THE DYNAMIC STABILITY ANALYSIS OF INDUCTION GENERATORS

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Abstract

Induction generators can be used to supply power either in an isolated system or connected to the grid. The continuity of generation of power during disturbances depends on the availability of magnetic flux in the core, which is proportional to the exciting current, and the mechanical input power. The stability analysis of synchronous generators in power systems has been well established. However, the stability analysis of induction generators during disturbances is not well documented. This paper deals with the stability analysis of different induction generator schemes for grid-connected as well as isolated system applications during electrical and/or mechanical disturbances.

1. INTRODUCTION

With the development of new technologies, there is an increase in the usage of electric power. A continuous growth in electric power demand, the issue of green house effect and other pollution issues requires an increased installation of renewable energy sources. The characteristics of induction generators make them good candidates for the application of electric power generation from renewable energy sources such as wind energy, low-head hydro, etc [1-4].

The same induction machine which is used as an induction motor can be used as an induction generator by driving the induction machine from an external prime mover. Whether the induction machine is used as a motor or as a generator it requires external reactive power for its excitation to develop the magnetic flux needed in its iron core. An induction generator can be used in a grid connected mode or for supplying power in an isolated system. A grid-connected induction generator will get the excitation current from the grid or, if needed, capacitors can be connected at the terminals of the induction generator to improve its power factor especially during light loading. As the grid power system operates at constant voltage and frequency the excitation current drawn by the induction generator is constant irrespective of its loading. An induction generator operating in an isolated system or in a stand-alone system, like self-excited induction generator, can draw excitation current from a bank of capacitors. In a stand alone system the generated voltage and frequency are dependent on the capacitance value, rotor speed and loading. The continuity of generation of power during disturbances depends on the availability of magnetic flux in the core, which is proportional to the exciting current, and the mechanical input power.

The stability analysis of induction generators is not well established as compared with the stability analysis of synchronous generators, which is well documented [5]. This paper deals with the stability analysis of different schemes of induction generators for grid-connected and isolated-system applications during electrical and/or mechanical disturbances. A review will be made on the stability analysis of synchronous generators in order to apply some of the methods to the case of stability analysis of induction generators.

2. ADVANTAGES OF INDUCTION GENERATORS

When a grid-connected induction generator is compared to a synchronous generator of similar capacity some of the advantages are:

- Induction generator is robust, brushless (squirrel cage), of a low cost and simple in construction.
- There is no need of a synchronization procedure.
- The transient response of induction generator is extremely fast. Hence the power transfer after a

given disturbance is fast with reduced frequency oscillations [2].

- Increasing the speed of the prime mover increases the output power of the generator without affecting the frequency and voltage.
- The induction generators have less stability problems, as they return quickly to their steady state operation provided that their terminal voltage comes back to its normal value.

3. MODELING OF SYNCHRONOUS AND INDUCTION MACHINES

The modeling and analysis of the steady state stability and transient stability of synchronous machines are well established [5-7]. The objective here is to use the analysis of the stability limits of synchronous generators and develop a similar way of analysis for the stability limits in induction generators. The simplified model of a synchronous machine operating under balanced three phase positive sequence conditions, neglecting machine looses, saturation and saliency, is given in Fig. 1.

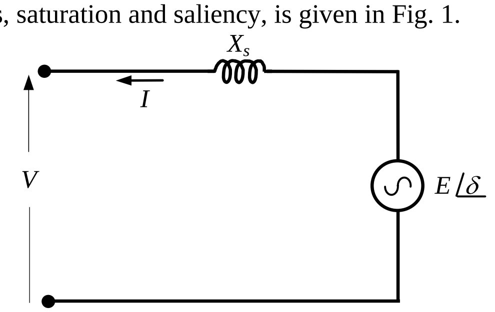

Fig. 1 Simplified equivalent circuit of synchronous machine

The real power delivered by the synchronous generator to the grid is given by:

$$P_{elcc} = \frac{VE}{X_s}\sin\delta \qquad (1)$$

where P_{elec} is the electrical generated power

V - is bus (terminal) voltage

E - stator induced emf

X_s - equivalent reactance between the generator and the bus

δ - is the angle between V and E or it is the angle between the rotor axis and stator flux axis (both rotating at synchronous speed).

Neglecting all losses it can be shown that the per unit electrical generated power and the per unit mechanical input power are related by the following equation [7]:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{mech} - P_{elec} \qquad (2)$$

where P_{elec} - is the electrical output power

H - is inertia constant given in joules/VA or in per unit seconds

ω_s - is the synchronous angular speed

P_{mech} - is mechanical input power

In synchronous generator analysis Equation (2) is called the per-unit swing equation, which is the fundamental equation that determines rotor dynamics in transient stability studies [7].

For a steady state analysis the conventional model (or steady-state model) and the d-q (or D-Q) axes model of induction machine are the same. The advantage of the d-q axes model is its capacity to analyse the transient and steady state conditions, giving the complete solution of any machine dynamics. The d-q equivalent circuit of an induction machine when the rotor and stator variables are referred to a stationary reference frame fixed in the stator is given in Fig. 2 [8-11]. The induction machine equations with all quantities referred to the stator reference frame is given in Equation (3) [12-14]

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \qquad (3)$$

The electromagnetic torque T_e generated by the induction machine is given by [8]

$$T_e = \frac{3}{2} P_p \overrightarrow{\lambda_m} \times \overrightarrow{I_r} \qquad (4)$$

where $\overrightarrow{\lambda_m}$ - air gap flux linkage

$\overrightarrow{I_r}$ - rotor current space vector

P_p - number of pole pairs of the induction machine.

Solving the cross product in Equation (5) gives

$$T_e = \frac{3}{2} P_p L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \qquad (5)$$

The mechanical equation when the induction machine is operating in the generator mode is

$$T_m = J\frac{d\omega_m}{dt} + D\omega_m + T_e \qquad (6)$$

where T_m - mechanical torque in the shaft

Te - electromagnetic torque

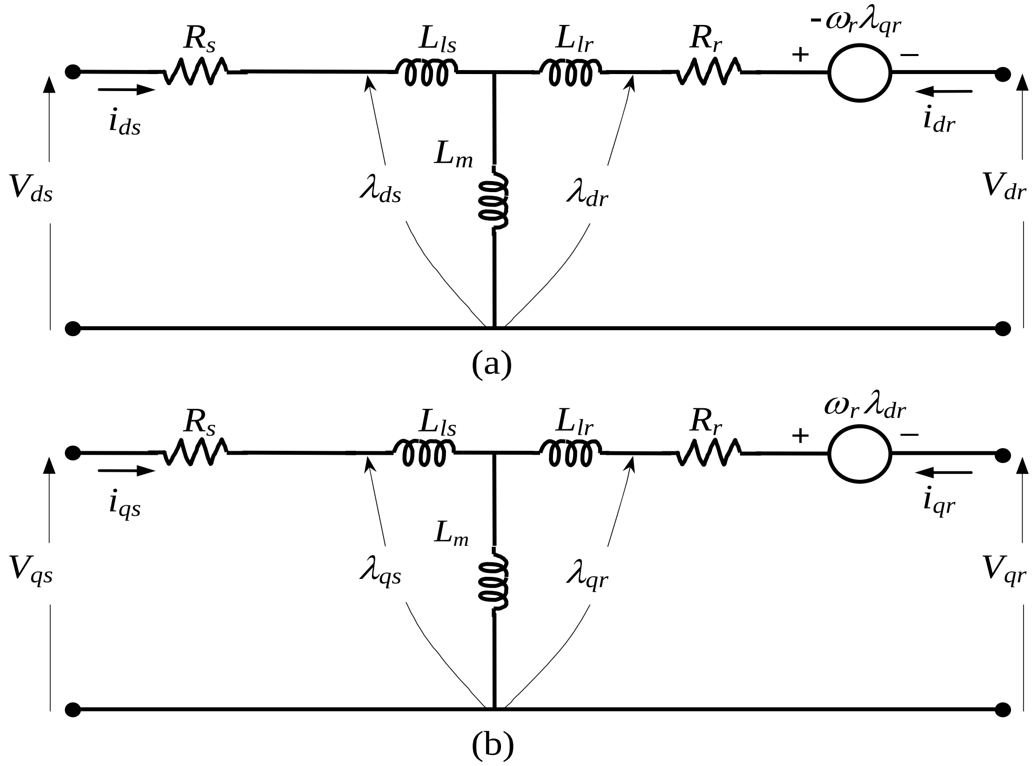

Fig. 2 D-Q representation of induction machine in the stationary reference frame (a) d-axis circuit (b) q-axis circuit

ω_m - mechanical shaft speed ($\omega_m = \omega_r / P_p$)
D - friction coefficient
J - inertia.

4. STABILITY OF INDUCTION GENERATORS

4.1 Steady state stability limit

A synchronous generator rotates at constant speed; any change in its output power is reflected as a change in the power angle δ. At steady state δ is constant and Equation (2) gives rise to mechanical input power equal to the electrical output power. Using Equation (1) the steady state stability limit of a synchronous generator, which is the maximum power that can be generated from a synchronous generator, is obtained by setting δ=90°.

The steady state stability limit for an induction generator is obtained using Equation (5). A typical plot for torque versus angular rotor speed of an induction machine is given in Fig. 3. Using Equation (6) for operating conditions between point ***A*** and ***B*** of Fig. 3 an increase in the mechanical input torque will increase the rotor speed and consequently the magnitude of the induced electromagnetic torque will increase. Hence there will be a steady state operating point where the mechanical input torque and the electrical torque will be equal. For operation beyond point ***B***, like point ***C***, for any decrease in mechanical input torque will decrease the speed and it follows with an increase in electrical torque. This increase in electrical torque will decrease the rotor speed further until it reaches an operating point between point ***A*** and ***B***.

Therefore the steady state stability limit for this induction generator is the rotor speed that corresponds to the peak torque indicted by point ***B*** in Fig. 3. The induction generator can operate at steady state any point between the rotor speed equal to the synchronous speed,. $\omega_{s,}$ indicated by point ***A***, and rotor speed that corresponds to point ***B***. Of course this operating range is practical provided that the electrical and mechanical rating is within the specification of the induction generator. The stator current corresponding to the peak torque will be much higher than the rated current. As a result the induction generator will not be able to operate close to the peak torque continuously.

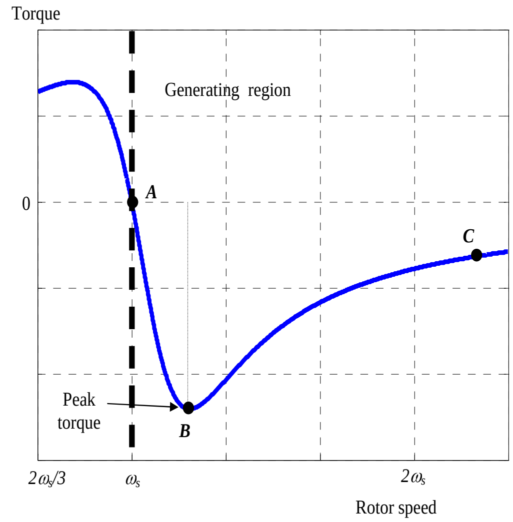

Fig. 3 Torque versus speed characteristics of induction machine.

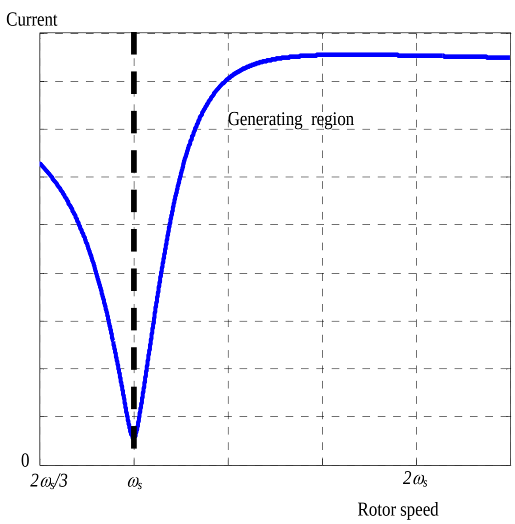

Fig. 3 Current versus speed for induction machine

From Fig.3 it can be observed that the current corresponding to the peak torque is about seven times the rated current. The steady-state operating range of the induction generator should be close to the synchronous speed which is low-slip value.

4.2 Transient stability limit

The transient stability limit of induction generator needs to be evaluated during disturbance in the system. This disturbance can be a change in the mechanical input power or it can be a three-phase to ground fault.

It is well known that during disturbances in a synchronous generator there will be a change in the operation of the generator as well as in the power balance between the input and the output. During faults the mechanical input power to the synchronous generator is assumed to be constant.

The transient stability limit of a synchronous generator is analyzed using the swing equation given in Equation (2). Equal area criterion is used to find the critical power angle [7]. During three phase fault the output power will be zero. i.e P_{elec} = 0. When Equation (2) is integrated twice, with the electrical output power set to zero and initial conditions $\delta(t) = \delta_o$ and $\frac{d\delta(0)}{dt} = 0$, gives:

$$\delta(t) = \frac{\omega_s P_{mech}}{4H} t^2 + \delta_o \quad (7)$$

Using Equation (7) the critical clearing angle δ_{cr} can be calculated from the critical clearing time t_{cr} or vise versa. The critical clearing time is the longest fault duration allowable for stability. If the fault is cleared within the critical clearing time, stability will be maintained. If the power angle δ at which the fault is cleared exceeds the critical clearing angle δ_{cr} or if the time taken to clear the fault is longer than t_{cr}, then stability will not be maintained

The procedure used in the transient stability limit of synchronous generators will be modified to be used in the analysis for the transient stability limit of induction generators. The motion equation of induction generator given in Equation (6) will be used to determine the transient stability limit of induction generator during electrical or mechanical disturbances.

When there is a three phase-fault at the terminals of the induction generator the terminal voltage drops to zero. From standard induction machine theory, the electromagnetic torque produced by the induction generator is proportional to the square of the terminal voltage. Hence during fault the electromagnetic induced torque, T_e, in the induction generator will be zero. For simplicity the friction coefficient D in Equation (6) will be neglected. Integrating Equation (6), with D = 0, and rearranging gives a time expression of:

$$t = \frac{J}{T_m}\left(\omega_m(t) - \omega_{mo}\right) \qquad (8)$$

Where $\omega_m(t)$ - is the rotor speed at any time and
ω_{mo} - is the rotor speed just before the fault.

The torque versus rotor speed curve given in Fig. 4 is used for the explanation of the transient stability limit of the induction generator. The mechanical input torque T_m to the induction generator is assumed to be constant during the fault.

Suppose the induction generator is operating at rotor speed ω_{mo}. Using the motion equation given in Equation (6) the induced electromagnetic torque in the induction machine will be produced equivalent to the mechanical input torque. This steady state operation will enable the induction generator to operate at constant rotor speed ω_{mo} and the rate of change of speed in Equation (6) will be zero.

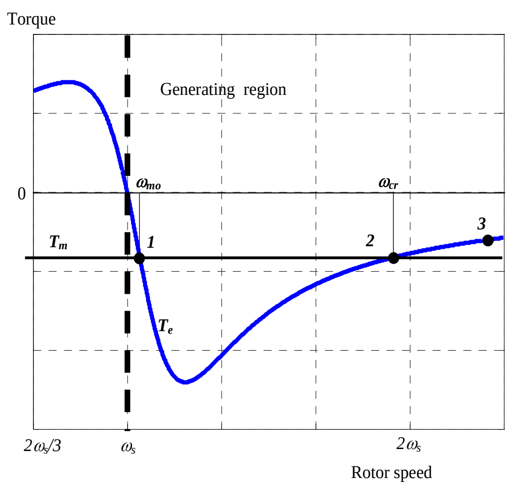

Fig. 4 Transient stability analysis for induction generator

If a fault occurs at point ***1*** while the induction generator was operating at rotor speed ω_{mo}, then the rotor speed of the induction generator will increase due to the net accelerating torque. The fault can be cleared quickly or slowly. The increase in angular rotor speed depends on the time taken to clear the fault.

If the fault is cleared before the rotor speed reaches ω_{cr}, operating point indicated as point **2**, in the then there will be net retarding torque because T_e is more than T_m. This retarding torque will decelerate the induction generator until it reaches its pre-fault operating point at rotor speed of ω_{mo}.

If the fault is cleared when the rotor speed of the induction generator is greater than ω_{cr}, for instance ther rotor speed indicated by point **2**, then there will be net accelerating torque because T_m is more than T_e. This accelerating torque will accelerate the induction generator further and stability will not be maintained.

Using Equation (8) the critical clearing time t_{cr} can be calculated from the critical clearing rotor speed ω_{cr} given by:

$$t_{ct} = \frac{J}{T_m}\left(\omega_{cr} - \omega_{mo}\right) \qquad (9)$$

5. STAND-ALONE INDUCTION GENERATOR

For a stand alone induction generator such as a self-excited induction generator, when there is a three-phase fault at the terminals of the generator the voltage will be zero and it stops generating. Due to this collapse in voltage the self-excited induction generator has got an inherent short-circuit protection mechanism. A change in loading will change the synchronous speed of the induction generator and as a result the frequency and the generated voltage [15].

6. CONCLUSION

In this paper the analysis of the steady state stability limit and transient stability limit of induction generators has been developed in a similar way to the well-established synchronous generator stability limit analysis. Induction generator will be able to continue to supply power if the fault is cleared while the rotor speed is less than the critical angular rotor speed. The analysis given in this paper for the stability of induction generators is based on the assumption that the terminal voltage will be recovered to its pre-fault condition after the fault is cleared.

The method discussed in this paper will have application in the growing application of induction generator connected to the grid.

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