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Power Flow and Stability Models for Induction Generators Used in Wind Turbines

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Abstract -- **Model initialization of the induction generator for wind power generation is investigated. Incorrect initialization may lead to numerical instability problems, not to mention erroneous results from dynamic simulations. The machine model is studied from the perspective of slip and reactive power calculation and tested for various cases. The dynamic reactive power calculation in well-known software package is discussed and the deviation of dynamic reactive power from the steady state reactive power is highlighted.**

Index terms -- **Dynamic induction machine model, load flow studies with induction generator, dynamic stability, model initialization.**

I. Introduction

Wind turbines are quietly becoming the fastest-growing energy source in the world. A record 6,868 megawatts (MW) of new wind power capacity was installed worldwide in 2002 bringing the total wind power capacity was 31,000 MW [1]. Total installed US wind energy capacity stood at 5,326 MW in October 2003 with California leading the way with about 2000 MW, followed by Texas with almost 1100 MW [2]. To get an idea of the rapid pace of wind power deployment in the US alone, one only has to compare the current rate of installation with previous years. In the one year period from 1998 to 1999, the increase was 1848 MW to 2511 MW – a 36% increase. In contrast, from 2000 to 2001 the increase was 2578 MW to 4275 MW – a 66% increase!

Despite this renewed interest in wind power, this form of renewable energy still generates less than 1 percent of the nation's electricity. Nonetheless, most planners in the electric utility business project wind power to have a larger role as they struggle to meet soaring electrical demands and face uncertainties in electricity prices. The good news is that with the development of bigger, more sophisticated turbines, the cost of wind-generated electricity, once seen as prohibitive, is now nearly competitive with that of its rivals, all but eliminating what was once a major barrier. The bad news is that the present day power system control structure may not be as yet ready to handle large scale penetration of wind power. Reactive power requirements as well as power quality issues continue to be hurdles and solution strategies are rather complex and expensive. Besides, system studies using standard power flow and stability tools are also not well defined. Most wind turbine manufacturers are now equipping their power generating units with induction generators and the behavior of these machines are a far cry from the conventional synchronous machines in both the steady state and dynamic domains. Consequently, power flow and transient stability models for these asynchronous machines have to be determined prior to assessing their behavior on the power system.

For representing the induction generator model in stability simulations, model initialization needs to be carried out as the initial conditions need to be matched before the simulations. This paper discusses the model initialization process, deviation of reactive power values in steady state and dynamic analysis for system studies. A technique to address the discrepancy between power flow and dynamic simulations is discussed. Simulations are performed with PTI's PSS/E software [3] due to its wide use and popularity.

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II. Induction Generator Model

In synchronously rotating frame, in terms of the d and q components, the stator and rotor flux linkages of a squirrel cage induction machine can be expressed by [4]:

$$\psi_{ds} = L_{ss} i_{ds} + L_m i_{dr} \tag{1}$$

$$\psi_{qs} = L_{ss} i_{qs} + L_m i_{qr} \tag{2}$$

$$\psi_{dr} = L_{rr} i_{dr} + L_m i_{ds} \tag{3}$$

$$\psi_{qr} = L_{rr} i_{qr} + L_m i_{qs} \tag{4}$$

where

$$L_m = 3/2 L_{aA}$$

The stator and rotor voltages in terms of the d and q components are

$$v_{ds} = R_s i_{ds} - w_s \psi_{qs} + p\psi_{ds} \tag{5}$$

$$v_{qs} = R_s i_{qs} + w_s \psi_{ds} + p\psi_{qs} \tag{6}$$

$$v_{dr} = R_s i_{dr} - s w_s \psi_{qr} + p\psi_{dr} \tag{7}$$

$$v_{qr} = R_r i_{qr} + s w_s \psi_{dr} + p\psi_{qr} \tag{8}$$

III. Modeling

For constructing a dynamic induction machine model, in the stator voltage equations, the stator transients are usually neglected which correspond to ignoring the dc component in the stator transient currents and hence only the fundamental frequency components are represented. This assumption works well when the induction machine slip is small and when the ac network frequency deviations are zero.

Upon neglecting the stator transients and on short circuiting the rotor, the stator and rotor voltages become:

$$v_{ds} = R_s i_{ds} - w_s \psi_{qs} \tag{13}$$

$$v_{qs} = R_s i_{qs} + w_s \psi_{ds} \tag{14}$$

$$v_{dr} = 0 = R_r i_{dr} - s w_s \psi_{qr} + p \psi_{dr} \tag{15}$$

$$v_{qr} = 0 = R_r i_{qr} - s w_s \psi_{dr} + p \psi_{qr} \tag{16}$$

For getting an induction machine transient model, the rotor currents are eliminated and a relationship is expressed between the stator current and voltage behind the transient reactance. From Eq. (3)

$$i_{dr} = \frac{\psi_{dr} - L_m i_{ds}}{L_{rr}} \tag{17}$$

Now substituting the above equation in (1)

$$\psi_{ds} = \frac{L_m}{L_{rr}} \psi_{dr} + \left(L_{ss} - \frac{L_m^2}{L_{rr}} \right) i_{ds} \tag{18}$$

Similarly,

$$\psi_{qs} = \frac{L_m}{L_{rr}} \psi_{qr} + \left(L_{ss} - \frac{L_m^2}{L_{rr}} \right) i_{qs} \tag{19}$$

For representing the stator voltages in terms of the d and q components, we substitute ψ_{qs} and ψ_{ds} terms in Eqs. (13) and (14):

$$v_{ds} = R_s i_{ds} - X_s' i_{qs} + v_d' \tag{20}$$

$$v_{qs} = R_s i_{qs} + X_s' i_{ds} + v_q' \tag{21}$$

where

$$v_d' = -\frac{w_s L_m}{L_{rr}} \psi_{qr} \tag{22}$$

$$v_q' = \frac{w_s L_m}{L_{rr}} \psi_{dr} \tag{23}$$

$$X_s' = w_s \left(L_{ss} - \frac{L_m^2}{L_{rr}} \right) \tag{24}$$

In Eq. (24), X_s' is the transient reactance of the induction machine.

The three state equations of the transient single-cage induction machine can be represented by eliminating the rotor currents and expressing the rotor flux linkages in terms of v_d' and v_q':

$$p(v_d') = -\frac{1}{T_0'} \left[v_d' + (X_s - X_s') i_{qs} \right] + p\theta_r v_q' \tag{25}$$

$$p(v_q') = -\frac{1}{T_0'} \left[v_q' - (X_s - X_s') i_{ds} \right] - p\theta_r v_d' \tag{26}$$

$$p(\omega_r) = \frac{1}{2H} (T_e - T_m) \tag{27}$$

A. *Induction Generator Model Used as a Wind Generator*

The most common way to treat induction generator-based wind generations in power systems is to run power flow and dynamic simulations iteratively to find a mismatch between the two program runs [5].

The model that was investigated for representing a dynamic induction model in PSS/E is the CIMTR1 model, which is basically an induction generator model that considers only rotor flux transients and neglects the stator transients. This model represents a fixed speed induction generator in the real world.

CIMTR1 model can be used to represent both a single cage and a double cage machine. In this paper, dynamic simulations have been done in PSS/E for both single cage and double cage machine. In the PSS/E power flow studies, a generator with a positive electrical power should be used for representing a wind generator. As there are no sub-transient reactances and sub-transient time constants associated with a single cage machine, either T'' (sub transient time constant) or X'' (sub transient reactance) should be set equal to zero and ZSORCE (generator dynamic impedance) in the power flow model should be set equal to X' (transient reactance). In case of a double cage machine, ZSORCE should be set equal to X'' while providing appropriate values for T'' and X''. A double cage machine will have time constants much smaller than T'' and, hence, a time step much smaller than the normal value of ½ cycle are necessary.

B. *Reactive Power Calculations*

The wind generating plants are usually modeled as collector systems that comprise of a large number of individual units that are interconnected with other units in radial or parallel arrangements .Power flow and transient stability models for induction generator models are not always well understood.

In this paper, several different scenarios cases have been investigated to gain an insight into how the asynchronous wind generating machines behave during system studies. Fig. 1 shows three wind collected buses connected to a larger power system. Studies are performed on this system.

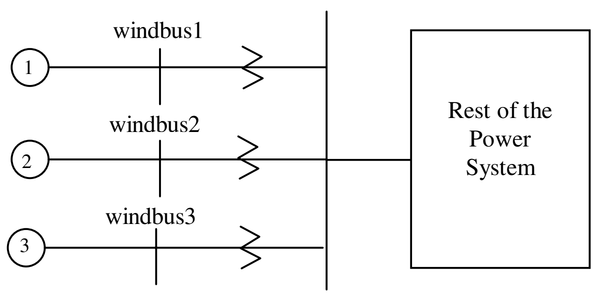

Fig. 1. Three wind collector buses as part of a large power system.

The dynamic induction generator model is tested for its behavior with regard to different sets of active power and voltage changes. The wind collector buses are located at windbus1, windbus2 and windbus3 buses. Dynamic simulations were first run with voltage at windbus1 scheduled at 1.02 pu. Unlike a synchronous generator, an induction generator does not have the capability to control its terminal voltage. Therefore, the CIMTR1 model consists of two internal variables called Var (L) and Var (L+1) that are used for calculating the reactive power output of the machine. Var (L) is the artificial shunt admittance corresponding to the Mvar difference in the initial condition. This fictitious admittance is placed at the wind generator bus so as to match the dynamic reactive power with the steady state reactive power and var (L+1) is the motor dynamic reactive power.

Thus, the total reactive power output of the induction generator is calculated using the formula given below:

$$Q_e = Var\left(L\right)x\left|V\right|^2 + Var\left(L+1\right)xS_b \text{ MVar} \qquad (28)$$

The value of Q_e then should match the steady state reactive power in the power flow solution.

Dynamic simulations were next carried out by varying the windbus1 bus voltage from 1.05 pu to 0.98 pu with active power at windbus1 being progressively decreased from 33 MW to 5 MW. The behavior of the model with respect to reactive power outputs and the two different variables var (L) and var (L+1) were observed. Table 1 shows this relationship.

TABLE I
VARIATION OF INTERNAL VARIABLES DUE TO CHANGES IN WIND BUS COLLECTOR VOLTAGE

Bus	V	MW	MVar	Var(L)	Var(L+1)
windbus1	1.05	33	10.9	0.3041	-0.2238
windbus2	1.02	33	-10.1	0.1096	-0.2145
windbus3	1.02	33	-10.1	0.1096	-0.2145
windbus1	1	33	-15.3	0.0561	-0.2090
windbus2	1.02	33	-2.5	0.1819	-0.2145
windbus3	1.02	33	-2.5	0.1819	-0.2145
windbus1	0.98	33	-30.2	-0.1029	-0.20272
windbus2	1.02	33	-0.3	0.2029	-0.2145
windbus3	1.02	33	-0.3	0.2029	-0.2145
windbus1	1.05	15	10.2	0.2516	-0.1751
windbus2	1.02	33	-12.1	0.0895	-0.2146
windbus3	1.02	33	-12.1	0.0895	-0.2146
windbus1	1	15	-17.4	-0.0171	-0.1570
windbus2	1.02	33	-4.2	0.1660	-0.2145
windbus3	1.02	33	-4.2	0.1660	-0.2148
windbus1	0.98	15	-30.5	-0.1629	-0.1487
windbus2	1.02	33	-0.1	0.2050	-0.2145
windbus3	1.02	33	-0.1	0.2050	-0.2145
windbus1	1.05	5	11.6	0.2513	-0.1596
windbus2	1.02	33	-9.9	0.1110	-0.2146
windbus3	1.02	33	-9.9	0.1110	-0.2146
windbus1	1	5	-11.2	0.0322	-0.1445
windbus2	1.02	33	-3.4	0.1732	-0.2145
windbus3	1.02	33	-3.4	0.1732	-0.2145
windbus1	0.98	5	-30.4	-0.1781	-0.1331
windbus2	1.02	33	0	0.2067	-0.2145
windbus3	1.02	33	0	0.2067	-0.2145

Fig. 2 shows the relationships between bus voltage and reactive power outputs In the plots, VAR101P1, VAR101P2 and VAR101P3 represent Var (L) for windbus1 at 33 MW, 15 MW and 5 MW respectively. Similarly, VAR104P1, VAR104P2, VAR104P3 represent Var (L) for windbus2 and windbus3 at 33MW, 15 MW and 5 MW respectively. Furthermore, VAR102P1, VAR102P2, VAR102P3 represent Var (L+1) for windbus1 at 33MW, 15 MW and 5 MW respectively, while VAR105P1, VAR105P2, VAR105P3 represent Var (L+1) for windbus2 and windbus3 at 33MW, 15 MW and 5 MW respectively.

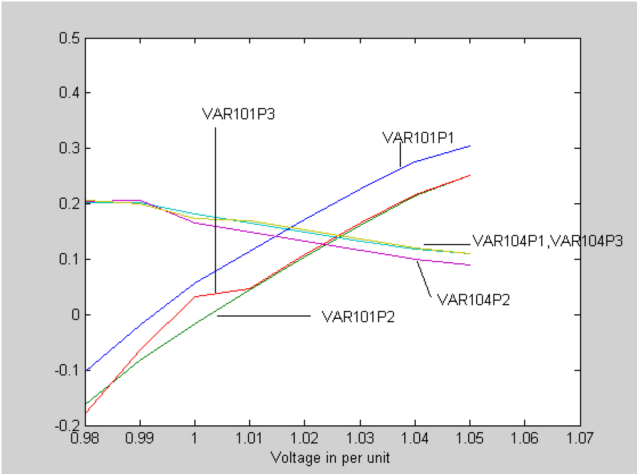

Fig. 2. Variation of internal dynamic variable Var (L) – the fictitious shunt admittance – with bus voltage.

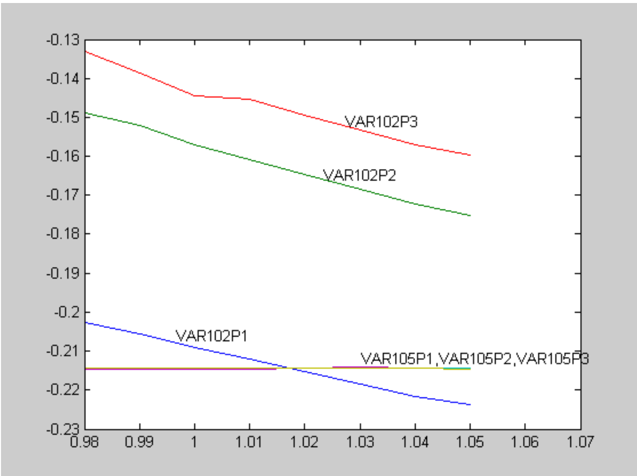

Fig. 3. Variation of internal dynamic variable Var (L+1) – the motor dynamic reactive power.

From Fig. 3, one can observe that as the voltage at windbus1 decreases from 1.05 pu to 0.98 pu, Var (L) – the fictitious shunt admittance - decreases at windbus1 while the shunt admittances at the other buses more or less remain constant. This is to be expected because changes in voltage are brought about only at windbus1. In Fig. 3, one can observe that as the voltage at windbus1 decreases from 1.05 pu to 0.98 pu, Var (L+1) - the motor dynamic reactive power - decreases at windbus1 while the reactive powers at the other buses remain perfectly constant. Again, this is to be expected because changes in voltage are brought about only at windbus1.

C. Reactive Power Initialization without Full Scale Dynamic Simulations

As obvious, it would be more beneficial to be able to calculate the correct reactive power output without resorting to full scale dynamic simulations. The set of equations (28) through (37) are useful for estimating the reactive power output from induction generators [6].

$$K_1 = X_r + X_m \tag{28}$$

$$x^2 A + xB + C = 0 \tag{29}$$

where $x = \dfrac{r_r}{s}$

$$A = P(r_s^{\,2} + K_3^{\,2}) - V^2 r_s \tag{30}$$

$$B = 2P(r_s K_2 + K_3 K_4) - V^2 (K_2 + K_1 K_3) \tag{31}$$

$$C = P(K_2^2 + K_4^2) - V^2 K_1 K_4 \tag{32}$$

where

$$K_2 = -X_S K_1 - X_r X_m \tag{33}$$

$$K3 = X_m + X_s \tag{34}$$

$$K4 = r_s K_1 \tag{35}$$

$$P = \frac{V^2\{xT1 + K_1 T_2\}}{T_3} \tag{36}$$

$$Q_C = \frac{-V^2\{K_1 T_1 - xT_2\}}{T_3} \tag{37}$$

where

$$T1 = xr_s - X_S K_1 - X_r X_m$$

$$T2 = x(X_m + X_S) + r_s K_1$$

$$T3 = T_1^2 + T_2^2$$

To illustrate the method, a 3 machine, 9 bus system, shown in Fig. 4, is tested for the initialization process. This test system has an induction generator at bus 8 which is modeled as a negative load. It is assigned a reactive load of 0.35 per unit in the power flow set up. The power flow data for this system is shown in the Appendix.

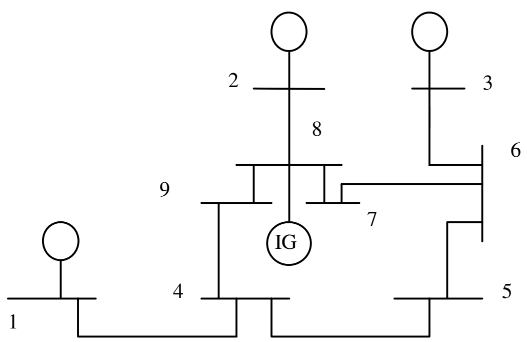

Fig. 4. A 3 machine, 9 bus test system.

In the process of calculating the reactive power, we obtain two values of slip. The lower value of slip is considered for further analysis as it lies in the stable region of active power versus slip characteristics of the generator. On substituting the system parameters and the active power of -0.5 per unit at a terminal voltage of 1.0089 pu, a reactive power of 0.3651 per unit is obtained. Hence, there is a mismatch of 0.0076.

In the general case, this amount of mismatch is represented by an artificial shunt admittance. In PSS/E this shunt admittance is represented by Var (L).

On varying the reactive loads at the induction generator buses, the reactive power mismatches vary widely. Table II shows the different reactive loads (Q), the slip (S) of the induction generator at voltage (V) and the reactive power, Q_c, that is calculated using Eqs. (28) to (37). The mismatches are in absolute values.

TABLE II
CALCULATION OF MISMATCH WITH VARYING INITIAL CONDICTIONS

V	Q, pu	Q_C, pu	Slip	Mismatch (abs)
1.00245	0	0.3682	0.0079	0.3682
1.0089	0.35	0.3576	0.0081	0.0076
0.9974	0.6	0.35	0.0083	0.25
0.988	0.8	0.3438	0.0085	0.4562

IV. CONCLUSIONS

The model initialization of the induction generator has been discussed with reference to adopted methods. The mismatch between the steady state reactive power and dynamic reactive power calculations is added as a fictitious admittance. Methods are available that may be used to calculate this mismatch without resorting to full scale dynamics. This allows convenient system impact studies with wind generators in the system.

V. APPENDIX

TABLE A.1
BUS DATA FOR THE 3-MACHINE, 9-BUS SYSTEM

Bus	V	P_g, pu	Q_g	P_l	Q_l	Type
1	1.04	0	0	0	0	Slack
2	1.025	1.63	0	0	0	PV
3	1.025	0.85	0	0	0	PV
4	1.0	0	0	0	0	PQ
5	1.0	0	0	0.9	0.3	PQ
6	1.0	0	0	0	0	PQ
7	1.0	0	0	1	0.35	PQ
8	1.0	0	0	-0.5	0.35	PQ
9	1.0	0	0	1.25	0.5	PQ

TABLE A.2
LINE DATA FOR THE 3-MACHINE, 9-BUS SYSTEM

From	To	R, pu	X, pu	B, pu
1	4	0	0.0576	0
4	5	0.017	0.092	0.158
5	6	0.039	0.17	0.358
3	6	0	0.0586	0
6	7	0.0119	0.1008	0.209
7	8	0.0085	0.072	0.149
8	2	0	0.0625	0
8	9	0.032	0.161	0.306
9	4	0.01	0.085	0.176

TABLE A.3
INDUCTION GENERATOR DATA

r_s	x_s	X_m	r_r	x_r
0.0574	0.0769	2.9061	0.0238	0.0709

VI. LIST OF SYMBOLS

ψ_{ds} d-axis stator flux linkage

ψ_{qs} q-axis stator flux linkage

ψ_{dr} d-axis rotor flux linkage

ψ_{qr} q-axis rotor flux linkage

i_{ds} d-axis stator current

i_{dr} d-axis rotor current

v_{ds} d-axis stator current

v_{qs} q-axis stator current

v_{dr} d-axis rotor current

v_{qr} q-axis rotor current

R_s stator resistance

R_r stator resistance

w_s angular velocity of the stator field

$v_d^{'}$ d-axis transient reactance

$v_q^{'}$ q-axis transient reactance

H inertia constant

T_e electrical torque

T_m motor torque

X_r rotor reactance

X_m magnetizing reactance

X_s stator reactance

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VIII. BIOGRAPHIES

Kiran Nandigam received his B.E degree in Electrical and Electronics Engineering from Andhra University, Visakhapatnam, India in 2000. He is presently an MS student at the Department of Electrical and Computer Engineering, University of Missouri-Rolla. His research interests are in power system modeling, stability and control.

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