Transient Stability Evaluation of Wind Farms Implemented with Induction Generators

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Abstract- The progress of wind-energy generation around the world in recent years has been consistently impressive. As more and more attention is paid to the increase of wind-turbine farms, a number of problems should be investigated in more detail. Among these problems, the transient stability of wind farms implemented with induction generators becomes necessary, especially when operating into a weak connection. The transient behavior and stability of wind farms with induction generators have been studied in this paper and some important operating conditions are analyzed. The impact of some important parameters such as strength of main grid, of X/R ratio of the transmission line on the transient stability of wind farm, and operation during severe faults are all investigated. The results of simulation show that these parameters have a great impact on the transient stability of wind farm. Power-system oscillation caused by a transient fault in the vicinity of a wind turbine is the worst case scenario, as the wind turbine has to ride through the fault and keep its stability.

I. INTRODUCTION

In many countries wind power expands, and covers a steadily increasing part of these countries power demand. The total operating wind power capacity in the world has increased from approximately 2000 MW in 1990 to well over 16,000 MW by the end of 2000. Continued rapid growth is expected, with a predicted 50,000 MW of operating wind power capacity by year 2010 [1]. This development is due to strong world wide available wind resources, environmental concerns, and the improved cost efficiency of new wind technologies. As more and more attention is paid to the increase of wind farm, a number of problems should be investigated in more detail especially in weak main grid. Among these, transient stability evaluation, voltage control assessments and reactive power compensation are increasingly important. The importance will be great in wind farms with induction generators. The voltage stability is one of the most important factors that affect the wind farm's stable operation. Voltage instability problems and collapse typically occur on power systems that are not able to meet the demand for reactive power, are heavily loaded and/or faulted [2]. In the present work, the problems related to the characteristics of the wind turbine induction generators are paid more attention than the ordinary loads in the system. On the other hand, generation can also be viewed as a complex load, but with a negative real part (representing production) in contrast to an "ordinary" load.

The voltage stability phenomenon covered by the present work may be classified as transient voltage stability, since the power output of the wind turbine generator normally varies significantly within a time frame of a few seconds, reflecting the incoming wind speed variations at the wind turbine.

This work focuses on the impact of different parameters on the transient stability of wind farms with induction generators. The simulation results show that the transient instability of wind farms and network voltage are relative to the strength of main grid. The *X/R* ratio of the transmission line impedance also has great impact on the output of the induction generators.

The rest of this paper is organized as follows: section II describes system components modeling. Section III explains the study system. The results of simulation are presented in section IV. Conclusions are finally made in section V.

II. SYSTEM COMPONENTS AND MODELING

A. Wind Energy Conversion System Model

The complete model of a wind energy conversion system is constructed from a number of components. The detail model is depicted in Fig. 1. For the modeling of the wind turbine rotor aerodynamic, the aerodynamic power coefficient method is used:

$$T_a = \frac{1}{2}\rho\, C_t(\lambda)\pi\, R^3 V_w^{\ 2} \qquad (1)$$

where T_a is the aerodynamic torque, ρ is the air density, R is the wind turbine radius, $\lambda = R\,\Omega_b / V_w$ is the ratio of blade tip speed to wind speed, Ω_b is the wind turbine rotational speed (rad/sec).

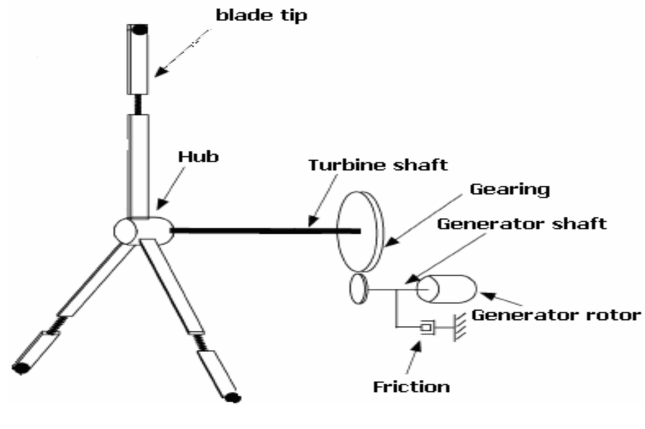


Fig. 1. Detailed model of a single wind energy conversion system.

The wind turbine blade aerodynamics is characterized by a nondimensional curve of torque coefficient C_P as a function of tip speed ratio λ for various blade pitch angle β, so $C_t(\lambda)= C_p(\lambda,\beta)/\lambda$. Where $C_p(\lambda,\beta)$ is [3]:

$$C_p(\lambda,\beta)=c_1\left(\frac{c_2}{\lambda_i}-c_3\beta-c_4\right)e^{\frac{-c_5}{\lambda_i}}+c_6\lambda \qquad (2)$$

Where

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \qquad (3)$$

The value of c_i *(i=1,…,6)* coefficients are:
$c_1=0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21, c_6=0.0068.$

$C_p(\lambda,\beta)$ Characteristic of wind turbine is shown in Fig. 2[4]. The aerodynamic torque (T_a) shifts by gearbox ratio in to rotor shaft of induction generator. It is named electromagnetic torque (T_m). Wind turbine power Characteristic is shown in Fig. 3. For pitch angle control of wind turbine a suitable PI controller is used in this study.

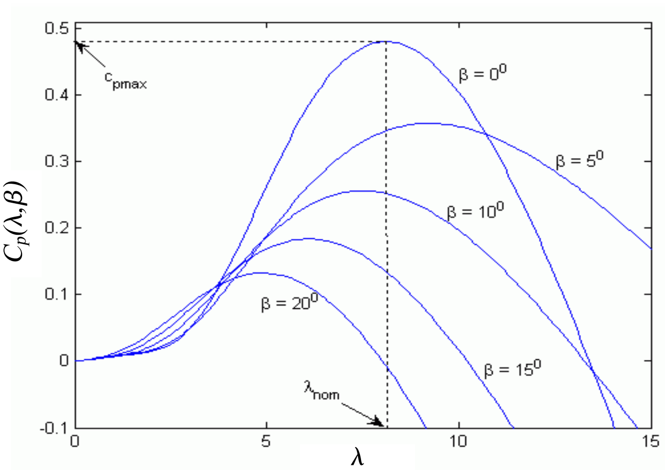


Fig. 2. $C_p(\lambda,\beta)$ Characteristic of wind turbine

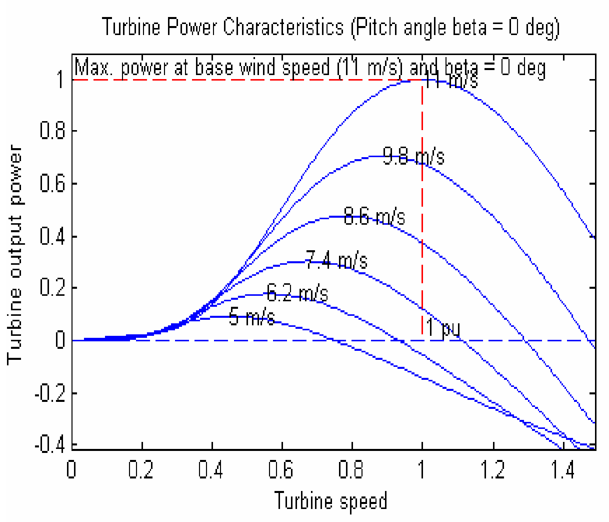


Fig. 3. Turbine output power Characteristic

B. Induction Generator Model

The equivalent circuit of induction generator is shown in Fig. 4. According to this model, voltage and torque equations are [5]:

$$V_r=\frac{j\,X_m\,V_t}{R_s+j\left(X_s+X_m\right)} \qquad (4)$$

$$T_e=\frac{3\,p}{2\,\omega_s}\frac{R_r}{s}\frac{V_r^{\,2}}{\left(R_e+\frac{R_r}{s}\right)^2+\left(X_e+X_r\right)^2} \qquad (5)$$

$$R_e+j\,X_e=\frac{j\,X_m\left(R_s+j\,X_s\right)}{R_s+j\left(X_s+X_m\right)} \qquad (6)$$

Mechanical model of system is given by:

$$\frac{d}{dt}\omega_r=\frac{p}{2\,J}\left(T_m-T_e-F\,\omega_r\right) \qquad (7)$$

Where R_S, R_r, X_s, X_m, X_r are stator and rotor resistances, stator reactance, magnetizing reactance, rotor reactance respectively. Also, p is the number of pole pairs, s is slip, T_e is electromagnetic torque, T_m is Shaft mechanical torque, and J is moment of inertia and F the combined rotor and load viscous friction coefficient. The induction generator and wind turbine parameters are set as shown in (all quantities are referred to the stator) Table I.

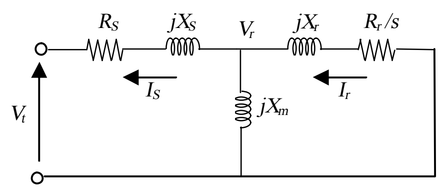


Fig. 4. Equivalent circuit of induction generator

TABLE I
INDUCTION GENERATOR AND WIND TURBINE PARAMETERS

Induction generator	value	Wind turbine parameter	value
R_S	0.00483	P_n(MW)	1.5
L_S	0.1248	V_W(m/s)	11
L_m	6.77	K_P	5
R_r	0.004377	K_i	25
L_r	0.1791	Pitch angle max(deg)	45
P	3	Max rate of change of pitch angle(deg/s)	2
H	5.04	---------	-------
F	0.01	---------	-------

III. STUDY SYSTEM

Fig. 5 shows a single-line diagram of the system used to investigate typical wind farm operational scenarios. Wind farm is connected to an electrical network through a short transmission line. The system also includes 6 wind turbine units that the capacity of each unit is 1.5 MW. The transmission line modeled with series impedance (R_L+jX_L) and its value depends upon the transmission type and the length. In this study, wind speed is assumed 11 km/sec. Also, it is assumed that the main power grid is weak.

IV. RESULTS

To evaluate the transient stability of wind farm implemented with induction generators (study system) under different conditions, several simulation scenarios are defined and several parameters are examined. The results of simulation and discussion are illustrated in the following sub-sections.

A. Impact of Variable Wind Speed on wind farm terminal Voltage

Wind speed variation often result in wind turbine active and reactive power fluctuations, especially when the wind farm connects to a weak main grid, voltage fluctuations resulting in flicker can occur. Fig. 6 shows the output real power changes with the wind speed. Accurate looking at Fig. 6 shows that the voltage at the terminal will change in the opposite direction. As the real power increases, the voltage decreases. The results of simulation can be analytically confirmed by using equations (1), (4), (5), (6) and (7). According to the equation (1), it is clear that torque and power is commensurate with square of wind speed.

$$\frac{d}{dt}\omega_r = \frac{p}{2J}\left(T_m - \frac{3p}{2\omega_s}\frac{R_r}{s}\frac{V_r^2}{\left(R_e+\frac{R_r}{s}\right)^2+\left(x_e+x_r\right)^2} - F\omega_r\right) \quad (8)$$

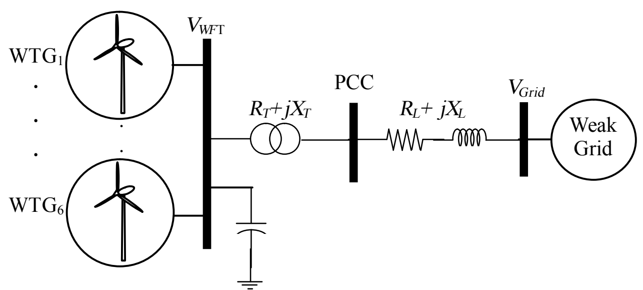


Fig. 5. Single-line diagram of wind farm with a weak grid

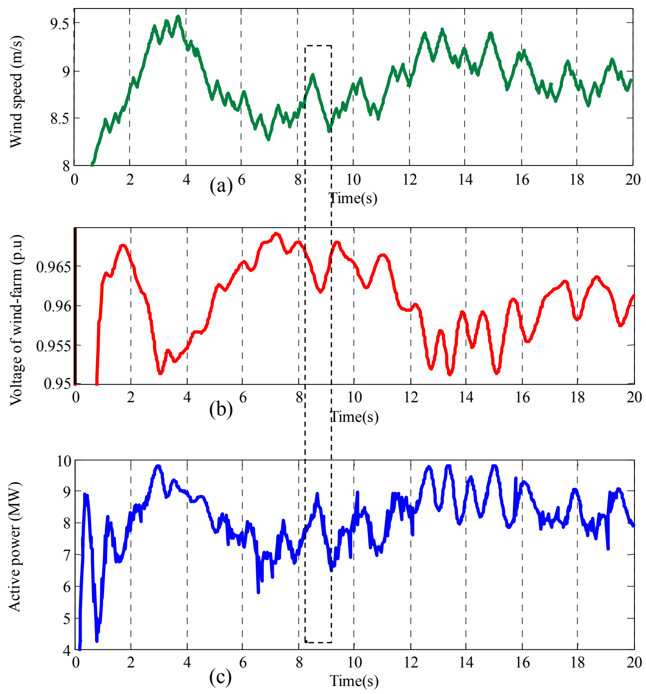


Fig. 6 (a) Wind speed (b) Terminal voltage of wind-farm (c) Output real power.

In induction generator, slip and torque is negative. Therefore:

$$V_r = \sqrt{\frac{\left(R_e+\frac{R_r}{s}\right)^2+\left(x_e+x_r\right)^2}{3p}\frac{s}{R_r}2\omega_S} \times \sqrt{F\omega_r - T_m + \frac{2J}{P}\frac{d}{dt}\omega_r} \quad (9)$$

If wind speed increases, torque (T_m) will increase then slip increase negatively. Consequently, terminal voltage (V_t) decrease.

B. Impact of main grid strength on the terminal voltage of wind farm

The short circuit ratio (*SCR*) has a great impact on the stability of HVDC systems. This parameter is defined as the ratio of AC system short circuit capacity (*SCC*) to DC power and can be used to investigate the system stability. Higher *SCR* can lead to a more stable operation. A similar parameter can be introduced for distributed generation (DG) system but defined as the ratio of SCC to total power of wind farm (SCR_{WF}). Fig. 7 shows that when this parameter is decreased (*A* increased from 5%-15%), terminal voltage of wind farm decrease. Also, from a certain value the voltage stability is missed and consequently the protection system of wind farm is set on 5 second.

C. Impact of X/R Ratio on the Voltage Stability

When a remote wind farm connects with the distribution network, in general, the transmission impedance ratio *X/R* is

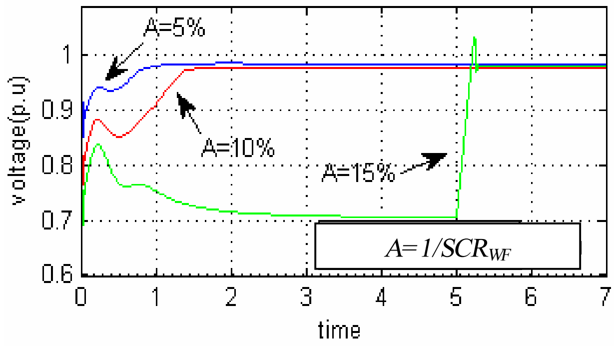


Fig. 7. Terminal voltage variation of wind farm under different SCR_{WF}

in the area from 2 to 10. Fig. 8 shows the relationship of the ratio *X/R* with the terminal voltage of the induction generator. When the ratio increases, the terminal voltage will decrease, and the stability of voltage also decreases. The results of the simulation can be confirmed using analytical form. Fig. 9 shows equivalent circuit model of system under study.
Current flow is given by:

$$S = V_{WFT}\ I^* \Rightarrow I = \frac{S^*}{V_{WFT}{}^*} \xrightarrow{S=P+jQ} I = \frac{P+jQ}{V_{WFT}{}^*} \qquad (10)$$

In the above equation, negative sign of reactive power (*Q*) is considered.

Terminal voltage (V_{WFT}) is given by:

$$V_{WFT}\angle\delta = V_{Grid} + (R+jX)\underbrace{\left(\frac{P+jQ}{V_{WFT}\angle-\delta}\right)}_{I} \qquad (11)$$

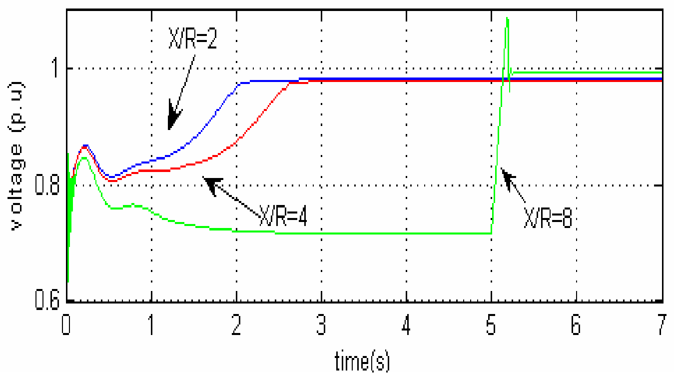


Fig. 8. Effect of different *X/R* values on the terminal voltage of the induction generator

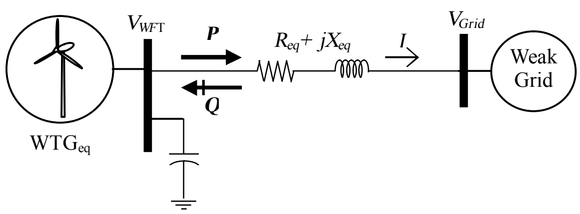


Fig. 9. Equivalent circuit model of system under study

If $\delta \approx 0$, then we can represent approximate method for terminal voltage calculation:

$$V_{WFT} = V_{Grid} + \frac{R\,P - X\,Q}{V_{WFT}} \approx V_{Grid} + \frac{R\,P - X\,Q}{V_{Grid}} \Rightarrow$$
$$V_{WFT} = V_{Grid} + \frac{R\left[P - \left(\frac{X}{R}\right)Q\right]}{V_{Grid}} \qquad (12)$$

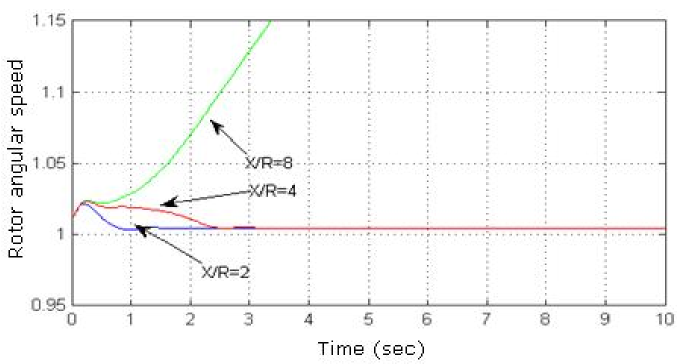
In the above equation, if *X/R* ratio increases, then V_{WFT} will decreases since active power (*P*) is positive. Consequently, stability of voltage terminal (V_{WFT}) reduced.

D. Impact of X/R Ratio on rotor angular speed of induction generator

To assess the impact of transmission line impedance *X/R* ratio of wind farm on rotor angular speed of induction generator an indicator for the transient stability is needed. Here, two indicators have been applied to the rotor speed oscillations of the generators in the study system that occurs after applying the fault, namely: Maximum rotor speed deviation, Oscillations duration. The meaning of the maximum rotor speed deviation reached by the generator during or after X/R Ratio variation. The duration of oscillation is defined as follows: "The oscillation duration is equal to the time interval between the Transmission Line Impedance X/R Ratio of wind farm varying and the moment after which the rotor speed stays within a bandwidth of 1 ± 10^{-4} p.u. during a time interval longer than 2.5 seconds" [6]. Thus, the oscillation duration is a measure for the time span that is needed to reach a new equilibrium after a disturbance. With increase of Transmission Line Impedance X/R ratio, stability of rotor speed of induction generator decreases. The results are shown in Fig. 10.

E. Impact of main grid strength on wind farm operation against three phase fault

Fig. 11 shows the transient response of the terminal voltage of the wind farms under various wind farm short circuit ratio (SCR_{WF}) when a temporary three phase fault occurs at the terminal. When the SCR_{WF} is decreased to a certain value (*A* is increased to 10%), the voltage can recover after the fault. In addition as the SCR_{WF} is increased, the dynamic response of the voltage increases as well.



10. Effect of X/R ratio on rotor angular speed of induction generator

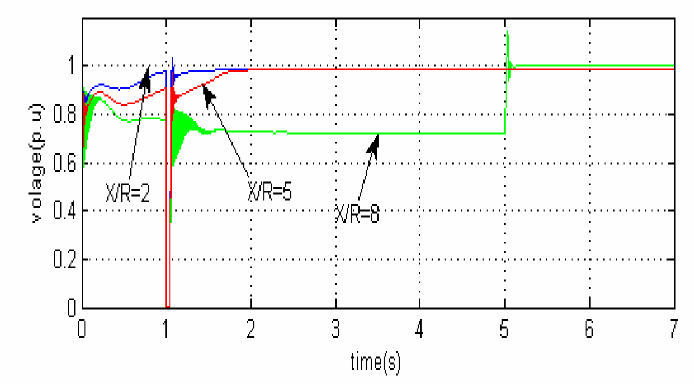


Fig. 11. Terminal voltage variation following a three phase fault for different $A=1/SCR_{WF}$

F. *Impact of X/R Ratio on wind farm operation against three phase fault*

In a reactive circuit (high *X/R* ratio), it is naturally more difficult for a protective device such as a circuit breaker to clear a fault. Protective devices clear a fault at a current zero. Within the interrupter, dielectric strength builds up to prevent the arc from reigniting after the current zero. In a resistive circuit (low *X/R* ratio), the voltage and current are in phase, so after a current zero, a quarter cycle passes before the voltage across the protective device (called the recovery voltage) reaches its peak. In a reactive circuit, the fault current naturally lags the voltage by 90^0; the voltage peaks at a current zero. Therefore, the recovery voltage across the protective device rises to its peak in much less than a quarter cycle (possibly in 1/20th of a cycle or less), and the fault arc is much more likely to reignite[7]. Fig. 12 shows the curve of the terminal voltage of the wind farms versus the transmission line impedance ratio *X/R* when there is three-phase-ground fault (fault lasts 0.055s). Fewer than three phase fault, when the ratio increases from 2 to 5, the terminal voltage can recover stability after clearing the fault. When the ratio is 2 and 5, after clearing the three phase fault, the terminal voltage recovers to the normal condition. All the induction generators retain stability after the fault is cleared. But when the ratio is increased to 8 or greater, the voltage cannot recover and the wind farm loses stability.

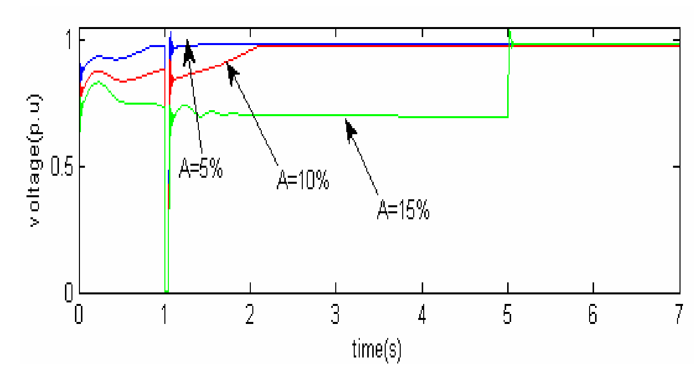


Fig. 12. Impact of Transmission Line Impedance *X/R* Ratio on wind farm operation against three phase fault.

V. Conclusion

This paper evaluates the transient stability of wind farm implemented with induction generators under different operating conditions. In this regard, the detailed wind energy conversion system model, induction generator model are used and the impact of different parameters on the transient stability is illustrated by simulation and confirmed by analytical solution as well. Simulation results show that:

a. The strength of main grid will limit the penetration of the wind farm; from a certain low strength the wind farm will be instable.

b. The ratio *X/R* of the transmission line impedance will affect the different voltage drop of wind farm. As the ratio is increased, the voltage drop will increase as well.

c. Increasing the *X/R* ratio, and regulating the voltage using PFC or other alternatives will improve the voltage transient response.

The voltage profile is the main issue when considering stable operation of a wind farm implemented with induction generators. In order to maintain the wind farm's stable operation and avoid over-speed of the induction generators, sufficient dynamic stability improvements and voltage control technologies should be taken into consideration during the design of the wind farm. In addition, the type of connection and the size of the wind farm will dictate the amount of voltage support required. Power-system oscillations caused by a transient fault in the vicinity of a wind turbine are the worst case scenario, as the wind turbine has to ride through the fault and keep its stability. The ability to control active power is important for two reasons: during normal operation to avoid frequency excursions; and during transient fault situations to maintain transient voltage stability. Power control is especially important for transient stability and voltage stability in case of faults. If the power can be reduced efficiently as soon as a fault occurs, the turbine can be prevented from running into over speed.

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