Power Swing and Stability of Wind Turbine Generators

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1. Introduction

Power swing and out of step power generation are essential issues in power system stability study and power system protection and security study. Power swing – either it's stable or unstable- can effect protection relays coordination – specially distance relay – and lead to unwanted trip or unwanted loose of power to a critical consumer. Therefore, it is important to find a way to unable these relays to distinguish between power swing phenomena and an electrical fault. Also, we have to find a relay that can differentiate between a stable power swing and unstable one. This is the focal point of this report.

2. Power Swing

Generally, in order to keep the power system stable, we are operating it close to its nominal frequency and voltage. The allowable variation in frequency is +/- 0.02 HZ and in voltage is within 5%. Due to the electrical faults, line switching and sudden- load or generation- disconnection the power lines experience a sudden change in electrical power while the mechanical power delivered to the generations units remains constant which lead to the oscillation in the machine rotor's angle. If the disturbance is not severe (instantaneous), the system power will swing for short time and eventually will return to the equilibrium state between electrical and mechanical power (stable condition). Otherwise, the disturbance will cause a large fluctuating in voltage and current. That will lead to lose of synchronism between the generation units or between adjacent utilities due to unwanted relay operation.

3. Wind Energy

Windmill mechanical system and the behavior of the power system affect the stability. The transient stability of the system depends on the system ability at post fault period, like the value of generation voltage at the terminals of the generator. So, every time the power system operating condition changed we have to determine a new stability limit [1-3]. The forecast for the growth of electricity generated by wind power till 2030 would be about 25%. That means there will be a huge demand for wind turbine electric generators [2]. If two wind farms are interconnected "the wind farm with a large rated power has predominate effect on the stability of that with the smaller rated power". The instability of the large farms will lead to the instability of the smaller one, not the other way round [2].

4. Swing Equation for Wind Turbine Generator

The following equations and the equal area criteria (Figure 1) are used to perform the numerical and analytical analysis of the test system at post-fault condition. In the equivalent single machine system, the pre-fault, the faulted, and the post-fault real power output of the generator is determined by expression: $P = V_1 V_2 \sin\delta / X_L$. In the presence of a fault in either of the lines in Figure 1, the generator gets accelerated due to insufficient power transmission capacity. The net acceleration energy of generator defined in Equation (1), increases rapidly during the fault period ($0<t<t_c$) and decreases immediately after the fault is cleared at instant, $t = t_c$.

$$E_i(t, t_c) = \begin{cases} KE = P_m * (\delta_c - \delta_o) & 0 \le t < t_c \\ PE = \int_{\delta o}^{\delta c} P_{\max} \sin(\delta) d\delta & t > t_c \end{cases} \quad (1)$$

In Equation (1), t_c is fault clearing time, and δ_0 is the pre-fault power angle. The test power system remains stable, if the fault is cleared before the critical clearing time (t_{cc}) and the net kinetic energy (KE) is

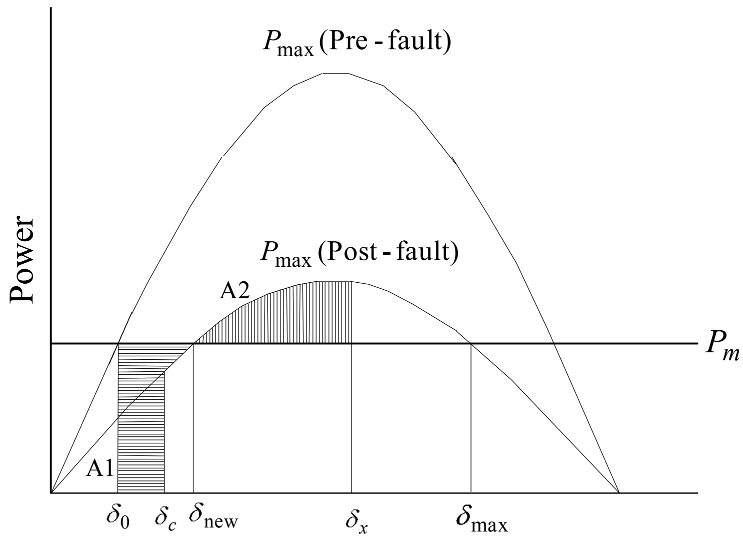

Figure 1. Power-angle characteristics of test power system.

equal to the net potential energy (PE). Contrarily, if the fault is cleared after critical clearing time $(t_c>t_{cc})$ the system becomes unstable.

A suitable controller is needed to reduce the post-fault angular velocity (ω) of generator and return the power angle (δ) to the stable region (0°< δ <90°). This can be realized by maximizing the transferred electric power from generator to infinite bus, thereby, releasing excess acceleration energy stored in the generator. Based on the speed and flexibility of advanced power electronic devices, the SSSC is potentially a practical device to control the transferable electric power (P_e) from the generator to infinite bus. The control function for the SSSC is derived using nonlinear equations of the test power system shown in Figure 1.

5. Dynamic Equations

Equation (2) is the dynamic equation of the test power system (Figure 1).

$$m\ddot{\delta} + D\dot{\delta} = P_m - P_e \tag{2}$$

where,

$p_e = |V_1||V_2|\sin\delta / X_L$ and $\ddot{\delta} = \omega$ = angular deviation of generator speed form synchrnous value

The effect of damper winding is considered in Equation (2) as the rate of change of angular velocity from the synchronous value. The damper winding produces a breaking power proportional to the relative movement between the air-gap field (produced by stator) and the damper winding field. This phenomena helps in damping out rotor angle (δ) oscillations, however an excessive heat generated due to damper copper loss (I^2R) limits the level of excitation needed to completely damp out rotor oscillations.

The conventional approach to control the state variables (δ and $\dot{\delta}$) of a generator is to design a feedback controller for the input mechanical power through its governor [5]. Equation (3) represents state space equations for a system with input mechanical power (P_m) as the manipulated variable.

$$\begin{bmatrix} \dot{\delta} \\ \ddot{\delta} \end{bmatrix} = \begin{bmatrix} \dot{\delta} \\ -(1/M)\left(|\mathrm{V}_1||\mathrm{V}_2|\sin(\delta)/(X_L) + D\dot{\delta}\right) + (1/M)(P_m) \end{bmatrix} \tag{3}$$

or

$$\begin{bmatrix} \dot{\delta} \\ \ddot{\delta} \end{bmatrix} = \begin{bmatrix} \dot{\delta} \\ -(1/M)\left(|\mathrm{V}_1||\mathrm{V}_2|\sin(\delta)/(X_L) + D\dot{\delta}\right) \end{bmatrix} + \begin{bmatrix} 0 \\ (1/M) \end{bmatrix} (P_m) \tag{4}$$

An alternative to Equation (4) is proposed in Equation (5), where the input control signal is an electrical signal ($1/X_L$) instead of a mechanical signal (P_m).

$$\begin{bmatrix}\dot{\delta}\\ \ddot{\delta}\end{bmatrix}=\begin{bmatrix}\dot{\delta}\\ (1/M)\left(P_m-D\dot{\delta}\right)\end{bmatrix}+\begin{bmatrix}0\\ -(1/M)\,V_1V_2\sin(\delta)\end{bmatrix}\left(\frac{1}{X_L}\right) \tag{5}$$

A desired value of ($1/X_L$) can be realized by the following nonlinear controller.

$$u(\delta,\ \dot{\delta})=\frac{1}{X_L}=\frac{M\dot{\delta}^2\sin(\delta)-P_m\cos(\delta)+D\dot{\delta}\cos(\delta)+w}{-V_1V_2\sin(\delta)\cos(\delta)} \tag{6}$$

The transient stability of constant frequency wind turbines is not rich. It becomes worse with the increase of these wind turbines in regions electrically far from synchronous generators [4-5].

6. Stability Evaluation

The stability of wind turbine generator can be tested by Lyapunov criteria. The obtained integrated model is used to find out system's Transient Energy Function (TEF). It is well known that the loss of a transmission line will instantaneously decrease the transferable electric power capacity of remaining transmission system between generating units to load centers or infinite bus, whereas, mechanical input power to generating units remains constant at its pre-fault value for few seconds. This causes an imbalance between mechanical input power and transmitted electric power with latter being smaller than the former one. This power imbalance during the fault causes the system's kinetic energy to increase that drives the generator towards an unstable region of operation ($\delta \geq 90°$). In Figure 1, the post-fault generator remains stable if extra energy stored in the generator during the fault is completely absorbed by transmission system. It is quite possible that post-fault power system may settle down to a new stable operating point provided the fault is cleared quickly and the post-fault power transmission capacity is restored to a desired level. On the other hand, a slow switching scheme employed for fault clearance may not prevent the generator to become unstable due to unmanageable energy imbalance. Therefore, it can be stated that the stability problem could become more acute if the transmission capacity is not restored to a required level in a post-fault power system. The post-fault maximum transmission capability (P_{max}) is very close to mechanical input power, P_m, therefore, the fault has to be cleared very quickly to ensure that Area A1 stays equal to area A2. However, the test power system equipped with SSSC doesn't exhibit this constraint as we can control maximum transmission capability (P_{max}) by lowering the line reactance to a desired value within the operating voltage limit of the SSSC. The TEF is the time integral of swing equation (Equation 2) of the test power system. The lower limit of the integration is the instant of the fault (t = 0, $\delta = \delta_0$), and the upper limit is the time instant when $\dot{\delta}$ becomes zero. The upper limit cannot exceed t_{max} that correspond to δ_{max} (= $\pi - \delta_0$). The transient energy contained in the test power system is a time integral of accelerating power (Equation 2). Therefore, the time integral of Equation (2) provides the TEF of the test power system, as expressed below:

$$\text{TEF} = \int_0^{t_x}\left(M\ddot{\delta}+D\dot{\delta}+\frac{V_1V_2\sin(\delta)}{X_L}-P_m\right)dt \tag{7}$$

Equation (7) helps us to determine if the wind turbine generator will remain stable after the fault or not.

7. Conclusions

Wind Turbine generators will be a big player in the future electricity market. It is clean and environmental friendly. It has zero cost for its fuel and can be used in remote areas. It has some stability problem when it is connected to electricity network with synchronous generators.

8. References

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Author Biographies

Dr. Majid Poshtan was born in Tehran, Iran and received his B.S.in Electrical Engineering from Tehran University, Tehran, Iran, in 1988, the M.S. degree in Electrical Engineering from the University of New Brunswick, Fredericton, NB, Canada, in 1992 and the Ph.D. degree in Electrical Engineering from Tulane University, New Orleans, LA, U.S.A., in 2000. He is currently an Assistant Professor in the Department of Electrical Engineering, The Petroleum Institute, Abu Dhabi, U.A.E. Before joining the Institute, Dr. Poshtan has worked in different electric power projects in Entergy Corp, U.S.A. His research interests include power system analysis, power system protection and power quality studies. Dr. Poshtan received the IEEE Region 5 graduate paper contest Award in 1998 and 1999, and he is also the recipient of Petroleum Institute Outstanding Faculty Award in 2005. Dr. Poshtan is an active member of IEEE and he is serving as the Petroleum Institute IEEE Student Branch Advisor.