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MODELING AND SIMULATION OF ENGINE DRIVEN INDUCTION GENERATOR USING HUNTING NETWORK METHOD

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ABSTRACT

This paper presents hunting network method to analyze the behavior of poly-phase induction machine under the influence of a periodic pulsating torque. The differential equation, which describes the dynamic behavior of induction machine, is nonlinear and until the advent of mechanical differential analyzer in the early 1940's, it was not feasible to solve these equations. Now solution of these equations is common place using either digital or analog computers. In this paper digital simulation of induction machine dynamics using MATLAB package is analyzed. The calculation method is outlined to predict the current, power and torque pulsation along with power factor and slip. While considering induction generator driven by a diesel engine, a large error can occur in the prediction of current, power and torque pulsation if the induction generator steady state characteristics are used in the analytical solution. A numerical solution in which the induction generator is analyzed by using hunting network method.

Keywords: model, induction generator, hunting network, pulsation, synchronizing, damping, torque, harmonic frequency.

1. INTRODUCTION

In recent years considerable attention is focused on induction generators for low and medium power generation. Induction Generators are increasingly being considered for autonomous applications in micro-hydro, bio-gas, wave and wind power systems. Its low unit cost, less maintenance, rugged, brushless cage rotor construction, asynchronous operation, absence of a separate dc source, better transient performance and inherent over load protection are its main advantages over the conventional alternators. The energy crisis has necessitated the tapping of the vast mini-hydro and wind energy potential available in isolated locations. Since these generating units have to operate at remote unattended sites, a maintenance free system is desirable and the induction generator is highly suitable in such cases. Sudden load disturbance causes wide fluctuations in stator and rotor current as well as torque of the machine. The electrical transients are of very short duration as compared to the motional transients. Keeping this in view computers are widely used to analyze the behavior of the machine for the above conditions [1]. Before modeling a system, one must be clear as to which model out of a variety of models should be selected, since one model may be more accurate or simpler or superior to another from the point of system design or optimization. In this paper, hunting network method for analyzing the dynamics of a grid connected symmetrical induction machine working on a balanced three phase supply and subjected to a periodically pulsating shaft torque is considered. An example of such a system is an induction motor driving a reciprocating compressor or a diesel engine driving an induction generator. The software used for the simulation is the MATLAB package and a diesel engine driving an induction generator is taken and analyzed using the hunting network method.

2. THE HUNTING NETWORK MODEL

Steady state equivalent circuit method has been widely used to analyze the operation of induction machines and quite familiar, very few references describe the use of the hunting network method. Riches (1961) developed a method of calculating the flywheel inertia required in a given induction motor driving a reciprocating compressor in order to keep the current pulsations within desired limits. This was adopted by Beama, uses the motor steady-state damping torque coefficient in the analytical solution. This solution refined by the introduction of the motor steady-state running torque/current characteristic to finally relate motor torque to current pulsation, be referred to as the 'steady-state' solution.

When subjected to a forced-slip oscillation, which occurs with a reciprocating compressor drive, an induction motor will exhibit a synchronizing capability, and a lower than steady-state damping torque. The coefficients for this torques can be obtained from the hunting equivalent circuits developed by Kron. That an induction motor can develop a synchronizing torque, and hence be capable, like the synchronous motor, of having a condition of resonance, is undoubtedly the most important feature missing from the 'steady-state' solution.

Riches neglected the synchronizing torque and considered only the damping torque [6]. Concordia (1952) showed that for an induction motor, when speed oscillations are imposed upon the rotor, the damping torque is markedly reduced, and additionally, a restoring or synchronizing torque will result. The analysis described by Riches is valid only for very low pulsation frequencies. He used the basic steady state and hunting networks developed by Kron (1959) as the starting point [5].

Bapat (1970) analyzed the hunting nature of an induction motor when driving a reciprocating compressor by linearising the transfer functions. It is shown that the

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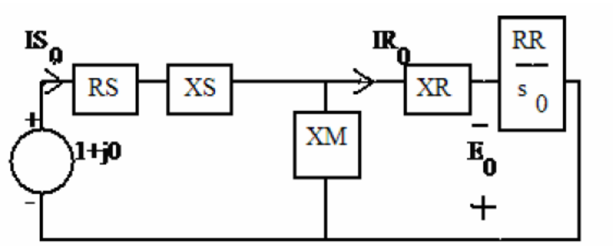
electrical torque developed by an induction motor has two components, the damping torque and the synchronizing torque .At first he neglected the effect of the stator resistance, and limited the investigation to small oscillation, these two characteristic torques are functions of the mean relative slip and hunting frequency and developed the expressions for the frequency responses of the slip, torque and current fluctuation. He showed the effect of the stator resistance on the damping and synchronizing torques and on the frequency response [5]. The influence of a periodic pulsating torque variation on a poly phase induction motor is described. A calculation method is outlined to predict the current, power and torque pulsation along with the effect on power factor, slip and efficiency. The calculation method is an extension of the method developed by Helberg for synchronous motors utilizing the steady state and hunting frequency networks from [4] to calculate the damping torque T_d and synchronizing torque T_s as a function of the per unit pulsation frequency *h*. The torque pulsation is determined by a modification and the current pulsation is determined by combining the hunting component of current with the steady state current. Current pulsation also estimated by assuming that the magnetizing component of current is constant and the load component of current pulsates in proportion to the power pulsation.

Cummings (1978) [5] developed a method to calculate the damping torque and synchronizing torque as a function of the per unit hunting frequency and hence the expected power and current pulsations for an induction motor driving a reciprocating compressor, utilizing the steady state and hunting networks from Concordia (1952). But he assumed that the shaft torque completes one cycle per rotation of the shaft. The procedure he has taken by utilizing these steady state and hunting networks is to calculate the synchronizing and damping torque coefficients of the motor for the per unit pulsation frequencies corresponding to the Fourier series representing the torque curve of the compressor. The per unit pulsation frequencies (h_n) are n X r/min/60 X f, where n is the order of the harmonic, i.e., 1,2,3,4 and f equals power supply frequency. The motor r/min (and hence the slip s, which appears in the resistance and voltage of the networks) should correspond to the average torque of the compressor under the load condition for which the current pulsation is being calculated.

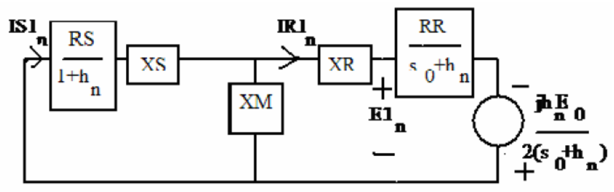
From the torque-angle curve (or crank-effort diagram) of the compressor, calculating the amplitude and phase angle (with any chosen angular position of the crank shaft as a reference) for n harmonics of the Fourier series that will adequately represent the torque-angle curve. The amplitudes of the harmonics are expressed in "per unit" of the average torque. The phase angles are the displacements of the harmonic represents 360^0. From the magnitude and phase angle of each of the torque harmonics of the compressor, the corresponding values of synchronizing torque and damping torque.

The hunting network method accounts for the effect of electrical transients. But it is a frequency domain simulation method. This method can be applied only when the shaft torque is periodic and it gives solution only for the period after the initial transients have died down and a steady state has been attained. It enables the instantaneous values of current, power, power factor and slip to be calculated for one complete cycle of shaft torque variation. It requires knowledge of the shaft torque harmonics. The hunting network method is implemented through the corresponding steady state and hunting network equivalent circuit representation [2] of the induction machine shown in Figure-1.

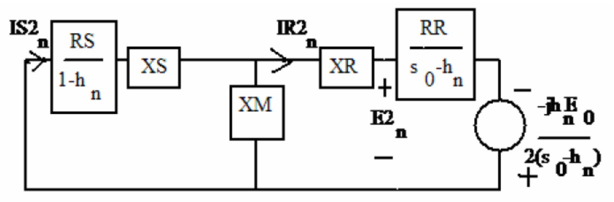
The hunting equation is given in equation 2. The algorithm for applying the hunting network method to an induction generator is described in Table-3.



Steady state and hunting network.



Positive frequency hunting network.



Negative frequency hunting network.

Figure-1. Hunting equivalent circuit for balanced operation of a symmetrical grid connected induction generator.

3. DERIVATIONS OF EQUATIONS FOR CALCULATION OF INDUCTION MACHINE TORQUE, POWER, CURRENT AND SLIP VARIATIONS

Note that generator convention is used in the nomenclature, and this is made clear by using italics where appropriate. This was done to make it easy to apply the hunting network methodology to generator analysis. The prime mover shaft torque can be represented by a Fourier series as

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$$TT(\theta) = TT_0 + \sum_{n=1}^{NMAX} |TT_n| \cos(n\theta + \angle TT_n) \qquad .1$$

The oscillation of the rotor produced by the n^{th} harmonic shaft torque gives rise to inertia and electrical torques which may be equated to the shaft torque to give.

$$J\frac{d^2\delta_n}{dt^2} + Td_n\frac{d\delta_n}{dt} + Ts_n\delta_n = TT(\theta) \qquad ... 2$$

The first term on the left hand side is the inertia torque and the remaining two terms adds up to the generator torque which opposes the shaft torque. The synchronizing and damping torque coefficients may be calculated using the following formulae derived from Concordia (1952):

$$Ts_n = \mathrm{Re}(IR_0(E1_n + E2_n)^* + (IR1_n + IR2_n)E_0^*) \qquad ... 3$$

$$Td_n = \mathrm{Im}(IR_0(E2_n - \dot{E}1_n)^* + (IR1_n - IR2_n)E_0^*)/h_n$$

The steady-state solution of equation (2) is

$$\delta_n(\theta) = |\delta_n| \cos(n\theta + \angle\delta_n)$$

where

$$|\delta_n| = \frac{|TT_n|}{Ts_n\sqrt{X_n^2 + Y_n^2}}, \quad \angle\delta_n = \angle TT_n + \tan^{-1}\frac{Y_n}{X_n}, \qquad ... 4$$

$$X_n = \frac{h_n^2 J}{Ts_n} - 1 \quad and \quad Y_n = \frac{h_n Td_n}{Ts_n}. \qquad ... 5$$

The total rotor displacement is obtained by adding all the harmonics with an average displacement (of zero) to give

$$\delta(\theta) = 0 + \sum_{n=1}^{NMAX} \delta_n(\theta) \qquad ... 6$$

The electrical torque developed by the generator for each value of n is given by

$$TG_n = Td_n\frac{d\delta_n}{dt} + Ts_n\delta_n = |TG_n|\cos(n\theta + \angle TG_n) \qquad ... 7$$

where

$$|TG_n| = Ts_n\sqrt{1 + Y_n^2}|\delta_n| \quad and \quad \angle TG_n = \angle\delta_n + \tan^{-1}Y_n$$

The total generator torque is

$$TG(\theta) = TT_0 - TL + \sum_{n=1}^{NMAX} TG_n(\theta) \qquad ... 8$$

The nth harmonic slip can be related to the nth harmonic rotor displacement by

$$s_n(\theta) = \frac{-1}{\omega_s}\frac{d\delta_n}{dt} = |s_n|\cos(n\theta + \angle s_n) \quad where \qquad ... 9$$

$$|s_n| = h_n|\delta_n|, \quad \angle s_n = \angle\delta_n + \frac{\pi}{2},$$

$$and \quad h_n = \frac{-n}{\omega_s}\frac{d\theta}{dt} = \frac{n}{\omega_s}\frac{d(\omega_T t)}{dt} = \frac{n\omega_T}{\omega_s} = \frac{nf_T}{f}$$

is the nth harmonic hunting frequency.

Hence total slip is

$$s(\theta) = s_0 + \sum_{n=1}^{NMAX} s_n(\theta) \qquad ... 10$$

The nth harmonic stator current is found as follows

$$\begin{aligned} IS_n &= \delta_n(IS1_n + jIS2_n) \\ &= \delta_n[(\sqrt{SR_n^2 + DI_n^2}\cos(n\theta + \tan^{-1}\frac{DI}{SR}) + \\ &\quad j(\sqrt{SI_n^2 + DR_n^2}\cos(n\theta - \tan^{-1}\frac{DR}{SI})] \\ &= Re(IS_n) + j\,Im(IS_n) \end{aligned} \qquad ... 11$$

where

$$\begin{aligned} SR_n &= \mathrm{Re}(IS1_n) + \mathrm{Re}(IS2_n) \\ DR_n &= \mathrm{Re}(IS1_n) - \mathrm{Re}(IS2_n) \\ SI_n &= \mathrm{Im}(IS1_n) + \mathrm{Im}(IS2_n) \\ DI_n &= \mathrm{Im}(IS1_n) - \mathrm{Im}(IS2_n) \end{aligned} \qquad ... 12$$

Here the currents obtained from the hunting networks have been multiplied by rotor displacement since those currents are for rotor displacement of one radian.

The nth harmonic real and reactive stator currents are given by

$$Re(IS_n(\theta)) = |Re(IS_n)|\cos(n\theta + \angle Re(IS_n)) \quad where$$
$$|Re(IS_n)| = \sqrt{SR_n^2 + DI_n^2}\,|\delta_n|, \qquad \angle Re(IS_n) = \angle\delta_n + \tan^{-1}\frac{DI}{SR} \qquad 13$$
$$Im(IS_n(\theta)) = |Im(IS_n)|\cos(n\theta + \angle Im(IS_n)) \quad where$$
$$|Im(IS_n)| = \sqrt{SI_n^2 + DR_n^2}\,|\delta_n|, \qquad \angle Im(IS_n) = \angle\delta_n - \tan^{-1}\frac{DR}{SI}$$

The real power fed to the grid and the lagging reactive power drawn from the grid are given by

$$P(\theta) = Re(IS(\theta)) = Re(IS_0) + \sum_{n=1}^{NMAX} -Re(IS_n(\theta)) \qquad 14$$
$$Q(\theta) = Im(IS(\theta)) = Im(IS_0) + \sum_{n=1}^{NMAX} Im(IS_n(\theta))$$

The total stator current magnitude and the power factor are given by

$$|IS(\theta)| = \sqrt{[Re(IS(\theta))]^2 + [Im(IS(\theta))]^2} \qquad 15$$
$$pf(\theta) = \frac{Re(IS(\theta))}{|IS(\theta)|}$$

4. ALGORITHM FOR ANALYSIS OF INDUCTION GENERATOR

Convert machine steady state and hunting networks, moment of inertia J and shaft torque TT(t) into per unit using base values given in Table-3.
From the crank angle diagram giving TT(θ), obtain the average value TT_0 and a sufficient number of harmonic components TT_n, n = 1..NMAX by Fourier analysis.
From the steady state equivalent circuit and TT_0, find the average slip s_0 by iteration and the corresponding steady state complex currents IS_0 and IR_0 and emf E_0.
For each value of n from 1 to NMAX, carry out steps A through C indicated below:
Step A: Define per unit nth harmonic hunting frequency as $h_n = n*f_s/f = 2n/p*(1-s0)$.
Step B: For this h_n, using s0, IS_0, IR_0 and E_0, and the hunting networks, calculate nth harmonic damping- and synchronizing- torque coefficients. Td_n and Ts_n from Eq (3).
Combine the average of each quantity, viz. TG0 = TT0 - TL, s0, Re(IS0) and Im(IS0) with its harmonics to get TT(θ), s(θ), Re(IS(θ)) and Im(IS(θ)). See Eq. (8), (10) and (14).
Calculate real power P(θ), reactive power Q(θ), stator current magnitude *IS*(θ) and power factor pf(θ) using Eq. (14) and (15).
Express the quantities calculated above as functions of time(t) by replacing θ by 2πfst. Reconvert them to their physical units by multiplying with their respective base values from Table-3.

5. INTERRELATIONS AMONG HARMONICS OF VARIOUS QUANTITIES

The relationships among the magnitudes and phase angles of the nth harmonic components of pertinent quantities are shown in Tables 1 and 2, respectively. Note that these tables can be used to obtain the harmonic components of all other quantities, given the harmonic components of any one quantity. Table-1 shows for example that the magnitude of the nth harmonic slip can be obtained by multiplying the magnitude of the nth harmonic shaft torque by

$$\frac{-J.h_n^2}{Ts_n\sqrt{X_n^2 + Y_n^2}}.$$

Similarly Table-2 shows that the phase angle of the nth harmonic slip can be obtained by adding

$$\tan^{-1}\frac{Y_n}{X_n} + \frac{\pi}{2}$$

to the nth harmonic phase angle of the shaft torque.

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Table-1. Relationships among magnitudes of the nth harmonic components.

	$\lvert TT_n \rvert$	$\lvert TG_n \rvert$	$\lvert s_n \rvert$	$\lvert Re(IS_n) \rvert$	$\lvert Im(IS_n) \rvert$
$\lvert TT_n \rvert$	1	$\sqrt{\frac{X_n^2+Y_n^2}{1+Y_n^2}}$	$\frac{Ts_n\sqrt{X_n^2+Y_n^2}}{h_n}$	$\frac{Ts_n\sqrt{X_n^2+Y_n^2}}{\sqrt{SR_n^2+DI_n^2}}$	$\frac{Ts_n\sqrt{X_n^2+Y_n^2}}{\sqrt{SI_n^2+DR_n^2}}$
$\lvert TG_n \rvert$	$\sqrt{\frac{1+Y_n^2}{X_n^2+Y_n^2}}$	1	$\frac{Ts_n\sqrt{1+Y_n^2}}{h_n}$	$\frac{Ts_n\sqrt{1+Y_n^2}}{\sqrt{SR_n^2+DI_n^2}}$	$\frac{Ts_n\sqrt{1+Y_n^2}}{\sqrt{SI_n^2+DR_n^2}}$
$\lvert s_n \rvert$	$\frac{h_n}{Ts_n\sqrt{X_n^2+Y_n^2}}$	$\frac{h_n}{Ts_n\sqrt{1+Y_n^2}}$	1	$\frac{h_n}{\sqrt{SR_n^2+DI_n^2}}$	$\frac{h_n}{\sqrt{SI_n^2+DR_n^2}}$
$\lvert Re(IS_n) \rvert$	$\frac{\sqrt{SR_n^2+DI_n^2}}{Ts_n\sqrt{X_n^2+Y_n^2}}$	$\frac{\sqrt{SR_n^2+DI_n^2}}{Ts_n\sqrt{1+Y_n^2}}$	$\frac{\sqrt{SR_n^2+DI_n^2}}{h_n}$	1	$\sqrt{\frac{SR_n^2+DI_n^2}{SI_n^2+DR_n^2}}$
$\lvert Im(IS_n) \rvert$	$\frac{\sqrt{SI_n^2+DR_n^2}}{Ts_n\sqrt{X_n^2+Y_n^2}}$	$\frac{\sqrt{SI_n^2+DR_n^2}}{Ts_n\sqrt{1+Y_n^2}}$	$\frac{\sqrt{SI_n^2+DR_n^2}}{h_n}$	$\sqrt{\frac{SI_n^2+DR_n^2}{SR_n^2+DI_n^2}}$	1

Table-2. Relationships among phases of the nth harmonic components.

	$\angle TT_n$	$\angle TG_n$	$\angle s_n$	$\angle Re(IS_n)$	$\angle Im(IS_n)$
$\angle TT_n$	0	$-\tan^{-1}\frac{Y_n}{X_n}-\tan^{-1}Y_n$	$-\tan^{-1}\frac{Y_n}{X_n}-\frac{\pi}{2}$	$-\tan^{-1}\frac{Y_n}{X_n}-\tan^{-1}\frac{DI_n}{SR_n}$	$-\tan^{-1}\frac{Y_n}{X_n}+\tan^{-1}\frac{DR_n}{SI_n}$
$\angle TG_n$	$\tan^{-1}\frac{Y_n}{X_n}+\tan^{-1}Y_n$	0	$\tan^{-1}Y_n-\frac{\pi}{2}$	$\tan^{-1}Y_n-\tan^{-1}\frac{DI_n}{SR_n}$	$\tan^{-1}Y_n+\tan^{-1}\frac{DR_n}{SI_n}$
$\angle s_n$	$\tan^{-1}\frac{Y_n}{X_n}+\frac{\pi}{2}$	$-\tan^{-1}Y_n+\frac{\pi}{2}$	0	$-\tan^{-1}\frac{DI_n}{SR_n}+\frac{\pi}{2}$	$\tan^{-1}\frac{DR_n}{SI_n}+\frac{\pi}{2}$
$\angle Re(IS_n)$	$\tan^{-1}\frac{Y_n}{X_n}+\tan^{-1}\frac{DI_n}{SR_n}$	$-\tan^{-1}Y_n+\tan^{-1}\frac{DI_n}{SR_n}$	$\tan^{-1}\frac{DI_n}{SR_n}-\frac{\pi}{2}$	0	$\tan^{-1}\frac{DI_n}{SR_n}+\tan^{-1}\frac{DR_n}{SI_n}$
$\angle Im(IS_n)$	$\tan^{-1}\frac{Y_n}{X_n}-\tan^{-1}\frac{DR_n}{SI_n}$	$-\tan^{-1}Y_n-\tan^{-1}\frac{DR_n}{SI_n}$	$-\tan^{-1}\frac{DR_n}{SI_n}-\frac{\pi}{2}$	$-\tan^{-1}\frac{DI_n}{SR_n}-\tan^{-1}\frac{DR_n}{SI_n}$	0

6. SYSTEM CONSIDERED FOR MODELING AND SIMULATION

Details of induction generator driven by diesel engine

To analyze the behavior of poly phase Induction machine under the influence of periodic torque, a 3 phase 200 hp induction generator driven by a diesel engine is considered. The crank angle diagram, i.e. shaft torque vs. angular shaft position in mechanical degrees for one cycle of operation of the diesel engine is shown in Figure-2. The torque has been expressed in the per unit system.

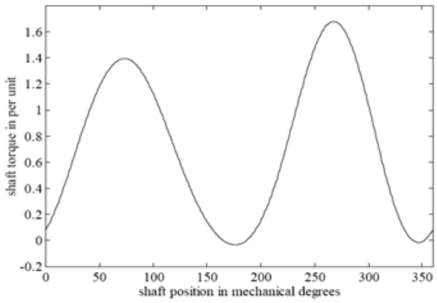

Figure-2. Crank angle diagram of diesel engine.

In order to describe the crank angle curve in software, the following method is employed: Since the curve is irregular but periodic, it is convenient to perform Fourier analysis on it and express it as the sum of an average component and a sufficient number of harmonic components having both magnitudes and phase angles. In the present example, four harmonics are considered sufficient since the magnitudes of the higher order harmonics are found to be negligible compared to that of the first four. The shaft torque harmonics obtained through Fourier analysis of the above curve are as follows:

Shaft torque harmonics obtained though Fourier analysis:

Average, t0 = 2759.7 Nm
Magnitude of fundamental, t1 = 496.4 Nm
Magnitude of second harmonic, t2 = 2907.2 Nm
Magnitude of third harmonic, t3 = 543.8 Nm
Magnitude of fourth harmonic, t4 = 114.7 Nm
Phase angle of fundamental, a1 = 0.537 mech. rad.
Phase angle of second harmonic, a2 = -2.839 mech. rad.
Phase angle of third harmonic, a3 = -1.983 mech. rad.
Phase angle of fourth harmonic, a4 = -0.0175 mech. rad.

Induction generator parameters

Number of poles, p = 14
Stator resistance per phase, rs = 0.054 Ω
Rotor resistance per phase wrt stator, rr = 0.031 Ω
Stator leakage inductance, ls = 0.0051 H
Rotor leakage inductance wrt stator, lr = 0.0057 H
Mutual inductance, lm = 0.005 H
Rated line current, irated = 258 A
Rated phase voltage, vrated = 265.6 V
The operating conditions are:
Supply frequency, f = 60 Hz
Moment of inertia of the system, j = 22.67 kgm^2

Per Unit System

It is often convenient to express machine parameters and variables as per unit quantities. If, on the other hand, the machine is a part of a power system and if it is desirable to convert entire system to per unit quantities, then only one power base (VA base) is selected which would most likely be different from the rating of any machine in the system. Here, we considered the machine separately with the rating of the machine taken as

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base power. The base values used for conversion to and from the per unit system are calculated from expressions given in Table-3.

Table-3. Choice of base values.

Quantity	Base value	Symbol	Unit
Real power	Rated 3 phaseVA	PB	W
Reactive power	Rated 3 phase VA	PB	VA
Voltage	Rated phase voltage	VB	V
Current	PB/(3VB)	IB	A
Impedance	VB/IB	ZB	Ω
Mech. ang. velocity	4πf/p	ωB	rad/s
Torque	PB/ωB	TB	Nm
Moment of inertia	(2/p)TB/(ωB)2	JB	kgm^2

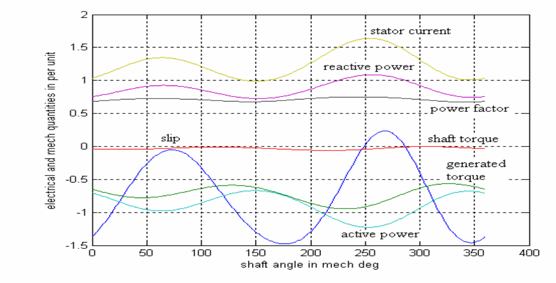
After considering the base values any quantity can be converted into per unit by the relation Per Unit quantity = Actual quantity / Base quantity in the same unit.

7. SIMULATION RESULTS

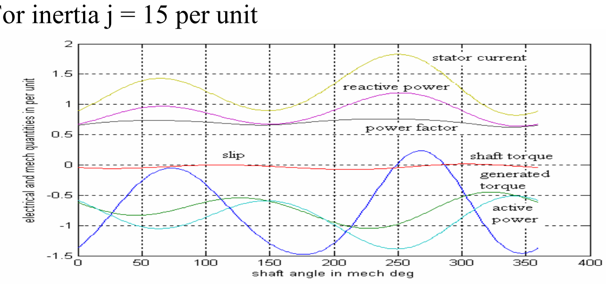
Average torque = -0.97176, tt0 = -0.723 and slip (s0) = -0.03 per unit.

Predicted steady state dynamic performance of an induction generator though hunting network method for different values of inertia

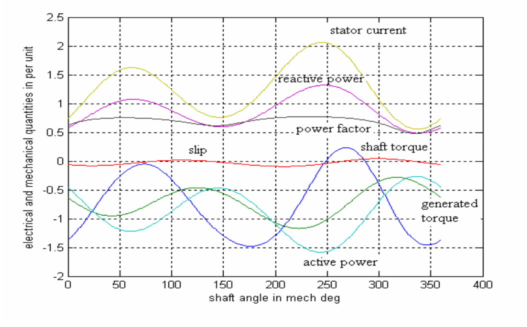
For inertia j = 22.57 pu unit



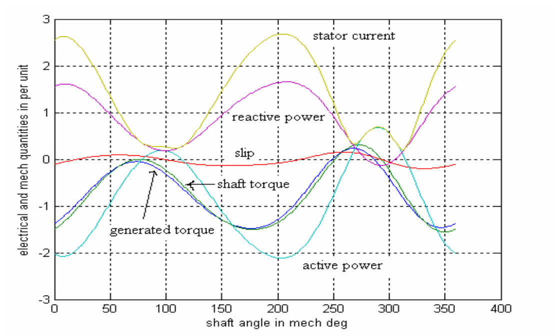
For inertia j = 15 per unit



For inertia j = 10 per unit

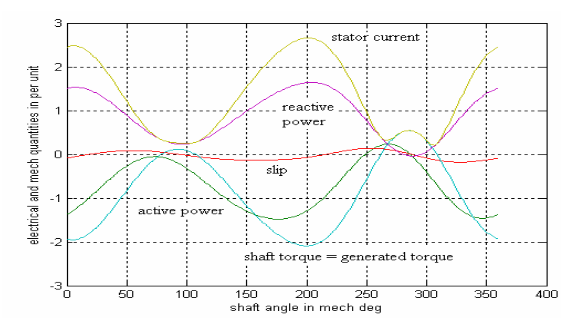


For inertia j = 0.5 per unit



With the reduction in inertia the loss due to the parameter j is negligible; hence the generating torque and shaft torque are almost equal.

For inertia j = 0



8. CONCLUSIONS

The hunting network method accounts for the effect of electrical transient. But it is a frequency domain method. This method can be applied only when the shaft torque is periodic and it gives solution only for period after the initial transients has died down and a steady state has been attained. It enables the instantaneous values of current, power factor and slip to be calculated for one complete cycle of shaft torque variation. It requires knowledge of shaft torque harmonics. It has the advantages of yielding explicit algebraic expressions, and avoiding differential equations by bypassing the initial transient state. Hence it results in much faster simulation method.

For the diesel engine driven an induction generator the steady state equivalent circuit method is not adequate to predict the steady state dynamics. Hence the hunting network method is used. The merit of the hunting

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network lies in the fact that it yields explicit algebraic expressions and gives solution for the steady state operation without going through the transient stage, resulting in much faster simulation.

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