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Transient Stability Improvement of Squirrel Cage Induction Wind Turbine Generator using Plugging Mode

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Abstract: Squirrel cage induction generator has been seen as best electrical machine so far for fixed speed wind turbine generator applications. As wind power plants are always connected to grid, any fault on the power system may lead to voltage and rotor speed instability. The condition arises especially when strength of the system is relatively lower than power delivered by induction generator (IG). This paper focuses on improvement in transient stability of power system connected to IG using plugging as it is very easier and economical than other methods such as braking resistors and use of FACTs devices. The unique property of squirrel cage machines is that reversal of direction of rotating flux is very simple and less time consuming without need of any auxiliary equipment. Thus after clearing the fault, the machine is operated in reverse direction for short period of time. This causes opposition between mechanical torque and rotating flux preventing generator from further acceleration during fault condition. The simulation of proposed method is carried out which shows that the method can be effectively used in transient stability improvement. The major advantage of this method is that there is no need of auxiliary equipment which makes this method more attractive than existing methods from economic point of view.

Keywords - Squirrel Cage Induction Generators, Plugging Mode, Transient Stability, grid connected, auxiliary equipment, rotor flux.

I. INTRODUCTION

Due to continuous increasing demand of electrical energy, the capacities of renewable energy based electricity generation systems are being explored. Out of all renewable energy sources wind turbine generation systems have been proved to be sole representative. All the wind turbine systems are either equipped with squirrel cage or wound rotor induction generator. The possibility of transient instability occurs when generator is penetrating high power to comparatively weak networks [1]. Under such condition, if fault occurs on a system then it leads to over speeding of generator causing voltage instability [2]. It is well known that small disturbance in a power system makes significant variation in rotor speed of generator. Even after clearance of fault and voltage recovery, the speed of generator is so high that it may not come to stable value [3].

As far as previous researches are concerned, there are various methods to control transient instability of IGs like Flexible AC Transmission Systems (FACTS) devices, rotor circuit control and braking resistors. In [4] effect of voltage regulation to control transient instability by FACTs devices is explained. Effect of voltage regulation during and after the fault in order to prevent instability with the help of SVC and STATCOM is presented in [5] and [6]. [7] analyzes the effect of unified power flow controller (UPFC) on voltage instability and also improvement in fault ride through capability of IGs. But the solution of FACTs devices is considered to be very expensive.

In [8] and [9] transient stability improvement using rotor circuit control has been presented. Electronically controlled external resistance connected to rotor windings and or static converter based voltage injection connected to rotor windings are some possibilities [8]. However these methods are only applicable to double fed induction generators (DFIGs) where rotor is wound but not to squirrel cage induction generator. In [10] and [11] transient stability improvement using braking resistor has been investigated. Braking resistors absorb power during fault condition thereby reducing rotor speed and preventing instability of generator. However absorption of power by braking resistor is less effective in case of long duration of fault which makes this method ineffective for improving transient stability of IGs [11].

All the three methods mentioned above need additional equipment such as SVC, STATCOM, UPFC, external resistance or braking resistors. [12] has elaborated importance of plugging operation in induction machine which highlighted the possibility of using plugging to improve transient stability.

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In this paper plugging operation is used to improve transient stability of grid connected squirrel cage generator without using any equipment.

The possibility of altering the induction machine's operating mode is employed in proposed method. After clearing the fault the operating mode of machine is changed from the generating mode into the plugging mode just by interchanging any two of the stator leads. 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. MATHEMATICAL MODELING

Mathematical model of the system is the equivalent circuit representing all the parameters of the machine. Mathematical model is best suited for analysis of the machine as all the parameters affecting performance of the machine can be viewed on single diagram and thus analysis becomes easier. Thus it is always recommended to build equivalent circuit of an electrical machine for the analysis purpose.

For transient analysis of any system, equivalent circuit of that system proves vital role in analyzing the system. Transformer model of an induction machine can be represented as follows:

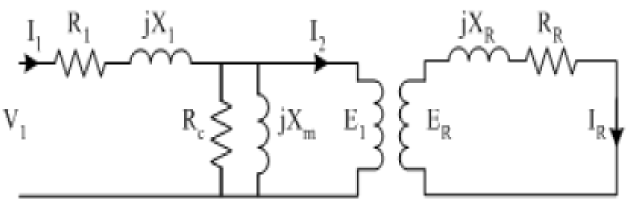

Fig.1 Equivalent circuit of induction machine

where,

V_1 = Phase RMS Voltage
I_1 = Stator Phase Current
R_1 = Stator Winding Resistance
X_1 = Stator Winding Leakage Reactance
X_m = Magnetizing Reactance
Rc = Core Loss Resistance
E_1 = Air Gap Voltage
I_2 = Rotor Current Referred to Stator
E_R = Rotor Induced Voltage (Actual)
I_R = Rotor Current Voltage (Actual)
X_R = Rotor Leakage Reactance (Actual)
R_R = Rotor Resistance (Actual)

Full Equivalent Circuit referred to the stator is as follows,

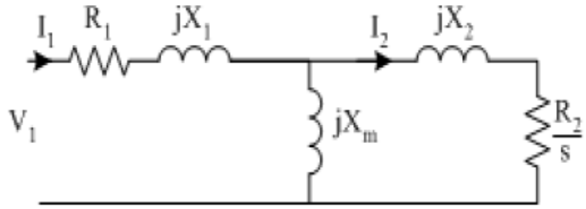

Fig.2 Equivalent circuit of IM referred to stator

The above circuit can be redrawn as follows,

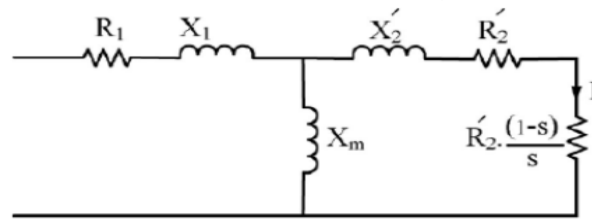

Fig.3 Approximate Equivalent circuit of IM

The input power to a three-phase induction machine is given by

$$P_{in} = \sqrt{3}V_{LL}I_L\cos\theta = 3V_1I_1\cos\theta \quad \ldots\ldots\ldots\ldots(1)$$

From the above circuit, it can be seen that the total power transfer to the rotor is given by

$$P_{gap} = \frac{3I_2^2R_2}{s} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

To find the power converted to the mechanical system the rotor joule loss must be subtracted from the total rotor power

$$P_{conv} = P_{gap} - P_{RCL}$$

$$P_{conv} = \frac{3I_2^2R_2}{s} - 3I_2^2R_2$$

$$P_{conv} = 3I_2^2R_2\frac{(1-s)}{s} \quad \ldots\ldots(3)$$

From the above equations, it can be seen that power converters to the mechanical system is a function of the air gap power and slip

$$P_{conv} = (1-s)\,P_{gap} \quad \ldots\ldots\ldots..(4)$$

Equation of total power converted P_{conv} is the required equation which has been used in analysis. This equation is used to calculate amount of power dissipated in the rotor during plugging operation.

III. TRANSIENT STABILITY OF IG

The method of equal area criteria which was developed for synchronous generators is not suitable for stability analysis of induction generators. Generalized torque-slip and absorbed reactive power-slip characteristics of induction generator are shown in figure 4.

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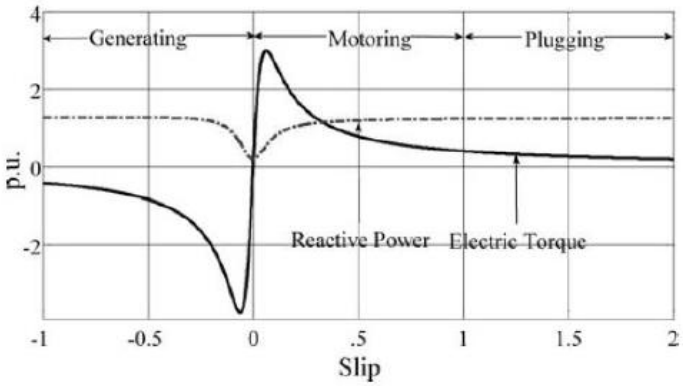

Fig.4 Torque-slip and reactive power-slip curves

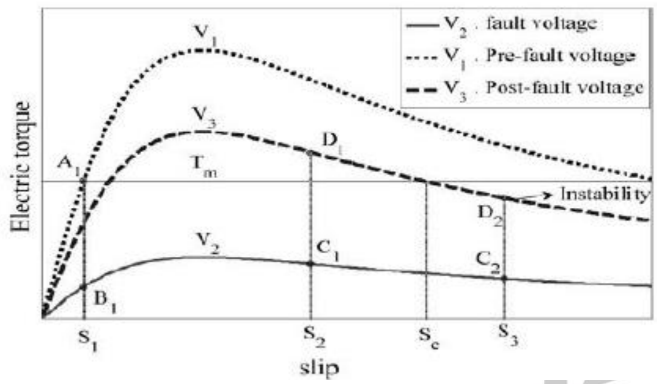

Fig. 5(a) Torque-slip curves during transient period

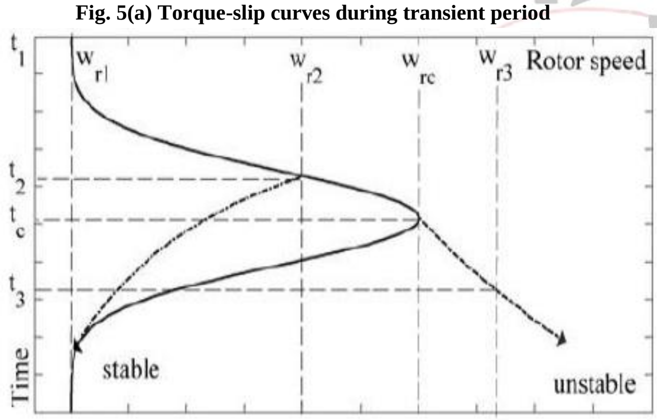

Fig. 5(b) Rotor speed-time curves during transient period

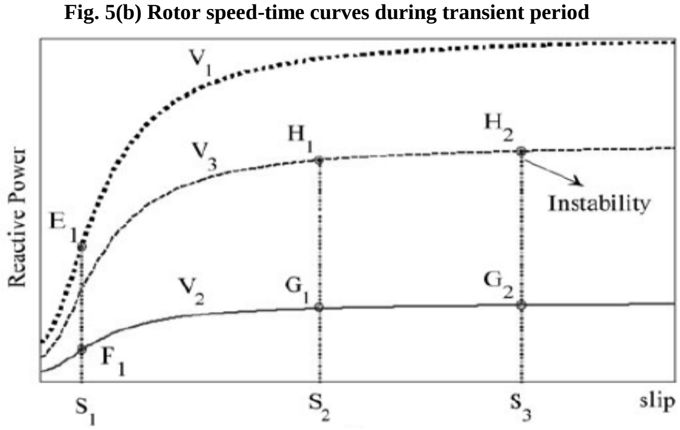

Fig. 5(c) Reactive power - slip curves during transient period

A. Stable Operation

Initially and during the normal operation, the electrical generator torque and the mechanical turbine torque are balanced. 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 ωr1. At this point, the IG is operating at steady state. When a system fault occurs at $t = t_1$, 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 A_1 to point B_1 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_1 in Fig 5(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 to the points D_1 and H_1. 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.

B. Unstable Operation

If the faults were ON for a longer period and not cleared until time $t = t_3$, 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. 5(b), 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 (Sc in Fig. 5) 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.

IV. PLUGGING OF INDUCTION MACHINE

Plugging induction motor braking is done by reversing the phase sequence of the motor. Plugging braking of induction motor is done by interchanging connections of any two phases of stator with respect of supply terminals. And with that the operation of motoring shifts to plugging braking. During plugging the slip is (2 - s), if the original slip of the running motor is s, then it can be shown in the following way.

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$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$

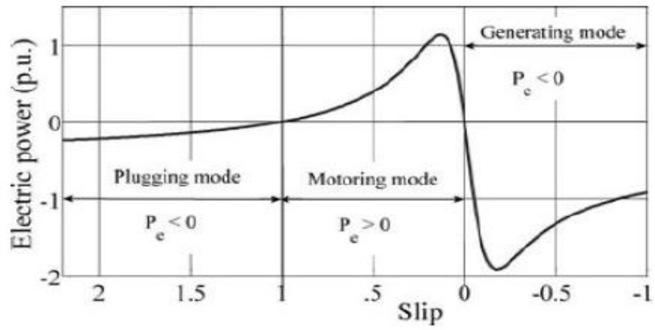

Fig. 6 Electrical Power - slip curves during generating, motoring, and plugging mode

Authors suggested that this same method can be used for induction generator connected to grid. Induction generator running at full speed if plugged then due to interchanging of phase sequence reversal of rotating field happens which causes the braking effect on the rotor to reduce its speed.

V. Simulation and Results

A. Plugging of Induction Machine:

Following model shows plugging operation of induction machine. Standard SI Unit Asynchronous Machine form Sim Power Systems has been used and it has been supplied by three separate sources. Breakers are used to switch on and switch particular line and this switching is used for plugging operation. As in plugging, we have to change phase sequence of machine so provide that condition breakers have been used. This is just to understand the concept of plugging. This methodology has been used in actual model as one subsystem.

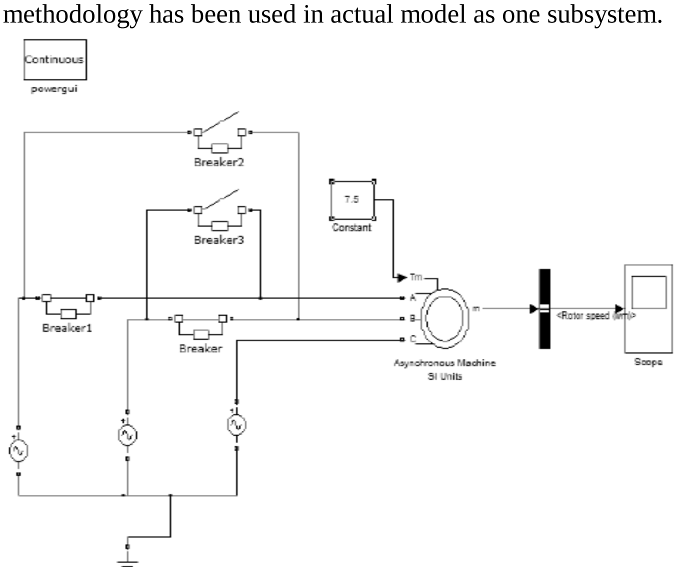

Fig.7 Simulink diagram of plugging of IM

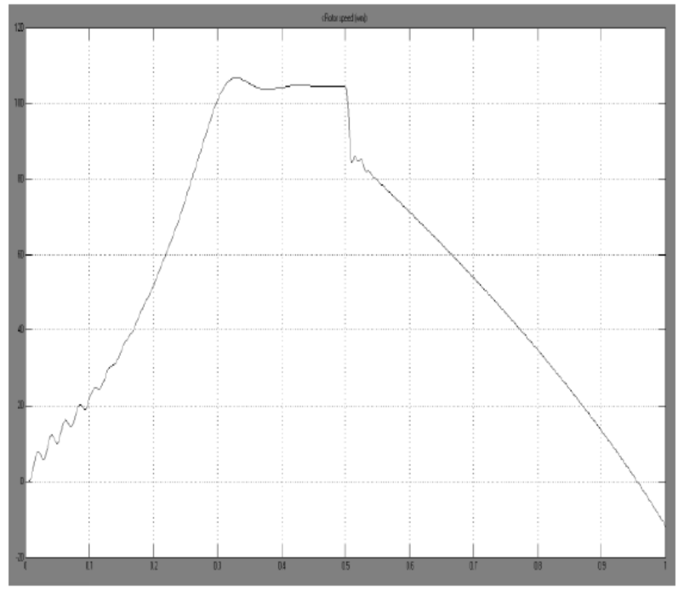

Fig.8 Rotor speed vs time before and after plugging

B. Induction Generator connected to Grid:

Figure shows the actual system of squirrel cage induction generator connected to grid. In this model 480 V, 60 Hz, 300 kVA three phase source has been used as grid. Asynchronous motor has been used as induction generator and torque generation required for induction generator is fulfilled by wind turbine. Wind turbine block has been taken as it is from sim power systems. The specifications of Induction generator are 480 V, 60 Hz, 4 pole , 275 kVA. Three phase breaker has been used to create three phase to ground fault. 250 kW load is connected to the system. VM is the three phase voltage measurement unit. Plugging is the subsystem used to create plugging condition.

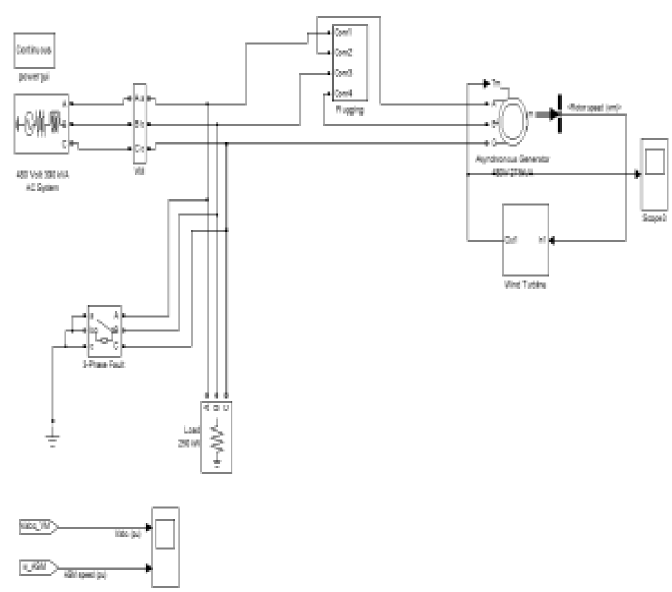

Fig.9 Induction Generator connected to Grid

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C. System with Short Duration Fault and Without Plugging (Stable):

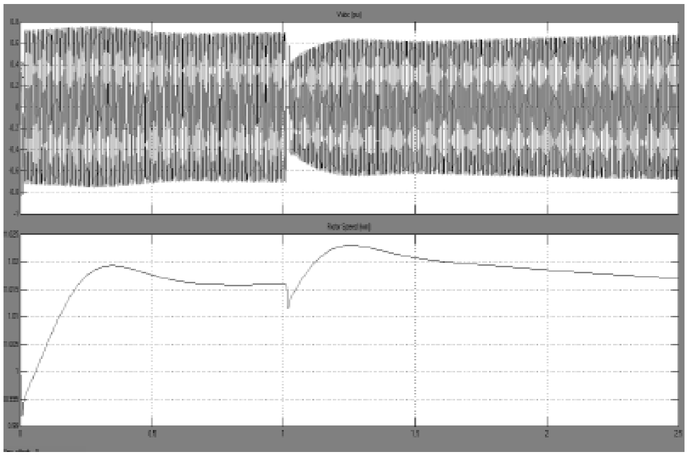

Fig.9 Voltage and rotor during short duration fault

When fault for short period of time occurs on the system then rotor speed increases for that period before clearing of fault. Just after the clearance of fault rotor speed decreases and becomes stable. During fault period voltage fluctuates but becomes stable just after the clearance of fault. Thus if fault is for shorter interval then system remains in stable mode.

D. System with Long Duration Fault and Without Plugging (Unstable):

When the fault occurs on the system for longer duration, rotor speed and voltage start becoming unstable. But after the clearing the fault rotor speed reaches to so high value in unstable region that it may not come to normal mode and system becomes completely unstable.

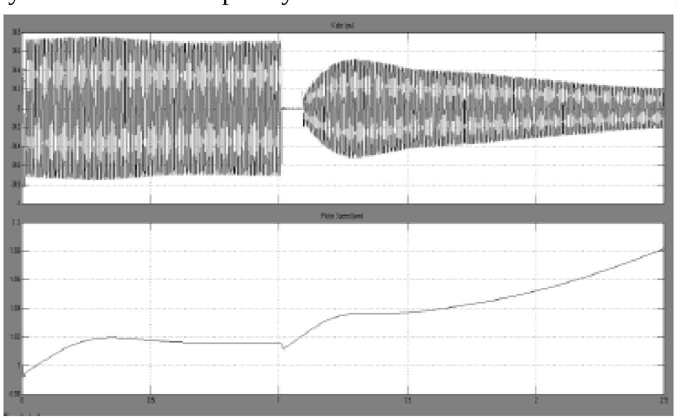

Fig.10 Voltage and rotor during long duration fault without plugging

E. System with Long Duration Fault and With Plugging (Stable):

During longer fault period even though rotor speed and voltage go in the unstable region, just after the clearance of fault if induction generator is operated in plugging mode then rotor speed gradually decreases and comes to stable value. Similarly the reduction in voltage due to fault gets compensated by reactive power and voltage profile comes to its rated value.

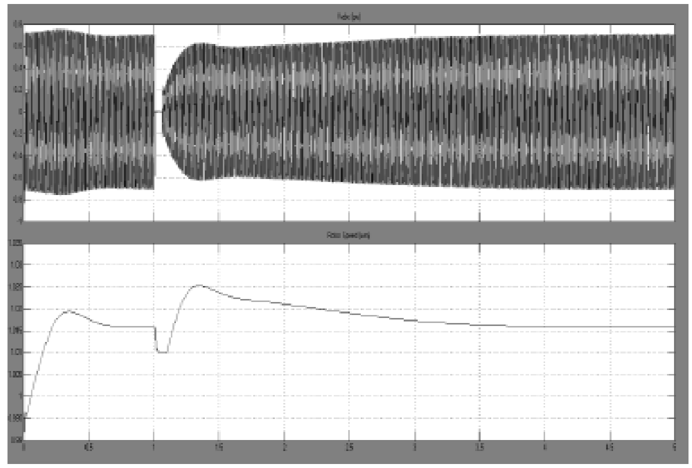

Fig.11 Voltage and rotor during long duration fault with plugging

VI. 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 limitations of the wind turbine systems that equipped squirrel cage induction 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. From the simulation results it has been observed that speed of machine decreases because of plugging and stabilizes to rated value after the clearance of fault. Simulation results confirm the effectiveness of the given method, which seems to be a more economical alternative in comparison with the other methods like braking resistor and FACTs devices.

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