Considerations about Reactive Power Compensation and Short Circuit Levels on Constant Speed Wind Turbines

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***Abstract*-- Inductions generators are more favorable to applications of renewable energies due to low cost and high reliability. The applications of single cage induction generator in power systems has been demonstrated especially in wind energy conversion system based on constant speed wind turbines. The main objective of this article is to conclude over of general considerations of reactive power compensations and short circuit levels on distributions network with the integration of induction generators. In this article a simple test system that contains an induction generator delivering power is used to simulate the behavior of a great wind farm with some wind turbines. Then the effects of the induction machines over requirements of reactive power and voltage support is investigated on the stability of the voltage, all that by means of numerical simulations.**

***Index Terms*—Induction generator, power factor, reactive power, voltage support.**

I. NOMENCLATURE

V_{nom}	Rated voltage [V]
S_{nom}	Rated power [kVA]
f	Rated frequency [Hz]
R_s	Stator resistance [p.u]
R_r	Rotor resistance [p.u]
X_r	Rotor reactance [p.u]
X_s	Stator reactance [p.u]
X_m	Magnetizing rectance [p.u]
H	Inertia constante [s]
T_{base}	Rated torque [N.m]
T_{max1}	Maximum torque, motor mode [p.u]
T_{max2}	Maximum torque, generator mode[p.u]
$s_{max1,2}$	Slip at max torque [p.u]
I_{rb}	Bloqued rotor current [p.u]
$s_{nom,mot}$	Slip at rated current, motor mode [p.u]
$s_{nom,gen}$	Slip at rated power, generator mode[p.u]
I_0	No load current [p.u]
$P_{elec,max}$	Maximum electrical power, generator mode [p.u]
s_{max}	Slip at $P_{elec,max}$ [p.u]
Q_0	No load reactive consumption [p.u]

II. INTRODUCTION

INDUCTION generator is an electrical machine that for his simplicity and hardiness of construction is used in multiple applications of distributed generation [1]. Particular characteristics of this type of generation technology, united to the fact of his potential to penetrate intensely the market of the distributed generation, make pertinent that in this article devotes itself to the analysis of the behavior in stationary regime of this type of generator [2]. Induction generator is induction machine in which there is applied he torque in shaft and is made turn over the synchronous speed. Though some modifications done to the design of the machine optimize the performance as generator [3]-[5]. Wound rotor machines in spite of being used in some units of distributed generation, are not of common use; whereas simple squirrel cage induction generator, it is possible to find in a great variety types of distributed generation sources, since for example: micro-turbines of split shaft turbines, constant speed wind turbines and mini hydro [5]. Initially in this paper we shows aspects inherent in the modeling of simple cage induction machine, so much in steady state and as dynamic state. Then we present results of simulation in steady state to characterizing the operation of the induction generator using the typical curves. We show results of the evaluation on dynamic state of induction generator, first considering the natural response before changes of mechanical power, and the evaluation of transient response before faults by short circuits.

III. MODELING

A. Steady State

Steady state of induction machine (single cage squirrel cage) in balanced conditions can be understood to fullness from the equivalent circuit (Steinmetz's circuit)

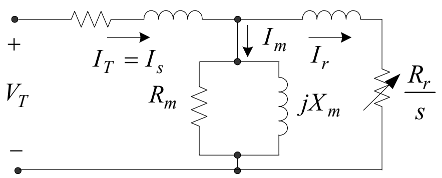

FIG. 1. Equivalent circuit of single cage induction generator on steady state.

We consider mechanical power (P_{mech}) and terminal voltage

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(V_T) known. All the quantities have been supposed in the system in per unit system at corresponding bases. By means of simple relations on the circuit of the Fig. 1, we can establish the main relations between principal electromechanical variables in the machine (to see Appendix).

B. Transient State

The detailed dynamic representation of the induction machine is based on a fifth order model [6], also called the model of Park that corresponds to the differential equations of the machine of idealized induction [7]. Even, this model is more than a representation simplified of an electromagnetic complex system [6].

Literature gathers in complete form [8] - [14], the models of induction machines; from the detailed complete model of 5th order [9] up to the limited model of 1th order, where there is combined equations steady state and movement equation [9]. In this paper to simulate the power system dynamic we choose 3th order model representation to the induction machine, since it is described in [8] and [14].

This model considers transient effect, but neglects sub-transients effect on the rotor circuit. The model assumes a balanced network and neglects dynamic effects of the stator circuit. All quantities are expressed on *dq0* axis, over stationary frame p8], [14]. Machine can be modeled as voltage source E', behind an impedance $R_s + jX'$ (Fig. 2) [13], [14].

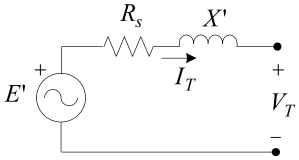

FIG. 2. Equivalent circuit of induction generator 2th order model.

The equations associated to the dynamic behavior of the internal voltage E' are given by [8], [11]:

$$\begin{aligned}\frac{dE_d}{dt} &= -\frac{1}{\tau'_0}E_d - \frac{(X-X')}{\tau'_0}I_q + sE_q \\ \frac{dE_q}{dt} &= -\frac{1}{\tau'_0}E_q + \frac{(X-X')}{\tau'_0}I_d - sE_d\end{aligned} \tag{1}$$

where τ_0, is open circuit transient time constant of the induction machine. This time constant characterize the transient decay of rotor quantities when stator circuit is open, and s is the slip of the machine.

$$\tau_o = \frac{X_r + X_m}{2\pi f R_r} \tag{2}$$

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{3}$$

Terminal current (I_T) is given by:

$$I_T = \frac{E' - V_T}{R_s + jX'} \tag{4}$$

The electrical model of induction machine is representing by following block diagram (Fig. 3).

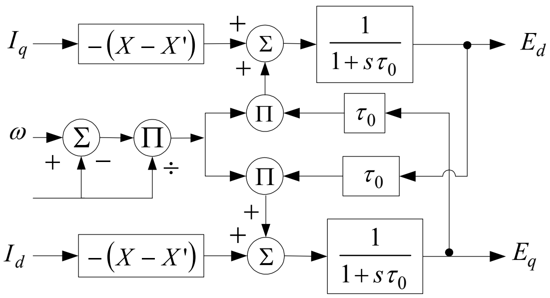

FIG. 3. Block diagram of the 2nd order model of induction machine.

Inertial dynamic of the machine rotor is given by [8], [15]:

$$\frac{d\omega}{dt} = \frac{1}{2H}T_{mec} - \frac{1}{2H}T_{elec} - D(\omega - \omega_s) \tag{5}$$

In this case, (5) has been written to generation operation mode of the induction machine, T_{elec}, y T_{mec}, electrical and electro-magnetic torque respective, and ω_s, is the synchronous speed.

$$T_{elec} = \frac{E_d I_d + E_q I_q}{\omega_s} \tag{6}$$

In this paper we prefer a direct formulation of change rate of the internal voltage behind reactance defined by [14]:

$$\frac{dE'}{dt} = -j2\pi f sE' - \frac{1}{T_o}\left[E' - j(X - X')I_T\right] \tag{7}$$

The electro-mechanical model is based [8]:

$$\frac{ds}{dt} = \frac{1}{2H}\left[\frac{P_{mec}}{1-s} - P_{elec}\right] \tag{8}$$

X y X' reactance would be obtained of the steady state model of induction machine (Fig. 1):

$$X = X_s + X_m \tag{9}$$

Blocked rotor reactance X' is:

$$X' = X_s + \frac{X_m X_r}{X_m + R_r} \tag{10}$$

IV. STEADY STATE RESULTS

In this article we are interested on steady state of main variables of single cage induction generators suitable to be used on wind energy conversion systems. We consider four (04) induction machines of single squirrel cage. Table 1 summarized the main characteristics and parameter of machines simulated.

TABLE 1.
CHARACTERISTIC AND PARAMETERS OF INDUCTION MACHINES CONSIDERED

Symbol	*Machine #1 [16]*	*Machine #2 [17]*	*Machine #3 [18]*	*Machine #4 [19]-[20]*
V_{nom}	0.66 kV	660 V	545 V	1000 V
S_{nom}	350 kVA	330 kVA	1.5 MVA	2 MVA
f	60 Hz	50 Hz	60 Hz	50 Hz
R_s	0.00571 p.u	0.00708 p.u	0.004843 p.u	0.01 p.u
R_r	0.00612 p.u	0.00759 p.u	0.004377 p.u	0.01 p.u
X_r	0.06390 p.u	0.23289 p.u	0.1791 p.u	0.08 p.u
X_s	0.18780 p.u	0.07620 p.u	0.1248 p.u	0.10 p.u
X_m	2.78000 p.u	3.44979 p.u	3.77 p.u	3.00 p.u
H	3.02500 s	3.0 s	0.5 s	0.50 s

A program Developer on MATLAB™ was used to evaluate the steady state behavior of induction machines, results are shown on Table 2.

Initially we can see for all induction machines considered, the maximum torque on motor operation mode is lower than generation operation mode. On characteristic curve of torque versus slip the difference of maximum torque is related (Fig 4).

TABLE 2.
MAIN OPERATION POINTS FOR INDUCTION MACHINES CONSIDERED [21]

Symbol	*Machine #1 [16]*	*Machine #2 [17]*	*Machine #3 [18]*	*Machine #4 [19]-[20]*
T_{base}	1856.80	1750.70	7957.74	10610.32
T_{max1}	1.79152	1.24626	1.53860	2.51188
T_{max2}	-1.86795	-1.92603	-1.58586	-2.79245
$s_{max1,2}$	0.02551	0.02401	0.01459	0.05648
I_{rb}	3.991	3.285	3.379	5.586
$s_{nom,mot}$	0.0062	0.0078	0.004359	0.0097
$s_{nom,gen}$	-0.0061	-0.0068	-0.004300	-0.0095
I_0	0.3369	0.2836	0.2568	0.3226

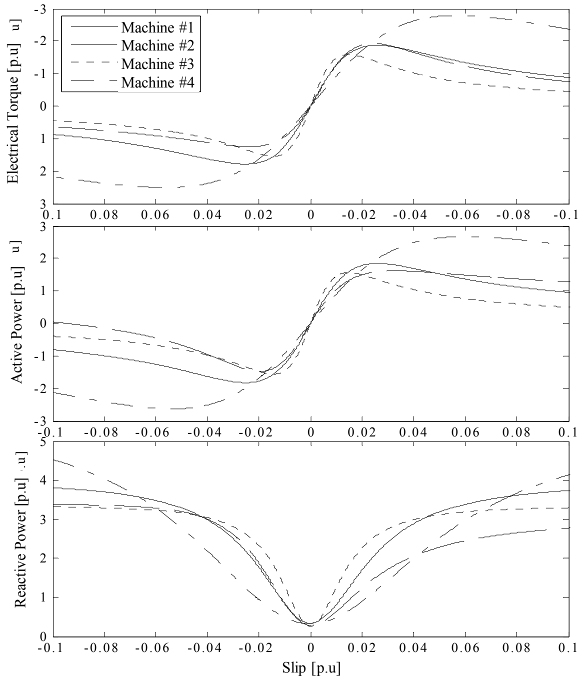

FIG. 4. Characteristic curves for several variables versus slip for induction machines considered, regulation slip zone of ±10%

To all induction machines the maximum operation torque is reached in motor operation mode is lower than generator operation mode. Machines considered 'small' #1, 350 kVA and #2, 330 kVA, the slip to which the maximum torque is achieved torque is lower than the machine considered like "big" #4, 2MW, nevertheless the machine #3 exhibits a low slip.

Machine #3 has lowest torque curve (values in per unit over rated values bases) and it is the sharpest of all. This machine limits the normal operation in steady state conditions to a slip below 1%. Machines considered 'small', machine #1 and #2, have similar torque curves through extreme values are more asymmetrical in motor and generator operation mode for 330 kVA, 660 V, machine #2.

The 2 MW Machine #4 has the largest torque curve and the largest maximum torque and reaches the biggest slip of all machines. This machine is design to give a wide range of speed regulation.

In Table 2 are shown the blocked rotor current (I_{rb}, @ $s = 1.0$ p.u.) for all induction machines considered. The largest machine (#4, 2MW) provides the highest current but machine #1, 350 kVA has the second largest current value.

Squirrel cage induction machine in generator operation mode has a static stability limit of maximum electrical power can be delivering. This limit is imposing by the maximum electro-magnetic torque can developed during normal operation. The value of this limit of maximum electrical power ($P_{elec,max}$) is shown on Table 3 with respective torque reached.

TABLE 3.
ACTIVE AND REACTIVE POWER VALUES FOR INDUCTION MACHINES CONSIDERED

Symbol	*Machine #1 [16]*	*Machine #2 [17]*	*Machine #3 [18]*	*Machine #4 [19]-[20]*
$P_{elec,max}$	-1.822	-1.481	-1.558	-2.63
s_{max}	-0.025	-0.0196	-0.0143	-0.0544
Q_0	0.3369	0.2835	0.2568	0.3226

Nevertheless, it is necessary to warn that stability limit rare times is reached in static form, due to the fact that induction machine operating in generator mode require reactive power form the supply which does the limit of capacity (Volt-Amperes)is reached first and before that achieves the limit of active power. Induction machine operating in generator mode require reactive power from the power supply network (Q_{elec}). This requisite increase when active power generated and the slip are increased. No load operation regime of induction machines requires a reactive power level (Q_0), this value is important for local power factor correction.

Table 3 show reactive power requirement for the induction machines considered. Machine #3 (1.5 MW) exhibit the lowest values of reactive power consumptions in no load regime, and machine #1 (350 kVA, 660V) has the largest requirements of reactive power in no load conditions.

A. Effect of Network Impedance

Induction generator operating connected to power grid has several operation restrictions impose by the impedance of source and feeder (X_e). The magnitude of voltage at terminals of induction generator is dependent of equivalent impedance between source and induction generator and this value affect the voltage regulation on the machine and reactive power consumption.

Fig. 5 show behavior of the terminal voltage (V_T) of machine #1 operating in generator mode, for several magnitudes of reactance (X_e) and stable operation power (P_{elec}).

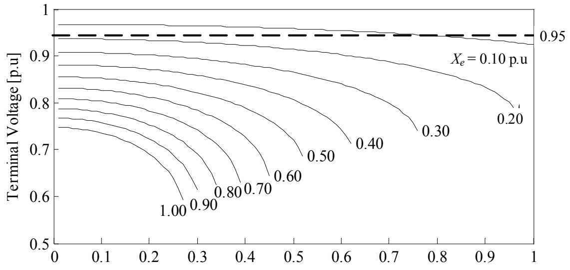

FIG. 5. Characteristics curves of Terminal voltage versus impedance of connection (no reactive compensation is considered)

High values of the connection circuit impedance can result in especially low operation voltages violating the lower limit of regulation (0.95p.u). Low connection impedance values ($X_e < 0.02$ p.u), induction machine operate between regulation limits, but higher values of impedance ($X_e > 0.14$ p.u) produce prohibitive values of Terminal voltages include in no load regimen.

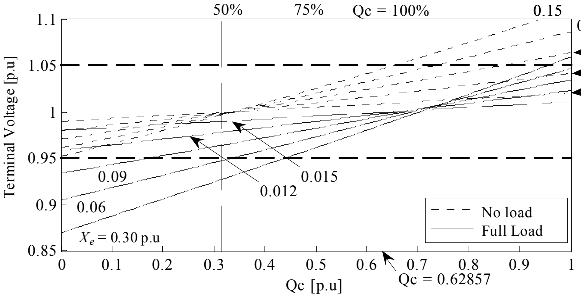

FIG. 6. Terminal Voltage for several impedance of connection, effect of reactive power compensation (Q_c)

Sensitivity analysis over reactive power (Fig. 6) demonstrates the dependence of terminal voltage over impedance connection circuit. Increases on impedance implicate increase of reactive power support requirements and this situation has positive correlation with the active power generated by the induction generator.

V. TRANSIENT BEHAVIOR RESULTS

In this section results of dynamic response simulations are shown. A program of power system dynamic developed in MATLAB™ by the author and including the model shown in this paper was used to simulate the dynamic behavior of the induction generator. This program employs partitioned implicit method with Euler method for resolve dynamic equations and special Newton-Raphson methods for algebraic equations. We consider Machine #1 (we shown only this results for space limitations), operating in generator mode connected to power utility system.

Show dynamic response of the induction generator without controls is evaluated. A step mechanical power (P_{mec}) on the generator shaft is applied. On Fig. 7, the response of speed and active power are shown for several step of change.

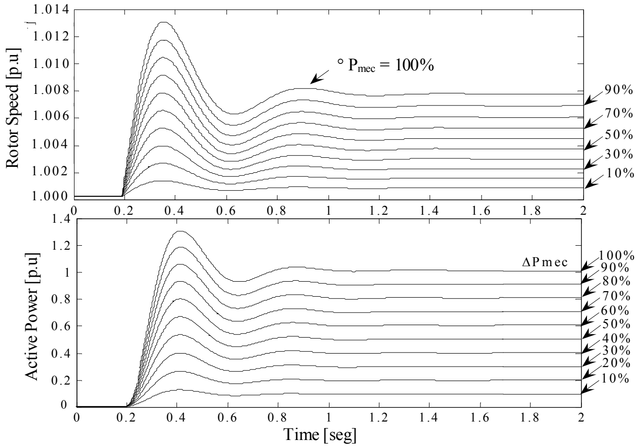

FIG 7. Speed and Active power response for several mechanic power step changes

Rotor speed exhibit under-damping responses with steady state, these values are increased when size of the mechanical power is increased (ΔP_{mec}). When the mechanical power is increased slip would be increased to reach the new state. Active power exhibit under-damping response with similar behavior like speed response as over shoot and peak time. For all disturbances considered the induction generator exanimate result stable.

To evaluate the dynamic response of induction machine for hardest disturbance we simulate the transient response of short circuit on induction generator terminals. Fig. 8, show the dynamic response of induction generator for several clearing times (t_c).

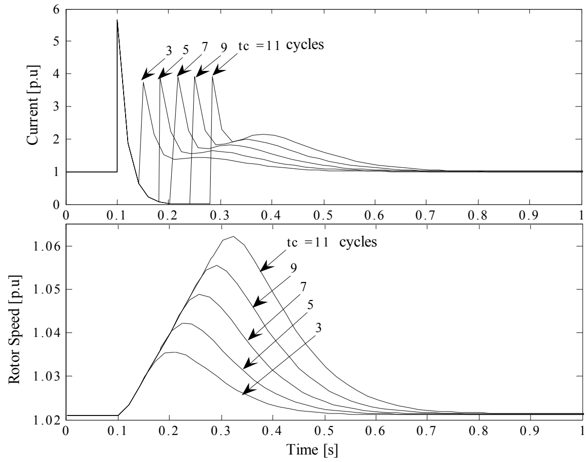

FIG 8. Dynamic behavior of induction generator variables for several clearing times.

Induction generator current response exhibit a initial peak dependent of operation conditions and machine parameters. This initial current irruption decay quickly due the fault interrupt reactive power flow from the source. When the fault is retired a secondary current peak is present. This peak is dependent of the clearing time. This secondary peak would be larger the primary peak and this peak depend of generator parameter, short circuit impedance of the feeder circuit and clearing time.

Rotor speed of the induction generator increase during fault condition and after the fault is cleared rotor speed return to the equilibrium point prior the fault. Speed deviations depend of clearing time. Fig. 9 show maximum rotor deviations increase when clearing time is increased.

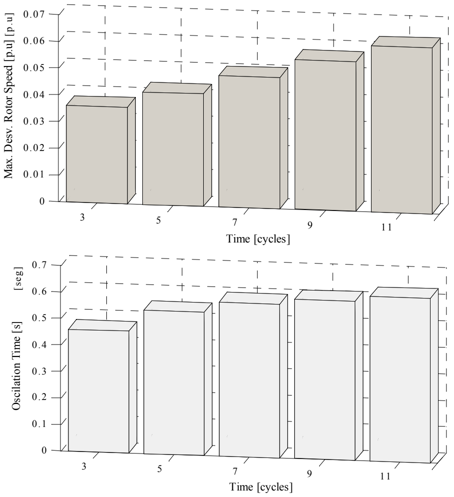

FIG. 9. Maximum deviation rotor speed and oscillation time on induction generator for several clearing time

VI. CONCLUSIONS

In this paper steady state performance of main variables associated with the operation of four induction machines were tested. These induction generators are simple squirrel cage induction generator considered of common use in wind turbines application. The good steady state performance and particular interest point have been exanimate by plotting characteristic curves and calculation of typical operation points.

The analysis has revealed that an induction generator connected to power network by a weak transmission system can cause stable normal operation, but prohibitively low voltage profiles, even violating the lower limit of regulation.

The effects of transmission network impedance on the reactive power suport for local power factor correction were exanimate. High impedance transmission system increases the requirements of power factor compensation and it influenced by power generation. The dynamic behavior of the induction generator shows a natural under damping response for changes of mechanical power.

Finally transient response of induction generator current before a short circuit in terminals exhibits a primary peak that depends on the operative condition and the machine parameters being highly damped. After clearing fault a secondary peak appears in the current, which depends on the clearing time and this peak could be bigger than the primary one. Consideration and discussion is necessary when the protection devices are setting by current.

VII. APPENDIX

Departing from the mechanical power that is injected into shaft (P_{mec}), and value of machine terminal voltage (V_T) we can calculate the slip (s) of operation by means of the calculation the roots of following polynomial:

$$\alpha_0 s^2 + \alpha_1 s + \alpha_2 = 0 \qquad \text{(a.1)}$$

Where poly coefficients are:

$$\alpha_0 = P_{mec} R_{eq}^2 + P_{mec}\left(X_{eq} + X_r\right)^2 + R_r \left|V_{eq}\right|^2$$

$$\alpha_1 = 2 R_{eq} R_e P_{mec} - R_r \left|V_{eq}\right|^2 \qquad \text{(a.2)}$$

$$\alpha_2 = R_r^2 P_{mec}$$

As soon as there are obtained the values the roots of slip quadratic polynomial, the most positive root takes.

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VIII. BIOGRAPHIES

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