ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.2, Pages : 79-84 (2013)
Special Issue of NCRTECE 2013 - Held during 8-9 February, 2013 in SMK Fomra Institute of Technology, OMR, Thaiyur, Kelambakkam, Chennai

Transient Stability Improvement by Plugging Mode Operation of Grid Connected Squirrel Cage Induction Generators

T.Maheswaran[1], M.Venkateswaran[2]

Department of Electrical and Electronics Engineering,

Adhiyamaan College of Engineering, Hosur, India

[1]tmmaheswaran@gmail.com

[2]venwara@yahoo.co.in

Abstract **- Recently a new and simple method to mitigate the transient instability of squirrel cage induction generators (IG) without using any additional equipment. The majority of the fixed speed wind turbines are equipped with squirrel cage IG and ac connected to the power system. During a fault in power system, voltage and rotor speed instability may occur, especially when the strength of the system compared to the power delivered by the IG is relatively low. For stability improvement, the possibility of altering the operating mode of the induction machine from the generating to the plugging mode for a short time. A simulated model of the system is developed with MATLAB and the system studies of induction machine are carried out with this model.Simulation results show that the proposed method can be effective in enhancing the transient stability. The speed, electric torque, stator and rotor current plots are obtained.**

Index Terms **- Induction generators (IGs), plugging mode, squirrel-cage, transient stability.**

I. INTRODUCTION

The major concern related to the high level of wind power penetration is their impact on power system stability. Many wind power generators are induction machines, either squirrel-cage or wound rotor. Under the conditions of rather high power of induction generators (IGs) connected to relatively weak networks, there is a possibility of transient instability [1]. Faults that occur on the transmission line can lead to wind generator over speed and cause instability of the network voltage [2]. It is well known that a severe disturbance due to a fault in the connected network may cause a significant speed increase of the turbine and the rotor. After fault clearance and voltage recovery, the rotor speed of the IG may be so high that it does not return to a stable value [4].

Previous researches have revealed that flexible ac transmission system (FACTS) devices, rotor circuit control, and braking resistors are three methods that can improve the IGs stability.

In [5], the effect of FACTS devices on regulating bus voltage and, therefore, on improving transient stability is presented. In [6] and [7], it is shown that SVC and STATCOM considerably improve the system stability during and after disturbances. Also in [8], the effect of unified power flow controller (UPFC) on improving the rotor speed stability and voltage ride-through of IG are analyzed. But solutions based on the FACTS devices have been recognized as expensive methods.

Approaches based on the rotor circuit control have been investigated in [9] and [10]. One possibility is to employ an electronically controlled external resistance connected to the rotor windings [9]. Another one is to control the voltage applied to the rotor through a static converter in doubly fed IGs [9]. However, this method is only applicable to the wound rotor IGs and cannot be applied to the squirrel-cage IGs. In [11] and [12], using the braking resistor is introduced as a solution for improving transient stability of IGs. Application of this method for transient stability enhancement of synchronous generators has been investigated for many years [13]. The braking resistor decreases the rotor speed and hence improves transient stability by absorbing electrical power during the fault. However, the operation of an IG is significantly different from that of a synchronous generator and the braking resistor is less effective for improving the IG's stability than synchronous generators stability. The absorbed electrical power by the braking resistor is proportional to the square of the voltage. For synchronous generators, during the fault, terminal voltage of the generators can be increased by increasing the amount of exciting current. Also, existence of the braking resistor improves the power factor of synchronous generators and, therefore, decreases the effect of armature reaction. Reduction of the armature reaction effect increases the terminal voltage of synchronous generator. But for IGs which the terminal voltage is dictated by the network, increasing the terminal voltage is not possible. Therefore, braking resistors that are connected to the IGs absorb less electrical power in comparison with the braking resistors that connect to synchronous ones and it shows that the braking resistor is less effective in improving the IGs stability than that of the synchronous generators.

Furthermore, all the three methods mentioned previously (FACTS devices, rotor circuit control, and braking resistor) need additional equipment such as SVC, STATCOM, UPFC, extension resistor, and braking resistor.

ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.2, Pages : 79-84 (2013)
Special Issue of NCRTECE 2013 - Held during 8-9 February, 2013 in SMK Fomra Institute of Technology, OMR, Thaiyur, Kelambakkam, Chennai

In this new method is proposed to mitigate the transient instability of squirrel-cage IGs without using any additional equipment. In the proposed method, the possibility of altering the induction machine's operating mode is employed. After clearing the fault, by just interchanging any two of the stator leads, the operating mode is changed from the generating mode into the plugging mode. In the plugging mode, the rotor speed of the induction machine is decreased as the kinetic energy of the shaft is conducted through the rotor winding and dissipated in the form of heat. Therefore, the deceleration of the rotor speed leads to reduction in reactive power absorbed by the machine, causing ac voltage to increase, and therefore, voltage and rotor speed stability will be improved.

II. STABILITY ANALYSIS OF IG

Basically, operation of IG is different from synchronous generator because of its asynchronous nature. The equal area criterion develop of IG is not a suitable method for evaluating the transient stability.

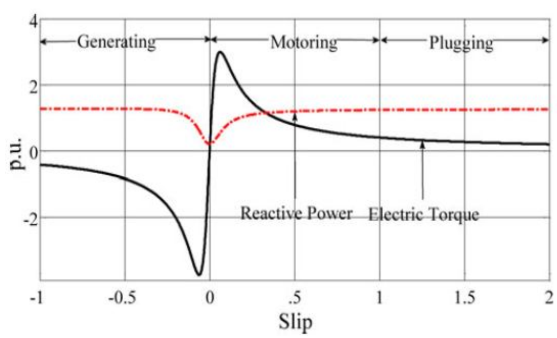

Fig. 1 steady state torque-slip and reactive power-slip curves.

IG's stability can be analyzed using the torque–slip and reactive power–slip curves [5] as shown in Fig.1

A. Normal Operation condition of IG

In the normal and initial operating condition of IG is stable because both the electric generator torque and mechanical turbine torque are balanced level.

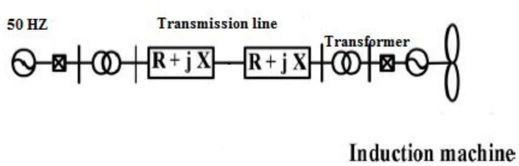

Fig. 2 schematic diagram of the system during pre-fault condition

Fig. 2 shows that the stable operating condition of IG during this condition rotor speed, terminal voltage and electrical torque limits in stable level.

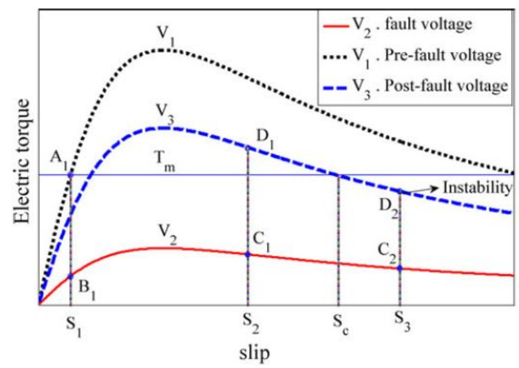

Fig. 3(a)Electric torque – slip curve for evaluation of transient stability of induction machine.

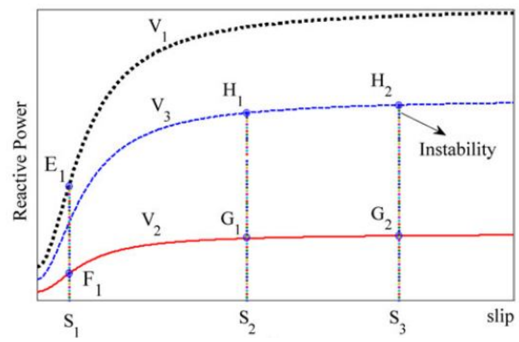

Fig. 3(b) Reactivepower – slip curve for evaluation of transient stability of induction machine.

From the Fig. 3(a) and Fig. 3(b) the IG operates at points $A_1$and $E_1$with an ac voltage of V_1, a rotor slip of S_1, and a rotational rotor speed of ω_{r1}.At this point, the IG is operating at steady state.

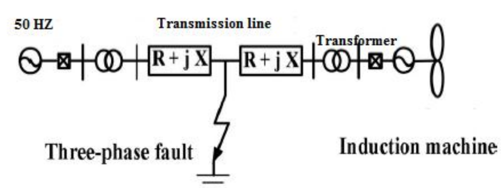

Fig. 4 schematic diagram of the system during post-fault condition

When a system fault occurs on a line at $t = t_1$ as show in Fig. 5, it will cause a sudden drop in the ac voltage, dropping from V_1 to V_2. This, in turn, causes the IG's electrical torque to fall from point A1 to point B1 and reactive power to fall from point E_1 to F_1. As the mechanical torque is much greater than the electric torque, the IG will begin to accelerate and the speed increases. Suppose that, when the fault is cleared at $t = t_2$slip is raised to S_2 , and rotor speed is raised to ω_{r2} corresponding to the operating points C_1 and G_1in Fig. 3(a) and (b). AC voltage will also start to recover. With the IG still operating at a slip of S_2 , it absorbs a large amount of reactive power. This causes the ac voltage to recover to a lower level of V_3 . The operating points will now move tothe points $D_1$and H_1.

ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.2, Pages : 79-84 (2013)
Special Issue of NCRTECE 2013 - Held during 8-9 February, 2013 in SMK Fomra Institute of Technology, OMR, Thaiyur, Kelambakkam, Chennai

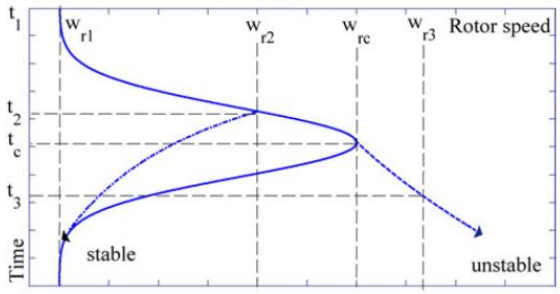

Fig. 5 Rotor speed instability curve.

The electric torque is now greater than the mechanical torque and this act like a braking torque reducing the speed of the rotor and the slip begins to decrease. Deceleration of the IG and decline of rotor slip means a reduction in the reactive power absorbed by the IG. This reduction in the absorbed reactive power, in turn, leads to a rise in ac voltage. As the ac voltage rises from $V_3$to V_1, the electric torque and reactive power will return to their pre fault conditions (points $A_1$and E_1, respectively), thus, the system remains stable [5], [13].

B. Abnormal Operation condition of IG

If the faults were ON for a longer period and not cleared until time $t = t3$, the slip would have increased up to a higher value, say S_3 and rotor speed would have increased to ω_{r3}, as shown in Fig. 7, corresponding to the points C_2 and G_2 . If the fault is cleared at this condition ($t = t_3$), the voltage recovery will push the operating points on D_2 and H_2 . But now the electric torque is still less than the mechanical torque; therefore, the rotor slip continued to increase, making the system unstable. Based on the previous discussion, at the moment of fault clearance, if the slip is less than (note that the slip in the generating mode is negative) critical slip (S_c in Fig. 6) or rotor speed is higher than ω_{rc}, the machine will be unstable; otherwise,it will remain stable. In other word, if the fault were cleared, at time $t<t_c$the system would be stable, and at $t > t_c$ the system would be unstable. Therefore, transient stability can be improved by decreasing the critical slip of the IG [8]. This can be achieved by [14]

1) Decreasing the value of stator resistance, stator reactance, mutual inductance, and rotor reactance.

2) Increasing the value of rotor resistance.

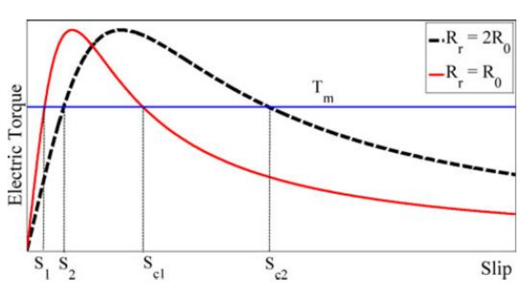

Fig. 6 Transient stability improvement by increasing the rotor resistance and, therefore, increasing the critical slip.

The most effective parameter is the rotor resistance [8]. Transient stability improvement by increasing the rotor resistance is shown in Fig. 6. With the rotor resistance R_0,the stable operating slip varies from its initial value S_1 to the critical slip S_{c1}. When the rotor resistance is increased to $2R_0$, the stable operating range is expanded as from S_2 to S_{c2} therefore, increasing the rotor resistance by a factor of 2 results in a significant expansion in the stable operating range.

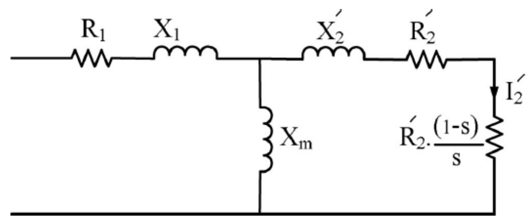

Fig. 7 Equivalent circuit of induction machine.

Nevertheless, in the case of squirrel-cage IG, there is no access to the rotor winding and increasing the rotor resistance isimpossible; therefore, the mentioned method is not applicable.

III. ELECTRICAL TORQUE IN THE PLUGGING MODE

After the fault clearance for transient stability improvement, the proposed method involves changing the operation mode of the machine from the generating mode to plugging mode. Electromagnetic torque of the machine in the plugging mode as backward field and its generating mode as forward field. According to this Fig. 8, the electromagnetic torque in both forward field (generating mode) and backward field (plugging mode) are negative.

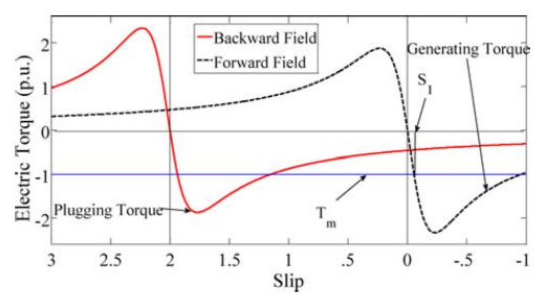

Fig. 8 Electromagnetic torque of induction machine in plugging and generating modes

Equation (1) confirms that it would lead to decrease in the rotor speed after the fault clearance

$$T_m - T_e = Jd\omega/dt \qquad (1)$$

Where

T_m: Mechanical Torque

ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.2, Pages : 79-84 (2013)
Special Issue of NCRTECE 2013 - Held during 8-9 February, 2013 in SMK Fomra Institute of Technology, OMR, Thaiyur, Kelambakkam, Chennai

T_e : Electrical Torque

J : Moment of inertia

ω: Rotor speed

Generating mode (slip <0) and plugging mode (slip>1), the machine power is negative. Negative P_e in the plugging mode implies that kinetic energy of the rotor is dissipated in the form of heat in the rotor winding

$$P_e = 3R'_2 I'_2 (1-s)/s \qquad (2)$$

From Fig. 8 at the operating slip of s_1 , the machine generates less electrical torque in the plugging mode than in the generating mode. Therefore, changing operating mode from generating mode to plugging mode makes the system more probable to instability. Because, in the plugging mode, the difference between the mechanical and electrical torques gets larger than that in the generating mode and according to (1), the machine in plugging mode accelerates much faster than in generating mode.

IV. SIMULATION AND RESULTS

A. MATLAB Simulation Model

The basic configuration of a DFIG driven by a wind turbine is shown in Fig. 9. The wind turbine is connected to the DFIG through a mechanical shaft system, which consists of a low and a high-speed shaft with a gearbox in between.

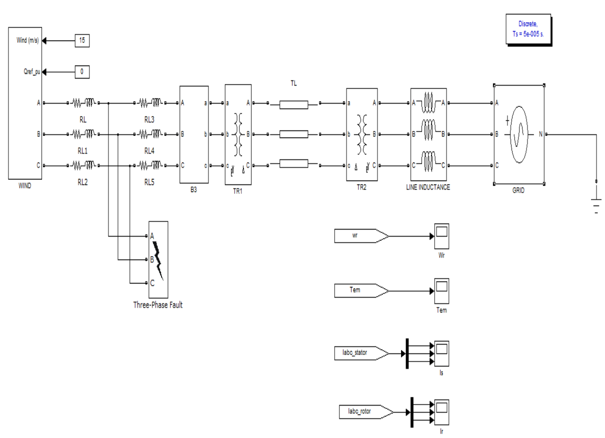

Fig. 9 Schematic diagram of MATLAB Simulation model

The Squirrel cage IG is directly connected through a transmission line to the utility grid as shown in Fig. 9.The simulation model is developed in MATLAB using Simulink and Sim Power System set toolboxes.
In the simulation model, DFIG wind turbine, three phase programmable voltage source, line inductance and three phase transformer (two winding) are provided.Thus, changing the machine operation into the plugging mode will have reverse effect on transient stability of this machine.

A. Simulation Results

After clearing the fault at 0.4s, the operating mode of machine is changed from generating to plugging mode in the interval between 0.4s and 0.5s. At time 0.5s, the machine is returned to the generating mode again.The successful solutions are those that can amplify electrical torque versus mechanical torque after fault clearance. The solution proposed in this paper involves changing the operating mode of the machine after clearing the fault from the generating mode to the plugging mode. It can be done as simply as by interchanging any two leads of the stator supply. By doing this, the direction of the rotating field is reversed. This causes a breaking effect on the rotor, thus decreasing the rotor speed.
The corresponding speed, torque and stator and rotor current curve are plotted below in Fig. 10

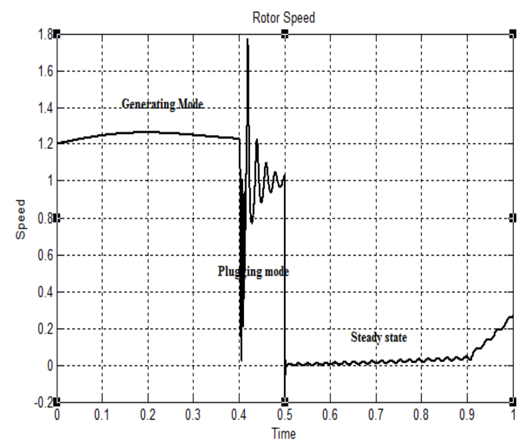

Fig. 10(a) Rotor speed curve in both generator and plugging mode

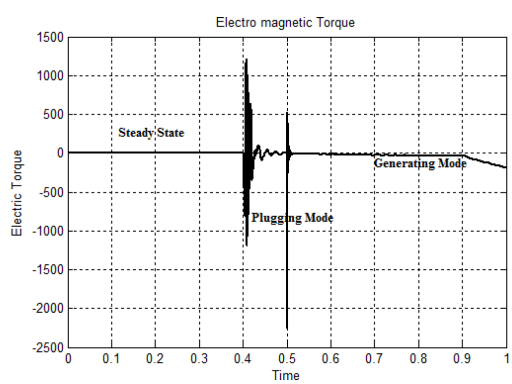

Fig. 10(b) Electrical torque curve in both generator and plugging mode

Starting current, short-circuit current, plugging current, and steady-state current of Fig. 10. As mentioned before, in the plugging mode, the machine produces reverse electromechanical torque, opposing the mechanical torque, which wastes the kinetic energy of the machines, as heat in the rotor winding, causing the rotor speed to be decreased. In order to complete the discussion, it should be investigated whether this intensive current in the plugging mode can cause damage to the rotor or stator windings or not.

During plugging, the machine current is approximately equal to starting current. Machine rotor and stator current variations, in start-up, fault, plugging, and steady-state operation, are plotted in Fig.10(c) and (d), respectively. These figures indicate that the rotor and stator currents in the plugging mode and starting condition are almost equal. The frequency of the rotor current in the plugging mode is twice that in the starting condition shows that rotor resistance in the plugging mode is about 0.4s times its value in the starting. Start-up takes about 0.45s, while the plugging period is about 0.4 to 0.5s.

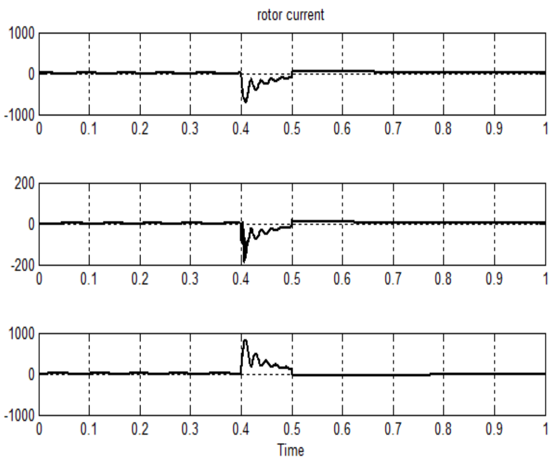

Fig. 10(c) Each phase rotor current in both generator and plugging mode.

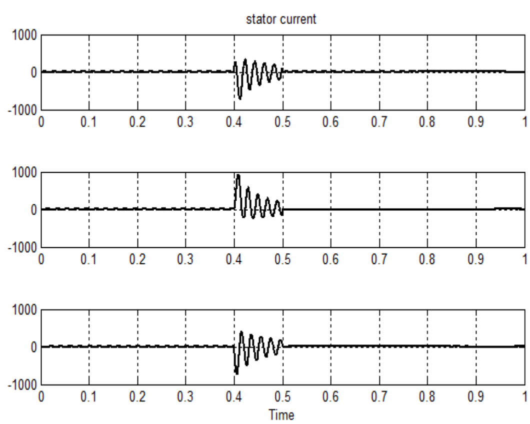

Fig. 10(d) Each phase stator current in both generator and plugging mode.

V. CONCLUSION

In wind energy systems one of the popular types used is squirrel-cage IG due to its simplicity, reliability, low weight, low cost, and low maintenance cost. One of the main disadvantages of the wind farms that equipped with this type of generators is the transient stability problem. In this paper, a simple method was presented for preventing instability of grid connected squirrel-cage IGs, when a fault occurs in the network. In the proposed method, the speed of the generator is controlled by changing the operating mode from generating to plugging, for limited time interval after fault clearance.

REFERENCES

[1] M. Rahimi and M. Parniani, “Dynamic behavior and transient stability analysis of fix speed wind turbine,” *Renewable Energy*, vol. 34, no. 12, pp. 2613–2624, Dec. 2009.

[2] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, “Definition and classification of power system stability,” *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387–1401, Aug. 2004.

[3] Mohammad Hassan Zamani, Seyyed Hamid Fathi, G. H. Riahy, MehrdadAbedi, and NazaninAbdolghani, “Improving transient stability of grid connected squirrel cage induction generators by plugging mode operation,” *IEEE Trans. Energy conversion*, vol. 27, no. 3, pp. 707–714, Sep. 2012.

[4] H. Li, Z. Chen, and L. Han, “Comparison and evaluation of induction generator models in wind turbine systems for transient stability of power system,” in *Proc.IEEE Int. Conf. Power Syst. Technol*., 2006, pp. 1–6.

[5] N. A. Lahacani, D. Aouzellag, and B. Mendil, “Static compensator for maintaining voltage stability of wind farm integration to a distribution network,” *Renewable Energy*, vol. 35, no. 11, pp. 2476–2482, Nov. 2010.

[6] L. Xo, L. Yao, and C. Sasse, “Comparison of using SVC and STATCOM for wind farm integration,” in *Proc.IEEE Int. Conf. Power Syst.* Technol., 2006, pp. 1–7.

[7] R. Jayashri and R. P. K. Devi, “Effect of unified power flow controller to mitigate the rotor speed instability of fixed-speed wind turbine,” *Renewable Energ*., vol. 34, no. 3, pp. 591–596, Mar. 2009.

[8] V. Akhmatov, H. Knudsen, A. HNilsen, J. K. Pedersen, and N.K. Poulsen, “Modeling and transient stability of large wind farms,” *Electr. Power Energy Syst*., vol. 25, no. 1, pp. 123–144, 2003.

[9] M. Nunes, J. Lopes, H. Z¨ urn, U. Bezerra, and Almeida, “Inuence of the variable-speed wind generators in transient stability margin of the conventional generators integrated in electrical grids,” *IEEE Trans. Energy* Convers., vol. 19, no. 4, pp. 692–701, Dec. 2004.

[10] W. Freitas, A.Morelato, andW. Xu, “Improvement of induction generator stability using braking resistors,” *IEEE Trans. Power Syst*., vol. 19, no. 2, pp. 1247–1249, May 2004.

ISSN 2278-3091

International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 , No.2, Pages : 79-84 (2013)
Special Issue of NCRTECE 2013 - Held during 8-9 February, 2013 in SMK Fomra Institute of Technology, OMR, Thaiyur, Kelambakkam, Chennai

[11] M. H. Ali and B. Wu, “Comparison of stabilization method for fixed speed wind generator systems,” *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 323–331, Jan. 2010.

[12] W. H. Croft and R. H. Hartley, “Improving transient stability by use of dynamic braking,” *IEEE Trans. Power App. Syst.*, vol. PAS-81, no. 3, pp. 17–24, Apr. 1962.

[13] J. Machowski, J. W. Bialek, and J. R. Bomby, *Power System Dynamic: Stability and Control*, 2nd ed. New York: Wiley, 2008.

[14] L. Dusonchet and E. Telaretti, “Effect of electrical and mechanical parameters of induction generator on the transient voltage stability of a fixed speed wind turbine,” *Electr. Power Syst. Res.*, vol. 81, pp. 1308–1316, Jul. 2011.

[15] C. D. Beck and R. G. Rhudy, “Plugging an induction motor,” *IEEE Ind. General Appl.*, vol. IGA-6, no. 1, pp. 10–18, Feb. 1970.

[16] W. Stepherd, “Voltage and impedance conditions for the rapid plugging of induction motors including saturator control,” *Proc. IEE*, vol. 111, no. 10, pp. 1713–1628, Oct. 1964.

[17] K. Oberretl, “Influence of skin effect onmutual inductance of double cage induction motors,” *Electr. Eng.*, vol. 87, pp. 103–111, 2005.

[18] J. Sim, K. Lee, G. Cha, and J. Lee, “Development of a HTS squirrel cage induction motor with HTS rotor bars,” *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 916–919, Jun. 2004.