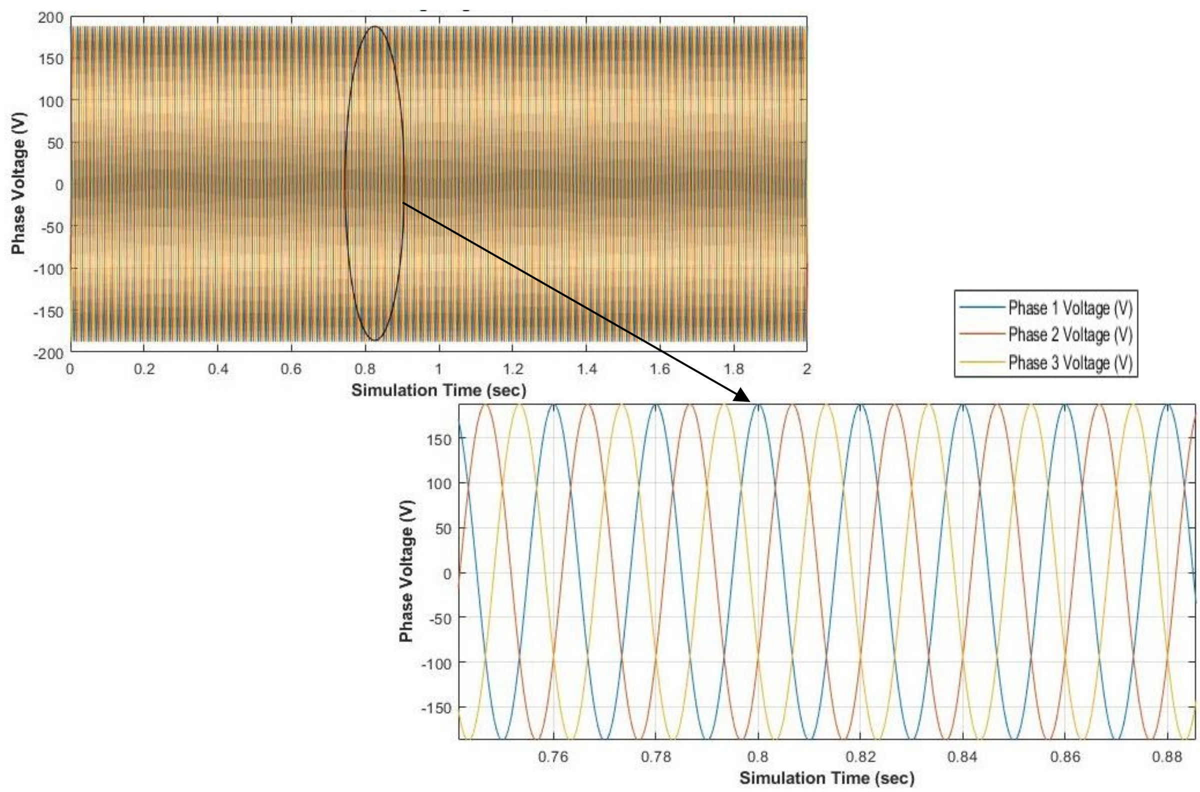


Figure 3d: The 3-phase voltage plot versus simulation time

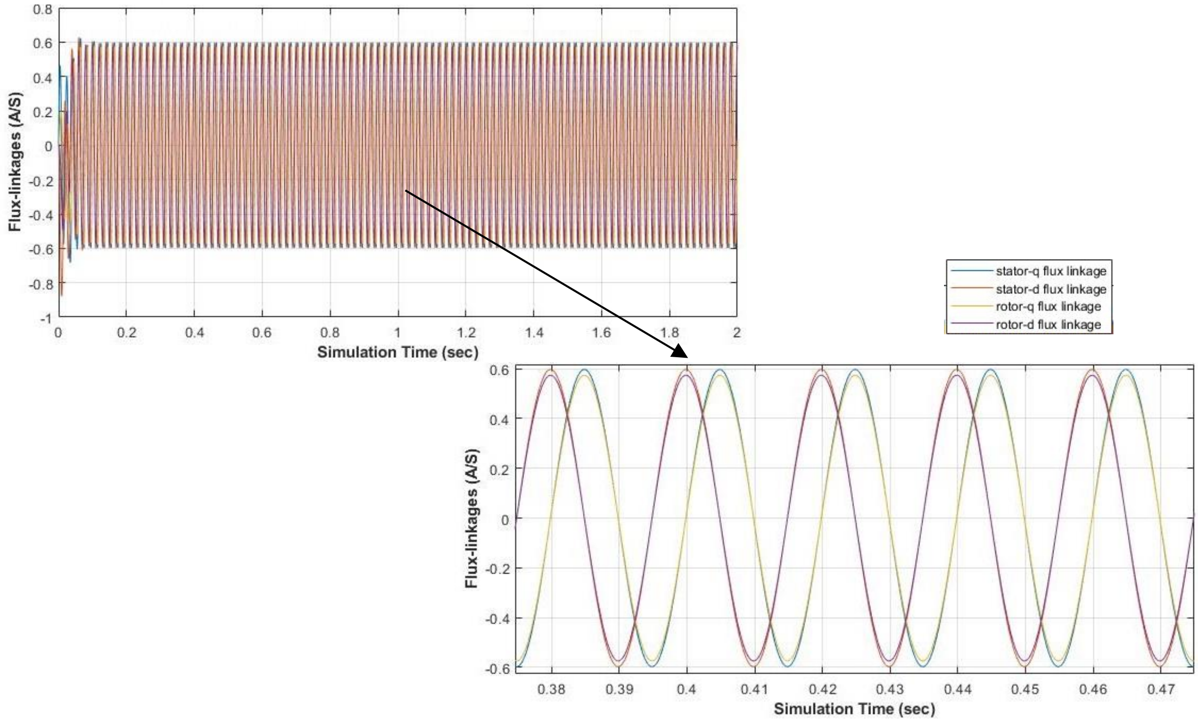


Figure 3e: The d-q flux linkage for both stator and rotor

Super-synchronous operation with soft connection

To operate a wind turbine at super-synchronous speed, a higher negative mechanical torque value corresponding to a higher wind speed is utilized. Figure 4c shows the plot of the induction generator speed (rev/min), figure 4b is the 3-phase current versus simulation time plot and figure 4c shows a plot of the electrical torque against simulation time for $T_m = -20Nm$ without a soft start connected.

Discussion and Observations

As the value of the mechanical torque was increased from 1-Nm to -20Nm with a soft start connection led to ripples in the speed and current of the induction generator. From figure 4a it can be seen that at the point of increment, the ripples in the rotor speed varied initially between 1522 (rev/min) to 1593 (rev/min) which gives a peak-to-peak value of 71 (rev/min) before settling 1561 rev/min (its steady state value). Also, it was observed that at the point the torque was increased, a surge occurred in the current which is drawn from the generator, causing the current to momentarily oscillate from $\pm 7.60A$ to $\pm 18.78A$ after which it settled at $\pm 14.5A$ which is its steady-state value, as indicated in figure 4b. Figure 4c is a plot which shows the ripple in the electrical torque, the ripple settles at an average value of -18.2Nm at steady state for a mechanical torque of $T_m = -20Nm$.

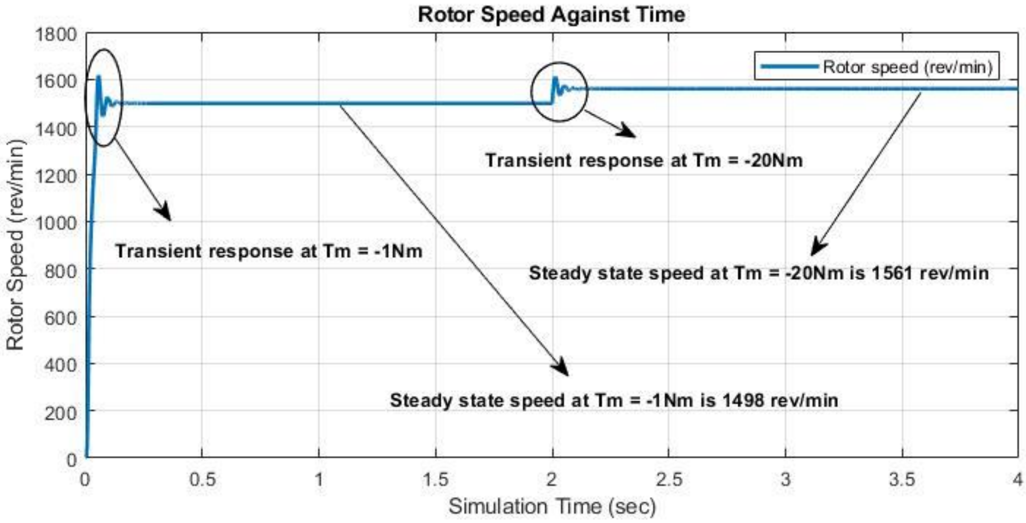


Figure 4a: Rotor speed response with a sharp increment in mechanical torque

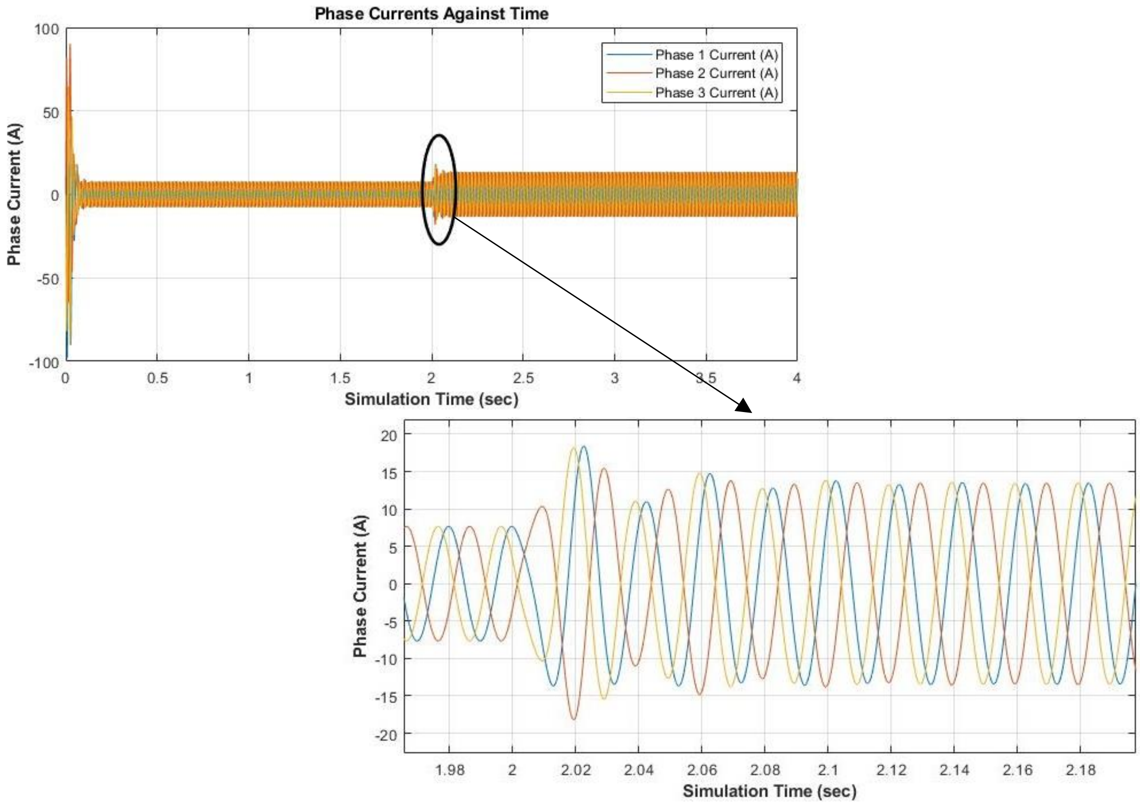


Figure 4b: The 3-phase stator current with sharp increment in mechanical torque

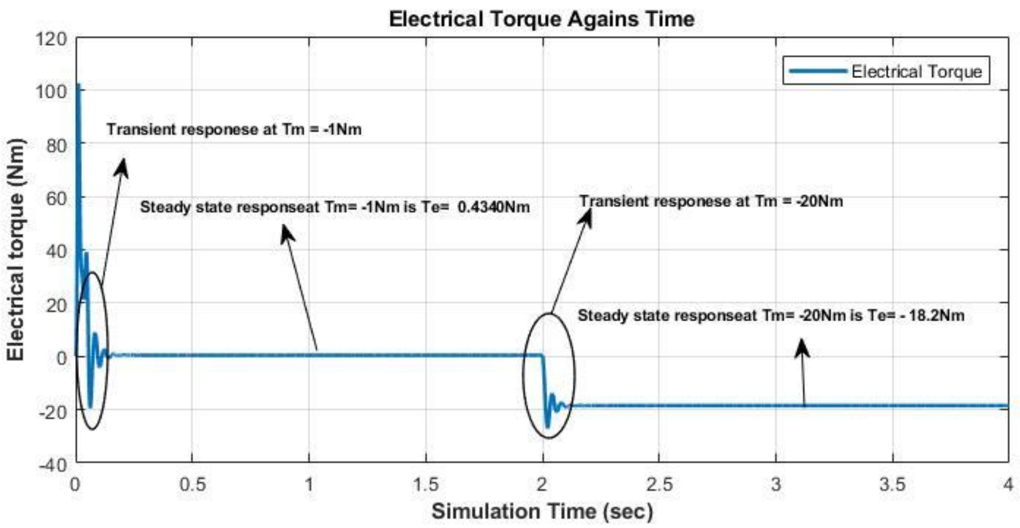


Figure 4c: The electrical torque response with sharp increment in the mechanical torque

Computation of machine parameters at $T_m = -20Nm$

Considering figure 4a, the rotor speed $\omega_r = 1561 rev / \min(163.47 rad / \sec)$, also the synchronous speed $\omega_s = \frac{4\pi f_s}{p} = \frac{4\pi * 50}{4} = 157.08 rad / \sec$ hence the slip

$$s = \frac{\Omega_s - \Omega_r}{\Omega_s} = \frac{1500 - 1561}{1500} = -0.041$$

Assuming that the frictional and windage losses are negligible $P_{mech} = T_m \omega_s (1 + |s|)$, then

$$P_{mech} = T_m * \omega_r = -20 * 163.47 = -3269.4W$$

The output power can be computed as $P_{out} = T_g * \omega_s = -18.2 * 157.08 = -2858.86W$

Efficiency, $\eta = \frac{P_{out}}{P_{mech}} = \frac{-2858.86}{-3269.40} = 87.44\%$

The generator torque is given by $T_g = \frac{3|I'_2|^2 \frac{R'_2}{s}}{\Omega_s}$

Where the transformation ratio is assumed as 1

$$|I'_2| = \sqrt{\frac{T_g * \Omega_s}{3 * \frac{R'_2}{s}}} = \sqrt{\frac{18.2 * 157.08}{3 * \frac{0.5673}{0.041}}} = 8.29A$$

Evaluation of the phase angle,

$$|Z| = \sqrt{(R_1 + \frac{R_2^{'}}{s})^2 + (X_1 + X_2^{'})^2} = \sqrt{(0.5673 + \frac{0.7091}{-0.041})^2 + (0.9456 + 0.9456)^2}$$

$$|Z| = \sqrt{(17.1602)^2 + (1.8912)^2} = 17.96 < 173.71^o ohm$$

Therefore, the stator current $|I_2^{'}| = 8.29 < -173.71^o A$

Similarly, the power factor $pF = \cos(\phi) = \cos(-173.71^o) = -0.99$ (where ϕ =-173.71)

From power triangle, we know that $S = P + jQ$ where S is the apparent power in VA, P is the real power in watts and Q is the reactive power in vars, and are equivalent to

Apparent power, $S = 3IV$ and real power $P = 3IV \cos\phi$ and reactive power $Q = \sqrt{S^2 - P^2} = 3IV \sin\phi$

The real power P = 2858.86W, then the voltage

$$V = \frac{P}{3I\cos\phi} = \frac{-2858.86}{3*7.42*\cos(-173.71)} = 129.21 < 0^o V$$

Similarly, the apparent power $S = \frac{P}{\cos\phi} = \frac{-2858.86}{\cos(-173.71)} = 2876.17VA$ and

$$Q = \sqrt{2876.17^2 - 2858.86^2} = 315.08Vars$$

The table below gives a summary of the measured and computed parameters for squirrel cage induction machine for $T_m = -20Nm$

Impedance	$17.96 < 173.71^o ohm$
Efficiency	87.44%
Real Power (watts)	2858.86 watts
Apparent power (VA)	22876.17 VA
Reactive power (Vars)	315.08 Vars
Phase angle	-173.71
Power Factor	-0.99
Stator Current	$\|I_2^{'}\| = 8.29 < -173.71^o A$
Input mechanical power	3269.40 Watts

Table: Induction machine measured and computed parameters for wind turbine $T_m = -20Nm$

Super synchronous operation mode with $T_m = -30Nm$

In this section, the operation involves a gradual increase in torque from -1 Nm to -30 Nm. It involves results gotten at steady speed operation with $T_m = -30Nm$. The plot of the rotor speed versus simulation time is shown in figure 5a which show from the plot that as the mechanical torque increases in magnitude, there is a decrease in the peak-to-peak transient response of the rotor speed. Figure 5a also shows that the value of the steady state rotor speed at $T_m = -30Nm$ is 1590 rev/min. Similarly, the three-phase rotor current and the electromagnetic torque at steady state are shown in figure 5b and 5c respectively.

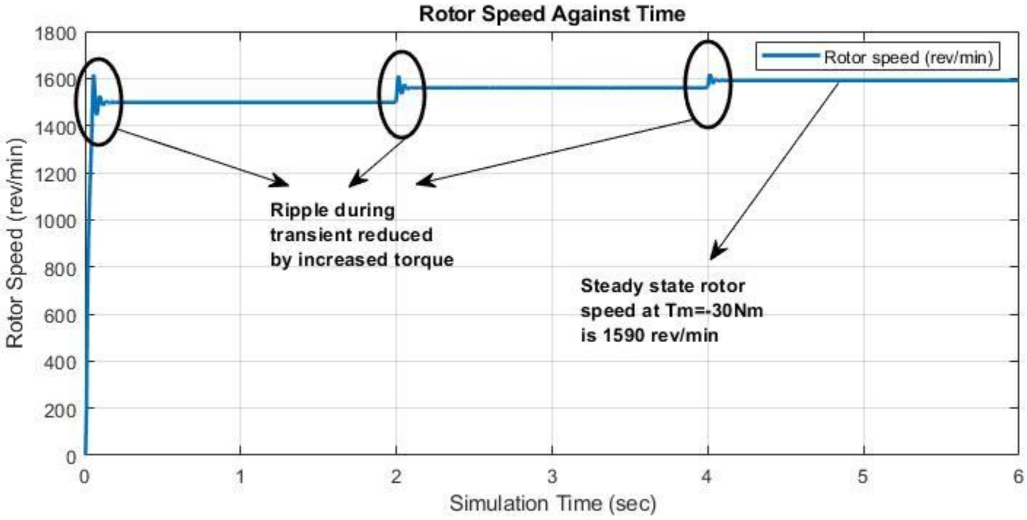


Figure 5a: Rotor speed transient and steady state response to increased mechanical torque

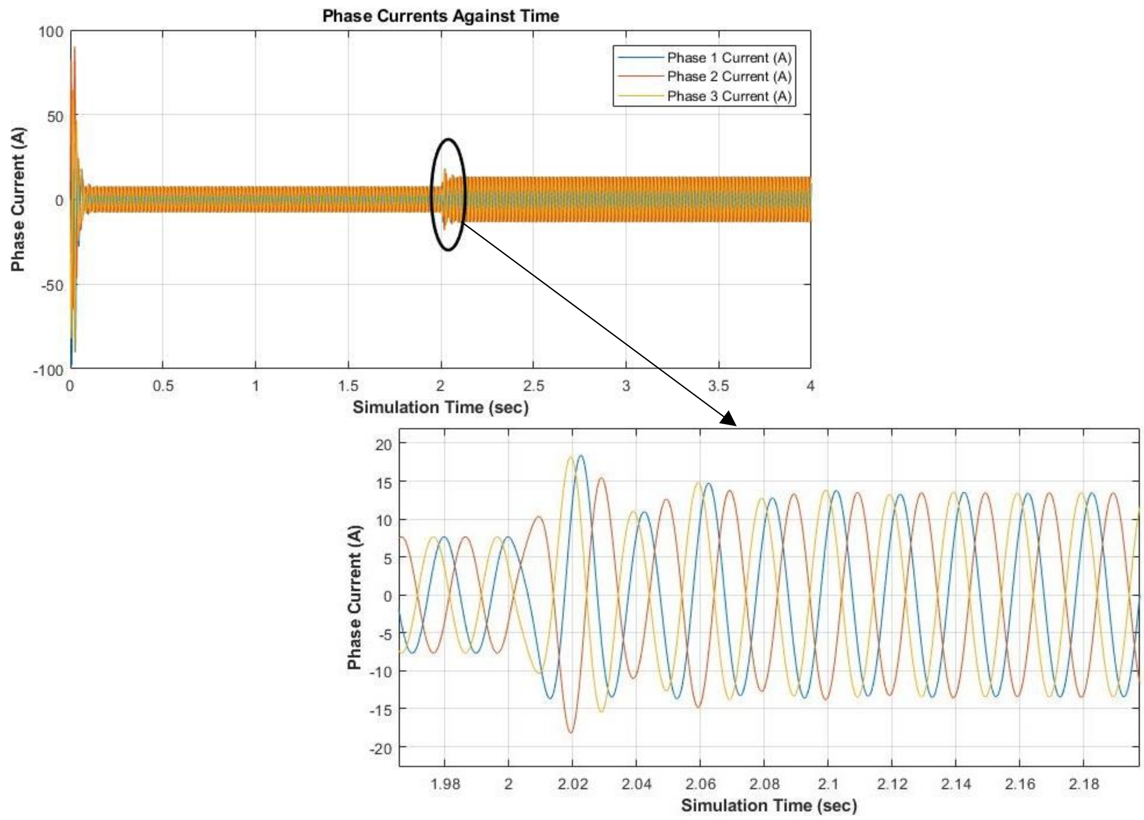


Figure 5b: The 3-phase stator current with increased mechanical torque

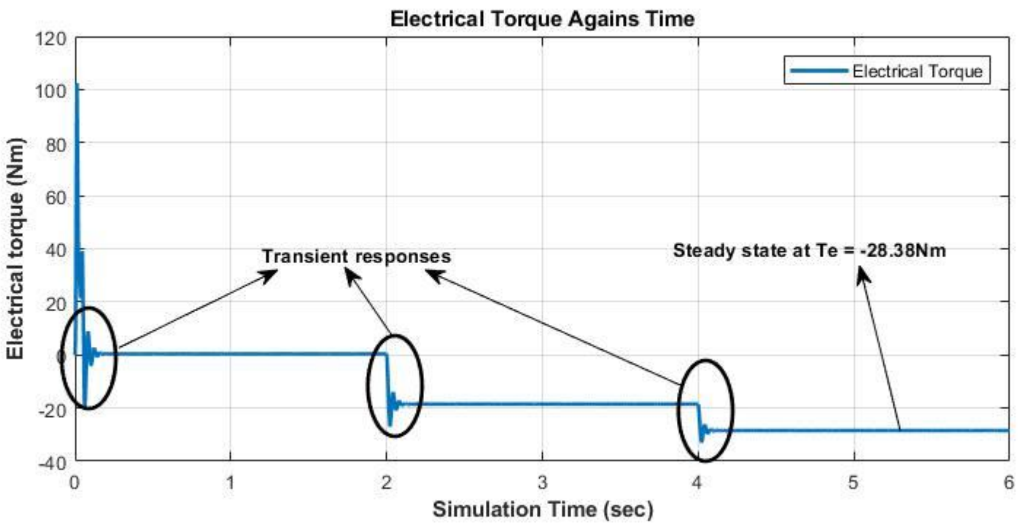


Figure 5c: Electrical torque response with increased mechanical torque

Computation of machine parameters at $T_m = -30Nm$

Considering figure 4a, the rotor speed $\omega_r = 1590 rev/\min(166.50 rad/\sec)$, also the synchronous speed $\omega_s = \frac{4\pi f_s}{p} = \frac{4\pi * 50}{4} = 157.08 rad/\sec$ hence the slip

$$s = \frac{\Omega_s - \Omega_r}{\Omega_s} = \frac{1500 - 1590}{1500} = -0.06$$

Assuming that the frictional and windage losses are negligible $P_{mech} = T_m \omega_s (1 + |s|)$, hence

$$P_{mech} = T_m * \omega_r = -30 * 166.50 = -4995W$$

The output power can be computed as $P_{out} = T_g * \omega_s = -28.38 * 157.08 = -4457.93W$

Efficiency, $\eta = \frac{P_{out}}{P_{mech}} = \frac{-4457.93}{-4995} = 89.25\%$

The generator torque is given by $T_g = \frac{3|I'_2|^2 \frac{R'_2}{s}}{\Omega_s}$

Where the transformation ratio is assumed as 1

$$|I'_2| = \sqrt{\frac{T_g * \Omega_s}{3 * \frac{R'_2}{s}}} = \sqrt{\frac{28.30 * 157.08}{3 * \frac{0.5673}{0.06}}} = 12.52A$$

Evaluation of the phase angle,

$$|Z| = \sqrt{(R_1 + \frac{R_2^{'}}{s})^2 + (X_1 + X_2^{'})^2} = \sqrt{(0.5673 + \frac{0.7091}{-0.06})^2 + (0.9456 + 0.9456)^2}$$

$$|Z| = \sqrt{(12.39)^2 + (1.8912)^2} = 12.53 < 171.32^o ohm$$

Therefore, the stator current $|I_2^{'}| = 12.52 < -171.32^o A$

Similarly, the power factor $pF = \cos(\phi) = \cos(-171.32^o) = -0.989$ (where ϕ =-171.32)

From power triangle, we know that $S = P + jQ$ where S is the apparent power in VA, P is the real power in watts and Q is the reactive power in vars, and are equivalent to

Apparent power, $S = 3IV$ and real power $P = 3IV\cos\phi$ and reactive power $Q = \sqrt{S^2 - P^2} = 3IV\sin\phi$

The real power P = -4457.93W, then the voltage

$$V = \frac{P}{3I\cos\phi} = \frac{-4457.93}{3*12.52*\cos(-171.32)} = 120.06 < 0^o V$$

Similarly, the apparent power $S = \frac{P}{\cos\phi} = \frac{-4457.93}{\cos(-171.32)} = 4509.58 VA$ and

$$Q = \sqrt{4509.58^2 - 4457.93^2} = 680.57 Vars$$

The table below gives a summary of the measured and computed parameters for squirrel cage induction machine for $T_m = -20Nm$

Impedance	$12.53 < 171.32^o ohm$
Efficiency	89.25%
Real Power (watts)	4457.93 watts
Apparent power (VA)	4509.58 VA
Reactive power (Vars)	680.57 Vars
Phase angle	-171.32
Power Factor	-0.989
Stator Current	$\|I_2^{'}\| = 12.52 < -171.32^o A$
Input mechanical power	4995 Watts

Table: Induction machine measured and computed parameters for wind turbine $T_m = -30Nm$

Challenge

The push over torque can be calculated as $S_B = \frac{R_2^{'}}{X_r} = \frac{0.7091}{1.8912} = 0.37$ But the slip at $T_m = -20Nm$ was gotten to be -0.04, which implies that there is no push over. If there is a little increase in the slip value to an assumed value of say 0.06, then the value rotor resistance that will be added to maintain the output power is calculated below

$P = 3(I_2^{'})^2 R_{new}^{'} / s$ where $R_{new}^{'} = R_2^{'} + R_{add}$ Hence we have

$$R_{new}^{'} = \frac{P * s}{3*(I_2^{'})^2} = \frac{2858.86*0.06}{3*8.29^2} = 0.8319\Omega$$

$$\Rightarrow R_{add} = R_{new}^{'} - R_2^{'} = 0.8319 - 0.7091 = 0.1228\Omega$$

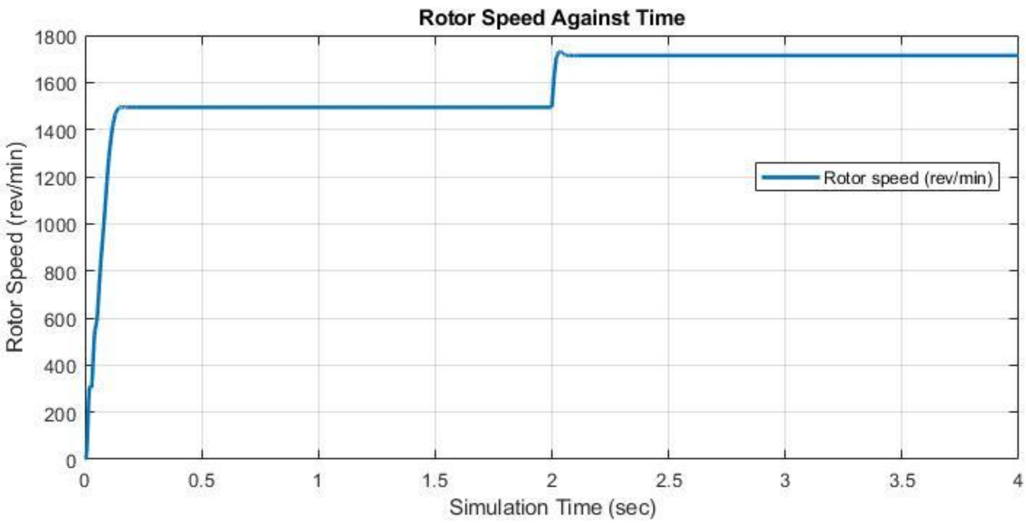


Figure 6a: Improved/smoothened rotor speed due to increased rotor resistance

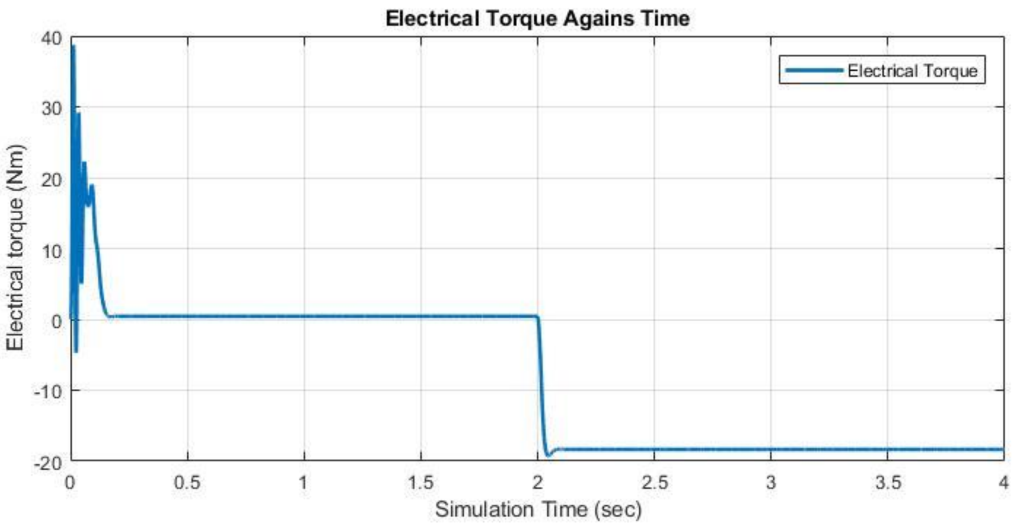


Figure 6b: Electrical torque for increased rotor resistance

Adding the additional rotor resistance produces a speed of 1580 rev/min and $T_e = -18.70Nm$ which in turn causes an output power close to $R_{new}^{'} = 1580 * \frac{2\pi}{60} * (-18.70) = -3094.05W$.

Comparing the calculated output power with the previous yields a 11.69% increase as shown

$$\text{\% increase in output power } = \frac{3094.05 - 2858.86}{2858.86} = 8.23\%$$

Comments on Simulation Method

The simulation method used is a one based on the Runge-Kutta 4th (RK4) order algorithm, it is a classical iterative computational technique available in getting the solution of ordinary differential equation (ODE). The precision of the RK4 method is based on the sampling time as smaller sampling time means improved result with a downside of increase simulation time. The RK4 method utilizes initial condition variables. When compared to the period the sampling time should be relatively small, this is because an increased sampling time leads to inaccurate result, which can also bring about damping and oscillation in the circuit.

Conclusion

In this work, the modelling and simulation of a wind turbine induction generator have been outlined in detail. The running and testing of the generator have been done in synchronous and in super synchronous speed, the machine parameters were also measured an evaluated. It was seen that when the mechanical input power is increased there is a corresponding increased in the in the rotor speed and the output power of the machine. Furthermore, it was observed that as the mechanical torque increases the peak-to-peak ripples reduces. Addition of rotor resistance and a scaled voltage provided a smoothening effect on the rotor speed transient response as indicated below.

References

[1] L. Zhang, ELEC5564: Power Generation by Renewable Source Laboratory Notes, Universiy of Leeds, 2017.

[2] H. S, Grid Integration of wind energy conversion systems 2nd edition, Chichester: Wiley, 2006.

Appendix

```
clear;
clc

%prompt and receives the total simulation time
sim_time=input('please enter total simulation time: ');

%declaration machine constants and parameters
Tm=-1; %maximum torque of machine in Nm
J=0.025284; %inertia of machine kg-m^2/s
B=0.005;    %machine friction in Nms
HP = 5; %machine rated power in Horse power (HP)
Pm= HP*746.15; %machine rated power in watts (3730.75W)
P=4;    %number of poles, thus, 2 pole pairs
Vm=230; %supply voltage in volts, 230
f=50;   %supply frequency in Hz
Rs=0.5673;  %stator resistance in ohms
Rr=0.7091;  %rotor resistance in ohms 0.7091
Lss=0.00301;    %stator leakage inductance in H
Lrr=Lss;    %rotor leakage inductance in H
Lm=0.075239;    %mutual inductance in H
Ls=Lss+Lm;  %stator self inductance in H
Lr=Lrr+Lm;  %rotor self inductance in H
a=1/((Ls*Lr)-(Lm^2));
Tp=1/f; %sampling period
ws=2*pi*f;  %synchronous speed
dt=0.0002;  %time step
rem=mod(Tp,dt); %get the remainder
simulation_period=round((Tp-rem)/dt);  %simulation period
sample_time=((simulation_period*sim_time)+1);  %sampling time
sim_time_array=(0:dt:(Tp*sim_time));    %array of total simulation time

%initialize variables and arrays
lqs=[1,sample_time];  %array of q-component of stator flux linkage
lds=[1,sample_time];  %array of d-component of stator flux linkage
lqr=[1,sample_time];  %array of q-component of rotor flux linkage
ldr=[1,sample_time];  %array of d-component of rotor flux linkage
rotor_speed=[1,sample_time];   %array
Va=[1,sample_time];   %array of stator voltage phase 1
Vb=[1,sample_time];   %array of stator voltage phase 2
Vc=[1,sample_time];   %array of stator voltage phase 3
Ia=[1,sample_time];   %array of stator current phase 1
Ib=[1,sample_time];   %array of stator current phase 2
Ic=[1,sample_time];   %array of stator current phase 3
Ia(1)=0;
Ib(1)=0;
Ic(1)=0;
Tem=[1,sample_time];  %electrical torque array
Tem(1)=0;
lqs(1)=0;
lds(1)=0;
lqr(1)=0;
ldr(1)=0;
rotor_speed(1)=0;

%Clarke's Transformation application%
Va(1)=Vm*sqrt(2)*cos(0)/sqrt(3);
Vb(1)=Vm*sqrt(2)*cos(-2*pi/3)/sqrt(3);
Vc(1)=Vm*sqrt(2)*cos(2*pi/3)/sqrt(3);
```

```
Vm=Vm*sqrt(2)/sqrt(3);
Te=0;
iqs=0;
ids=0;
iqr=0;
idr=0;
temp_var1=0;
rotor_fre=0;

for tm_s=1:sim_time  %for loop to evaluate the simulation period

    %Temporary storage of data%
    rTm=round(((tm_s-1)*simulation_period)+1);
    lqsinit=lqs(rTm);
    ldsinit=lds(rTm);
    lqrinit=lqr(rTm);
    ldrinit=ldr(rTm);
    asinit=rotor_speed(rTm);
    teinit=Tem(rTm);
    Lqs=zeros(1,simulation_period);
    Lds=zeros(1,simulation_period);
    Lqr=zeros(1,simulation_period);
    Ldr=zeros(1,simulation_period);
    As=zeros(1,simulation_period);
    tte=zeros(1,simulation_period);
    va=zeros(1,simulation_period);
    vb=zeros(1,simulation_period);
    vc=zeros(1,simulation_period);%phase voltages
    i1=zeros(1,simulation_period);
    i2=zeros(1,simulation_period);
    i3=zeros(1,simulation_period);%phase current
    Te=(3/2)*(P/2)*Lm*((iqs*idr)-(ids*iqr));%torque computation

    %pick the mechanical torque based on the value of the simulation time
inputted%
    if (tm_s<=100)
        Tm=-1;
        scale=1;
    elseif (tm_s>100 && tm_s<=200)
        Tm=-20;
        scale=1;
    elseif (tm_s>200)
        Tm=-30;
        scale=1;
    end

for i=1:simulation_period
    var_y=0;    %it is 1 for doubly fed machine
    Tst=i*dt;   %present simulation time

    if (abs(temp_var1-1500)<=5)
       rotor_fre=0;    %utilized for doubly fed
    else
       rotor_fre=50-(temp_var1/30);    %utilized for doubly fed
    end

    wr=2*pi*rotor_fre;  %evaluate the rotor frequency for doubly fed
machine
    temp_var2=((tm_s-1)*Tst);
```

```
    %transformation of the d-q vector component %
    vqs=scale*((2/3)*(Vm*cos(ws*Tst)))-((1/3)*(Vm*cos((ws*Tst)-(2*pi/3))))-
((1/3)*(Vm*cos((ws*Tst)+(2*pi/3))));
    vds=scale*-((sqrt(3)/3)*(Vm*cos((ws*Tst)-
(2*pi/3))))+((sqrt(3)/3)*(Vm*cos((ws*Tst)+(2*pi/3))));
    vqr=scale*((2/3)*(Vm*cos(wr*Tst)))-((1/3)*(Vm*cos((wr*Tst)-(2*pi/3))))-
((1/3)*(Vm*cos((wr*Tst)+(2*pi/3))));
    vdr=scale*-((sqrt(3)/3)*(Vm*cos((wr*Tst)-
(2*pi/3))))+((sqrt(3)/3)*(Vm*cos((wr*Tst)+(2*pi/3))));

    %Runge-Kutta RK4 starts%
     for j=1:4
       if j==1
           if i==1
          AS=asinit;     %initial rotor speed
          LQS=lqsinit;  %determination of stator q flux
          LDS=ldsinit;  %determination of stator d flux
          LQR=lqrinit;  %determination of rotor q flux
          LDR=ldrinit;  %determination of rotor d flux
           end
           if j>1
          AS=(As(i-1));
          LQS=(Lqs(i-1));
          LDS=(Lds(i-1));
          LQR=(Lqr(i-1));
          LDR=(Ldr(i-1));
           end

           %first update of RK4%
           rk1wr=(1/J)*2*(Te-Tm-(B*AS*2));
           rk1qs=(-(a*Rs*Lr)*LQS)+(a*Rs*Lm*LQR)+vqs;
           rk1ds=(-(a*Rs*Lr)*LDS)+(a*Rs*Lm*LDR)+vds;
           rk1qr=(a*Rr*Lm*LQS)+(-(a*Rr*Ls)*LQR)+(AS*2*LDR)+(var_y*vdr);
           rk1dr=(a*Rr*Lm*LDS)-(AS*2*LQR)-((a*Rr*Ls)*LDR)+(var_y*vqr);

           %second update of RK4%
       elseif j==2
           if i==1
           AS=asinit+(rk1wr*(dt/2));
           LQS=lqsinit+(rk1qs*(dt/2));
           LDS=ldsinit+(rk1ds*(dt/2));
           LQR=lqrinit+(rk1qr*(dt/2));
           LDR=ldrinit+(rk1dr*(dt/2));
           end
           if i>1
           AS=As(i-1)+(rk1wr*(dt/2));
           LQS=Lqs(i-1)+(rk1qs*(dt/2));
           LDS=Lds(i-1)+(rk1ds*(dt/2));
           LQR=Lqr(i-1)+(rk1qr*(dt/2));
           LDR=Ldr(i-1)+(rk1dr*(dt/2));
           end
           rk2wr=(1/J)*2*(Te-Tm-(B*AS*2));
           rk2qs=(-(a*Rs*Lr)*LQS)+(a*Rs*Lm*LQR)+vqs;
           rk2ds=(-(a*Rs*Lr)*LDS)+(a*Rs*Lm*LDR)+vds;
           rk2qr=(a*Rr*Lm*LQS)+(-(a*Rr*Ls)*LQR)+(AS*2*LDR)+(var_y*vdr);
           rk2dr=(a*Rr*Lm*LDS)-(AS*2*LQR)-((a*Rr*Ls)*LDR)+(var_y*vqr);

           %third update of RK4%
       elseif j==3
           if i==1
```

```
        AS=asinit+(rk2wr*(dt/2));
        LQS=lqsinit+(rk1qs*(dt/2));
        LDS=ldsinit+(rk1ds*(dt/2));
        LQR=lqrinit+(rk1qr*(dt/2));
        LDR=ldrinit+(rk1dr*(dt/2));
        end
        if i>1
        AS=As(i-1)+(rk2wr*(dt/2));
        LQS=Lqs(i-1)+(rk2qs*(dt/2));
        LDS=Lds(i-1)+(rk2ds*(dt/2));
        LQR=Lqr(i-1)+(rk2qr*(dt/2));
        LDR=Ldr(i-1)+(rk2dr*(dt/2));
        end
        rk3wr=(1/J)*2*(Te-Tm-(B*AS*2));
        rk3qs=(-(a*Rs*Lr)*LQS)+(a*Rs*Lm*LQR)+vqs;
        rk3ds=(-(a*Rs*Lr)*LDS)+(a*Rs*Lm*LDR)+vds;
        rk3qr=(a*Rr*Lm*LQS)+(-(a*Rr*Ls)*LQR)+(AS*2*LDR)+(var_y*vdr);
        rk3dr=(a*Rr*Lm*LDS)-(AS*2*LQR)-((a*Rr*Ls)*LDR)+(var_y*vqr);

        %fourth update of RK-4%
    elseif j==4
        if i==1
        AS=asinit+(rk3wr*dt);
        LQS=lqsinit+(rk3qs*dt);
        LDS=ldsinit+(rk3ds*dt);
        LQR=lqrinit+(rk3qr*dt);
        LDR=ldrinit+(rk3dr*dt);
        end
        if i>1
        AS=As(i-1)+(rk3wr*dt);
        LQS=Lqs(i-1)+(rk3qs*dt);
        LDS=Lds(i-1)+(rk3ds*dt);
        LQR=Lqr(i-1)+(rk3qr*dt);
        LDR=Ldr(i-1)+(rk3dr*dt);
        end
        rk4wr=(1/J)*2*(Te-Tm-(B*AS));
        rk4qs=(-(a*Rs*Lr)*LQS)+(a*Rs*Lm*LQR)+vqs;
        rk4ds=(-(a*Rs*Lr)*LDS)+(a*Rs*Lm*LDR)+vds;
        rk4qr=(a*Rr*Lm*LQS)+(-(a*Rr*Ls)*LQR)+(AS*2*LDR)+(var_y*vdr);
        rk4dr=(a*Rr*Lm*LDS)-(AS*2*LQR)-((a*Rr*Ls)*LDR)+(var_y*vqr);
    end %end of if condition
  end %end of for loop j

 %Runge-Kutta 4-summation %
 if i==1
 As(i)=asinit+((dt/6)*(rk1wr+(2*rk2wr)+(2*rk3wr)+rk4wr));
 Lqs(i)=lqsinit+((dt/6)*(rk1qs+(2*rk2qs)+(2*rk3qs)+rk4qs));
 Lds(i)=ldsinit+((dt/6)*(rk1ds+(2*rk2ds)+(2*rk3ds)+rk4ds));
 Lqr(i)=lqrinit+((dt/6)*(rk1qr+(2*rk2qr)+(2*rk3qr)+rk4qr));
 Ldr(i)=ldrinit+((dt/6)*(rk1dr+(2*rk2dr)+(2*rk3dr)+rk4dr));
 end
 if i>1
 As(i)=As(i-1)+((dt/6)*(rk1wr+(2*rk2wr)+(2*rk3wr)+rk4wr));
 Lqs(i)=Lqs(i-1)+((dt/6)*(rk1qs+(2*rk2qs)+(2*rk3qs)+rk4qs));
 Lds(i)=Lds(i-1)+((dt/6)*(rk1ds+(2*rk2ds)+(2*rk3ds)+rk4ds));
 Lqr(i)=Lqr(i-1)+((dt/6)*(rk1qr+(2*rk2qr)+(2*rk3qr)+rk4qr));
 Ldr(i)=Ldr(i-1)+((dt/6)*(rk1dr+(2*rk2dr)+(2*rk3dr)+rk4dr));
 end

 %Evaluate rotor and stator d-q current values%
 iqs=a*((Lr*Lqs(i))-(Lm*Lqr(i)));
```

```
    iqr=a*((Ls*Lqr(i))-(Lm*Lqs(i)));
    ids=a*((Lr*Lds(i))-(Lm*Ldr(i)));
    idr=a*((Ls*Ldr(i))-(Lm*Lds(i)));

    Te=(3/2)*(P/2)*Lm*((iqs*idr)-(ids*iqr));    %evaluate the electrical
torque
    tte(i)=Te;  %update the electrical torque matrix

    %Applying Inverse Clarke's Transormation%
    va(i)=vqs;vb(i)=(-0.5*vqs)+((-sqrt(3)/2)*vds);
    vc(i)=(-0.5*vqs)+((sqrt(3)/2)*vds);
    i1(i)=ids;
    i2(i)=(-0.5*ids)+((sqrt(3)/2)*iqs);
    i3(i)=(0.5*ids)+((-sqrt(3)/2)*iqs);
    temp_var1=As(i);
end %end of simulation period

for k=1:simulation_period %for loop to update matrices
     rotor_speed(1+((tm_s-1)*simulation_period)+k)=As(k);    %update rotor
speed matrix
     lqs(1+((tm_s-1)*simulation_period)+k)=Lqs(k);   %update stator q flux
matrix
     lds(1+((tm_s-1)*simulation_period)+k)=Lds(k);   %update stator d flux
matrix
     lqr(1+((tm_s-1)*simulation_period)+k)=Lqr(k);   %update rotor q flux
matrix
     ldr(1+((tm_s-1)*simulation_period)+k)=Ldr(k);   %update rotor d flux
matrix
     Tem(1+((tm_s-1)*simulation_period)+k)=tte(k);   %update electric
torque matrix
     Ia(1+((tm_s-1)*simulation_period)+k)=i1(k); %update phase 1 current
matrix
     Ib(1+((tm_s-1)*simulation_period)+k)=i2(k); %update phase 2 current
matrix
     Ic(1+((tm_s-1)*simulation_period)+k)=i3(k); %update phase 3 current
matrix
     Va(1+((tm_s-1)*simulation_period)+k)=va(k); %update phase 1 voltage
matrix
     Vb(1+((tm_s-1)*simulation_period)+k)=vb(k); %update phase 2 voltage
matrix
     Vc(1+((tm_s-1)*simulation_period)+k)=vc(k); %update phase 3 voltage
matrix
end %end of k for loop
end %end of total simulation time

for i=1:length(rotor_speed) %for loop to convert rotor speed to rpm
   rotor_speed(i)=(rotor_speed(i))*(30/pi); %convert rotor speed to rpm
end %end of loop

%Plots of results%
figure(1)
plot(sim_time_array,Ia,sim_time_array,Ib,sim_time_array,Ic);
xlabel('Simulation Time (sec)');
ylabel('Phase Current (A)');
legend('Phase 1 Current (A)','Phase 2 Current (A)','Phase 3 Current (A)');
title('Phase Currents Against Time')
grid on

figure(2)
plot(sim_time_array,rotor_speed,'linewidth',2);
```

```
xlabel('Simulation Time (sec)');
ylabel('Rotor Speed (rev/min)');
legend('Rotor speed (rev/min)');
title('Rotor Speed Against Time');
grid on

figure(3)
plot(sim_time_array,lqs,sim_time_array,lds,sim_time_array,lqr,sim_time_arra
y,ldr);
xlabel('Simulation Time (sec)');
ylabel('Flux-linkages (A/S)');
legend('stator-q flux linkage','stator-d flux linkage','rotor-q flux
linkage','rotor-d flux linkage');
title('Flux Linkages Aganist Time')
grid on

figure (4)
plot(sim_time_array,Tem,'linewidth',2);
xlabel('Simulation Time (sec)');
ylabel('Electrical torque (Nm)');
legend('Electrical Torque');
title('Electrical Torque Agains Time')
grid on

figure(5)
plot(sim_time_array,Va,sim_time_array,Vb,sim_time_array,Vc)
xlabel('Simulation Time (sec)');
ylabel('Phase Voltage (V)');
legend('Phase 1 Voltage (V)','Phase 2 Voltage (V)','Phase 3 Voltage (V)');
title('Phase Voltages against Time')
grid on

figure(6)
plot(sim_time_array,Va,sim_time_array,Ia,'linewidth',2)
xlabel('Simulation Time (sec)');
ylabel('Phase 1 voltage and current');
title('Phase 1 Voltage and Current Against Time')
```