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Generator Dynamic Response Analysis and Improvement Following Distribution Network Disturbance

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Abstract

Use of renewable energy sources for the purposes of electricity generation is increasing throughout the world. Connection of new generators, however, introduces significant challenges to power network operators and managers. The power system transient stability is affected by the grid connection of new generation units. The objective of this paper is to investigate asynchronous generator dynamic response issues and capabilities under three phase symmetrical fault conditions and to propose a methodological approach to designing a generator transient stability solutions. Analysis and methodology are introduced through a realistic generator connection example. Simulations show that power system stability can be significantly affected by the connection of new generators and that this phenomena needs to be carefully considered during the connection planning process. This paper is a part of an ongoing research on the distributed generation impact on power network and its aim is to provide two main contributions to the existing body of knowledge. Firstly, it is expected that this paper will contribute toward a better understanding of the influence that generators have on the power system transient stability. Secondly, this paper is expected to contribute towards the practical understanding of fundamental power system transient stability improvement solutions.

Keywords: *dynamic analysis, generator, power system, STATCOM, transient stability*

1. Introduction

Power system transient stability is extremely important for the adequate system operation and it can be significantly influenced by the connection of the new generation units and customer load. The most important physical quantities investigated during power system transient analysis are: active power, reactive power, voltage and rotor angle. The power system stability can be defined as the system's ability to regain a state of equilibrium after external disturbance is applied to it. This means that after the fault is cleared, the investigated quantities will bewithin prescribed levels. Unfortunately, power system transient stability is not always achieved. This is unfavourable operating condition which, if not addressed properly, might have devastating large scale effects.The equal area criterion can be very effectively used as a graphical approach to performing transient stability analysis. Let us define P_m andP_e as mechanical and electrical power respectively.Now, if themechanical torque τ_m from prime mover is greater than and the electromagnetic torque τ_e from the alternator, then there will be positive accelerating torque τ_a. The swing equation can be derived from Newton's second law of motion as follows:

$$J\frac{d^2\theta_m}{dt^2} = \tau_a = \tau_m - \tau_e \tag{1}$$

$$J\omega_m\frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \tag{2}$$

$$H = \frac{1}{2}\frac{J\omega_m{}^2}{VA_{base}} \tag{3}$$

$$\frac{2H}{\omega_m}\frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \tag{4}$$

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Finally, the swing equation can be expressed as:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{5}$$

Since the maximum amount of transmitted power depends on the terminal voltages and line reactance, power angle relationship in a classical model of a generator connected to an infinite bus via transmission system is represented in a following way:

$$P_e = \frac{E' E_b}{X_t}\sin\delta = P_{max}\sin\delta \tag{6}$$

The swing equation can be solved by investigation of the power angle characteristic dynamics. Figure 1 shows a simple illustration of the system power angle characteristic.

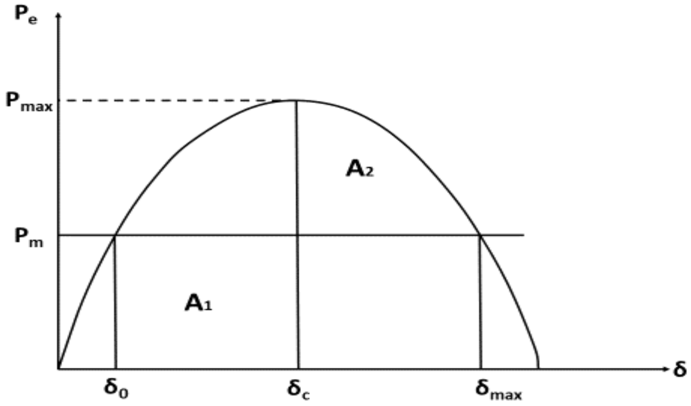

Figure 1. Power angle relationship for equal criterion illustration

Initial operating conditions satisfy stability criteria since mechanical power is equal to electrical power or P_m=$P_e$at an angle δ_0. When the fault is developed in the network, there will be a sharp reduction in P_e which is virtually reduced to zero. As a consequence, there will be the resultant positive accelerating torque τ_a which causes the angle increase from δ_0 to δ_c. At this point, the fault is cleared by the protection. Now, P_e>$P_m$which causes the generator rotor to deaccelerate. Areas A_1 and A_2 represent the integral of the power with respect to angle and are proportional to the accelerating and deaccelerating energy, respectively. In conclusion, the system is said to be transiently stable if a positive (accelerating) energy represented by A_1 is equal to negative (de-accelerating) energy A_2. Substituting for P_e in the swing equation, the equal area criterion can be expressed as:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - \frac{E' E_b}{X_t}\sin\delta \tag{7}$$

$$2\left(\frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right) = \left(\frac{d}{dt}\right)\left(\frac{d\delta}{dt}\right)^2 \tag{8}$$

$$\left(\frac{d\delta}{dt}\right)^2 \Big|_{\delta_0}^{\delta_{cr}} = \int_{\delta_0}^{\delta_{cr}}\left(P_m - \frac{E' E_b}{X_t}\sin\delta\right)d\delta \tag{9}$$

$$\int_{\delta_0}^{\delta_{cr}}\left(P_m - \frac{E' E_b}{X_t}\sin\delta\right)d\delta = \int_{\delta_{cr}}^{\delta_{max}}\left(\frac{E' E_b}{X_t}\sin\delta - P_m\right)d\delta \tag{10}$$

$$A_1 = A_2 \tag{11}$$

The use of Flexible Alternating Current Transmission Systems (FACTS) devices is another way of improving stability, controllability and power transfer capability of the power system because adequately rated FACTS device enables ride through severe power system faults [1, 2]. Dynamic response of a grid connected generator is particularly imporantin wind farm applications [3]. Even if generator dynamic response has been researched over the past few decades, it continues to attract new research interests [4, 5] and remains a vibrant research area.It also represents an important regulatory issue [6, 7]. This paper presents results of investigations related to the asynchronous generator dynamic response under three phase symmetrical fault conditions. The simulations are performed on a model of a realistic power system which proves the practical relevance and applicability of the proposed methodology. This paper further presents simulation results regarding the power system stability improvement using FACTS. The results are used to contribute toward a better understanding of the influence of asynchronous generators on the power system transient stability and to provide a practical understanding of sizing of fundamental power system transient stability improvement solutions. This topic is important for practical engineering applications, such as balance of plant design and specification.

2. Experimental Design

Figure 2 shows the single line diagram of the test system. The system consists of three customer zone substations marked as SUB A, B and C, which are fed by a total of six aluminium conductor lines. Lines L5 and L6 have the highest thermal and current rating and are used to connect SUB A, B, and C to the source station. The line L2 is altered to accommodate DG connection and is divided in L2a and L2b. In the test system, BB 10 is considered to be a swing bus and is used as reference point. Power transformers are modelled with resistance and reactance of 0.005 and 0.1 p.u. respectively and all transformer MVA ratings are per winding base. In the case of low load, scenario, the system power factor gets closer to unity. During low load, the demand for reactive power decreases and some or all capacitors need to be switched off. Capacitor banks which are installed in SUBA are rated at 6.8MVA. They are VAr controlled and switch on and off automatically based on the amount of reactive load requirements with step switch resulting in two effective capacitor banks each of 3.4MVAr. Controller settings result in stack 1 switching on at a feeder load of 2.0MVAr and switching off at a load of -2.0MVAr. Stack 2 switches on at a feeder load of 4.0MVAr and off at a load of 0.0MVAr. SUB B has two time clock controlled capacitor banks. Capacitor bank no.1 size is 2.5MVAr and is daily switched on, during the week days. Capacitor bank no.2 has is always on. SUB C does not have a zone substation capacitor bank.In this research, observed parameters in the analysis of system dynamic stability analysis are active power P, voltage V, the reactive power Q and rotor speed s. Some of the most important parameters that have a major influence on system stability are the fault clearance time, the fault location, and type of the fault - such as 3-phase, double line to ground, or single phase. The three phase symmetrical faults are simulated at each line of the proposed test power system. Even if the three phase symmetrical faults are statistically the least common faults, they are included in this experiment because of their capability to develop the highest fault currents. A generator is represented in simulation software by a Norton equivalent circuit in which the voltage source is replaced by an equivalent current source and the equivalent circuit is used to represent the generator as a boundary condition in the network solution.

The initial investigation of the system dynamic stability, without the use of FACTS devices was conducted in [8], where it was determined that the generator does not have a fault run through capability, given the existing fault clearance times and that it is necessary to apply appropriate solution in order to achieve dynamic stability. From a generator’s perspective, there are no measures that can be applied to influence the type and location of the grid disturbance. Transient stability design is therefore dedicated to the control of two very important quantities. First quantity is the fault clearance time, which is directly related to power angle relationship and plays major role in equal area criterion. This quantity can be influenced by the power system protection design which aims to achieve required fault clearance times. The second quantity is Q, which is one of the most important quantities to be observed in transient stability assessment, because its developments can significantly influence voltage profile and generator fault run through capability. In this paper, power system stability improvement using FACTS is proposed, in a simulation model with shunt compensationusing the with CSTATT Static Condenser (STATCON) model. Investigations are conducted by carrying out a series of fault simulations for the high load and low load scenario. The obtained results are compared with generators dynamic response results without the use of FACTS devices. The computational procedure which was carried out in this experiment to analyse the generator dynamic response is based on typical dynamic analysis software procedure. It is expected, based on accumulated body of knowledge [9, 10] that installing STATCOM at the generator connection point will improve voltage stability and maintain the smoother voltage profile during the network disturbance and enable the generator to run through disturbance. It was determined that reasonable protection settings can be reduced down to 150ms on all relays and this value is used as a minimum criteria in determining if the system will remain stable. In other words, if clearance times shorter than 150ms are required to maintain stability, the system will be considered to be dynamically unstable.

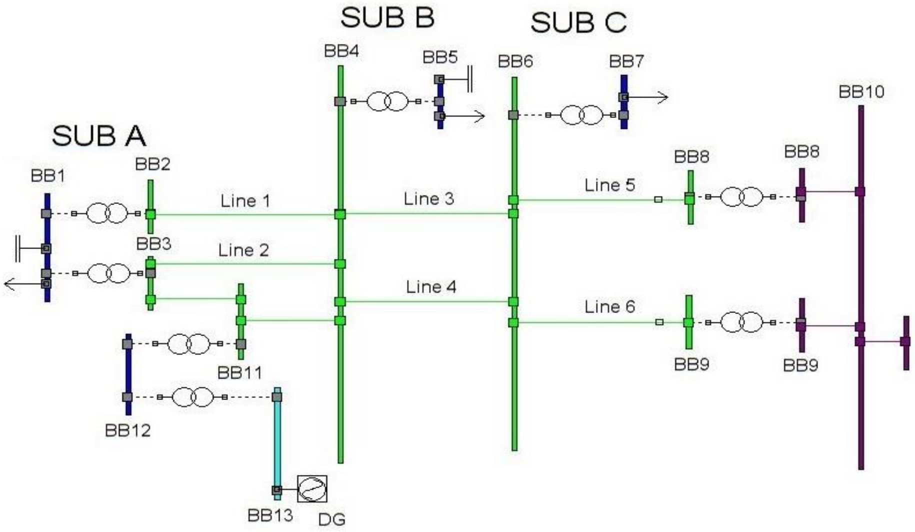

Figure 2. Single line diagram of the realistic 13 bus test system

3. Results and Analysis

3.1. Cstatt Statcon Model Simulation Resultsfor High Load Scenario

When the distribution network fault is simulated, the significant drop of Q is observed. It is crucial to ensure fast recovery of Q, which is related to active power, voltage and rotor speed recovery, in order to ensurepower system stability. Figure 3 shows Q developments at the BB12, for the case with and without STATCOM, with symmetrical three phase fault cleared by the protection after 0.05ms, placing the line L2 out of service. This case was chosen because it was determined to be the worst case scenario. Fault clearance time of 50 ms is represented because within this period system remains stable regardless of STATCOM presence. It can be observed that after the fault was cleared, Q curve has a steeper gradient in the case with STATCOM. This means that more reactive power is delivered in order to provide faster recovery, which demonstrated the beneficial effects of STATCOM installationon power system stability. Further, when the fault develops, there is a sharp increase in reactive power accumulated inside of the generator and it is higher in the case with STATCOM installed, because more Q is locally available. When the fault is cleared, the generator starts to draw reactive power from the grid. It can be observed that more Q is absorbed by the generator in the case with STATCOM which allows faster and smoother recovery of the reactive power profile. Finally, the reactive power curve has reached a pre fault level faster with STATCOM installed when compared to the case without it, which is evidence that STATCOM can be used as an effective tool for improving generator dynamic response.

Voltage development is another critical quantity in power systemstability analysis [11] and it is closely related to Q levels. When the fault develops, the stator magnetic field is no longer supported and voltage drops virtually to zero. Initially, voltage across STATCOM is zero, but when disturbance is developed, STATCOM develops voltage across its terminals and supplies capacitive current, causing voltage to rise. Figure 4 shows simulation results of voltage developments with and without STATCOM. It can be concluded that the voltage recovery occurs faster and smoother with the use of STATCOM because more Q is now available, allowing voltage value to return to normal level. It can therefore be concluded that the installation of STATCOM improves the voltage level recovery and provides a better dynamic response of the generator.

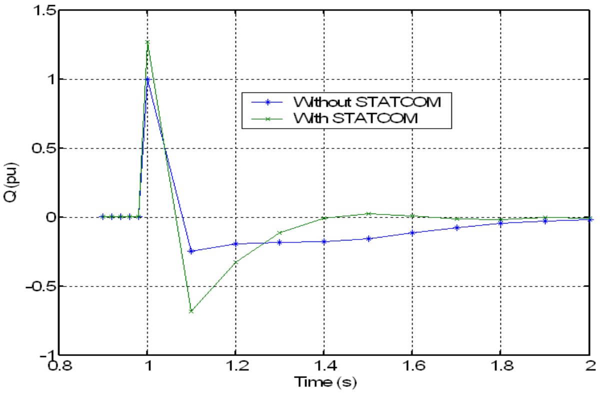

Figure 3. Reactive power development at the connection point with and without STATCOM

Another interesting relation was observed between reduction in voltage recovery to stability margine time and size of the STATCOM. Larger MVAr ratings allow faster recovery times, which proved crucial in improving system stability. This relation is shown in Figure 5 with voltage recovery times on the left y axis, as function of MVAr. Voltage magnitude also increases with increase in STATCOM size as shown on the right side y axis in Figure 5. Voltage magnitude was measured at the point of 1,25s for the same case as above. Diminishing marginal benefits of STATCOM with an increase in its size are also observed, which means that it is necessary to determine the optimum STATCOM rating when designing the appropriate dynamic response improvement solution of the generator. When the disturbance is developed in the network, P values drop virtually to zero. When the fault is cleared, the value of P rises sharply to reach levels higher than the observed during the prefault period. At this point P curve starts to oscillate. FACTS can be used also to improve large signal damping by supporting the system voltage [12] as shown in Figure 5. P curve developments with and without STATCOM are shown in Figure 6. Similar to voltage, P recovery is faster and smoother if the STATCOM is installed. P_e exceeds P_m much faster due to the reactive power provided by STATCOM and equilibrium condition described in the equation of motion is established faster. In addition to that, system oscillations are dampened faster. These factors enhance system stability. Figure 7 shows the effect of STATCOM installation on the increase of the maximum value of P. In Figure 8 it can be seen that P curve with STATCOM reaches its maximum faster when compared with simulation scenario in which STATCOM is not used. It can be concluded that the hypothesis relating the STATCOM and transient stability have been confirmed. Table 1 represents a summary of the result in numerical form relevant to the high load case simulations. The important conclusion is that STACOM greatly improved dynamic response capability of the generator. The second column of the Table 1 show fault clearance times without STATCOM. The third and fourth coloumn of the Table 1 represent the required fault clearance times with 20MVAr and 40MVAr STATCOM, respectively. The final conclusion is that the system can run through fault anywhere in the network, with 20 MVAr STATCOM installed on BB 12 for the case of high load scenario. The increase in the STATCOM size increases the clearance time margin and therefore improves generator dynamic stability.

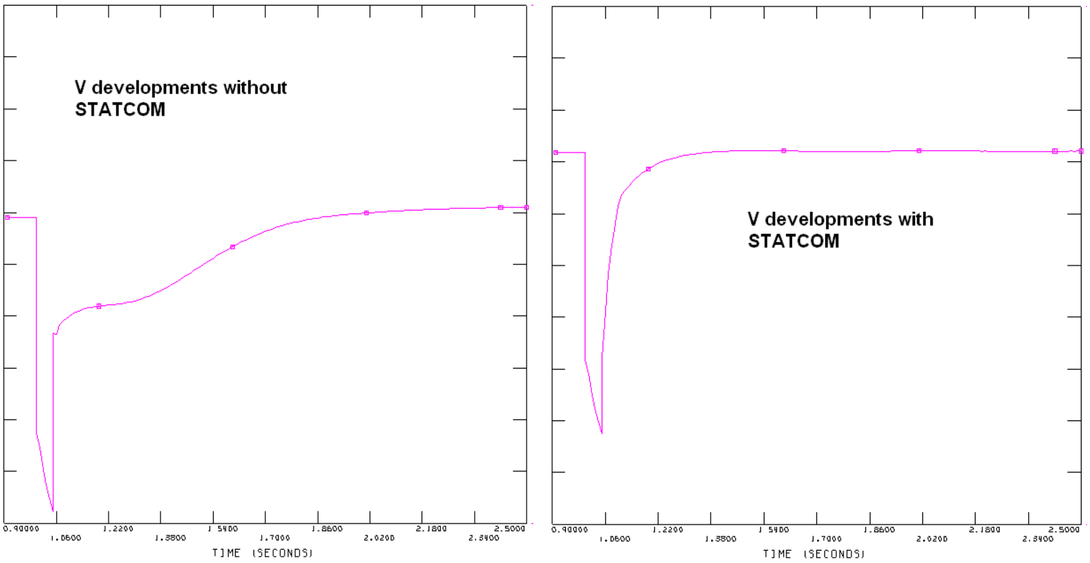

Figure 4. Voltage developments at the connection point with and without STATCOM

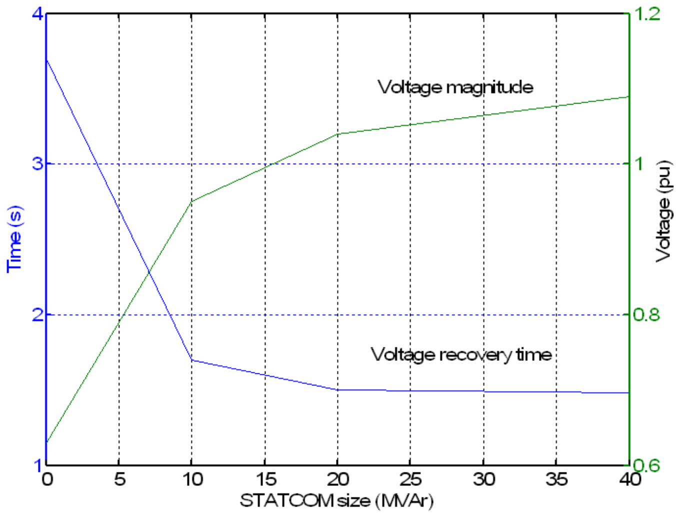

Figure 5. Voltage Recovery Time Magnitude as a function of STATCOM size

Table 1. Fault clearance times for high load conditions

Name of the line	Clearance times without STATCOM (s)	Required times with 20 MVAr STATCOM (s)	Required times with 40 MVAr STATCOM (s)
L_1	0.10	0.40	0.45
L_{2a}	0.05	0.30	0.33
L_{2b}	0.05	0.35	0.38
L_3	0.10	0.30	0.35
L_4	0.10	0.30	0.35
L_5	0.10	0.30	0.35
L_6	0.10	0.30	0.35

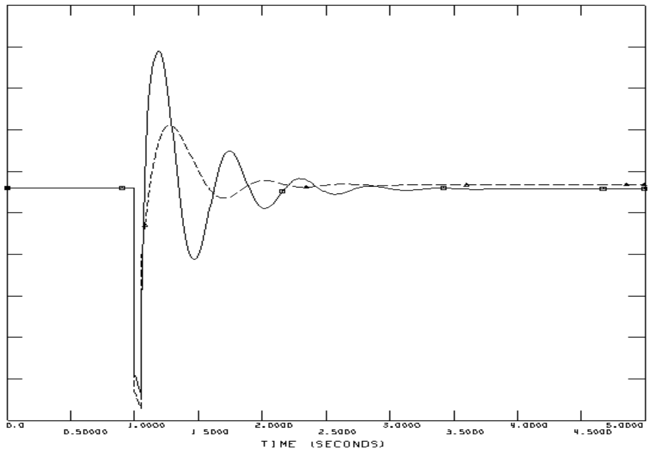

Figure 6. P developments with (dashed line) and without STATCOM on connection point

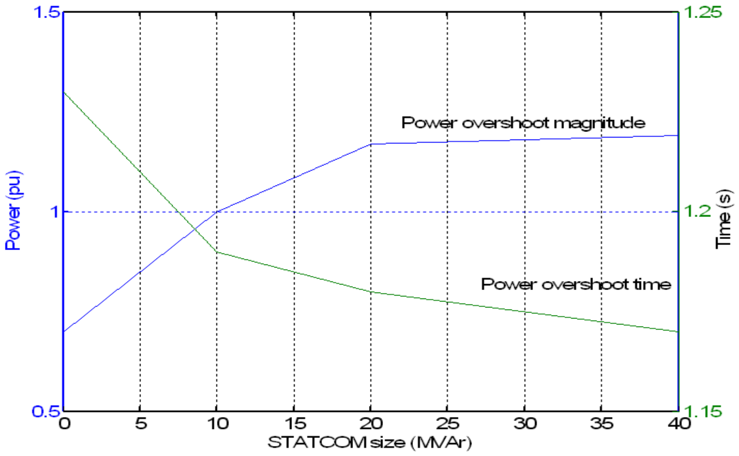

Figure 7. Power Overshoot magnitude and time as a function of STATCOM size

3.2. Cstatt Statcon Model Simulation Results for Low Load Scenario

The simulations demonstrated that the low load scenario was determined to be less stable when compared with high load scenario. This occurs because during the low load, there is less reactive power in the network. Results of the analysis for the low load case are summarised in Table 2. It can still be concluded that it is possible to stabilise transient response of the generators by the addition of the STATCOM. With 20 MVAr of capacity, the generator will safely run through required fault clearance times shown in Table 2. In this case as well, STATCOM size displays diminishing marginal benefits. The required clearance times increase very quickly at the beginning, and then the slope of the curve representing this increase becomesless steep, especially in the case of faults on line L2a, L5 and L6. It was demonstrated that STATCOM size of less than 20 MVAr would still guarantee stability, which means that reactive requirement are oversized. It is therefore desirable to find the minimum MVAr ratings of Q requirements which would ensure a stable dynamic response of a generator.

Now, the final aim is to minimize the size of STATCOM and still satisfy the required fault ride through minimum times.In order to make the decision making process, analysis is performed of the increase in the fault duration times that system can ride through as function of MVAr. The increase in STATCOM ratings gives an increase in the minimum fault clearance time for a three phase symmetrical fault on each line required for stable dynamic response of a generator. It is based on the low load case since it is the less stable case. Once this graph is obtained, the minimum size can simply be read by intercepting the curves produced with the required time on the y axis. For the 150ms with faults on L3 and L4, corresponding STATCOM size is cca 15 MVAr.

Table 2. Fault clearance times for minimum load conditions

Name of the line	Clearance times without STATCOM (s)	Required times with 20 MVAr STATCOM (s)	Required times with 40 MVAr STATCOM (s)
L_1	0.10	0.19	0.25
L_{2a}	0.05	0.17	0.18
L_{2b}	0.10	0.2	0.21
L_3	0.10	0.16	0.20
L_4	0.10	0.16	0.20
L_5	0.05	0.17	0.18
L_6	0.05	0.17	0.18

4. Conclusion

Power system control and stability considerations are very important for safe, secure and effective system operation. This paper investigated generator dynamic response issues and capabilities under three phase symmetrical fault conditions and proposed a methodological approach for designing a feasible dynamic stability solutions using FACTS. Simulations show that power system stability can be significantly affected by the connection of new generators and that this phenomena needs to be carefully considered during the connection planning process. This paper highlights the influence that generators have on the power system transient stability and draws attention to practical stability improvement solution. It was demonstrated, on a realistic generator connection example, that STATCOM installation at connection point provides a number of benefits to the system, such as faster and smoother voltage recovery and large signal dampening. It was shown that generators are capable to run through three phase symmetrical faults occurring anywhere in the network if STATCOM is installed at the generator connection point. Finally, the minimum required STATCOM size was found to be 15 MVAr, but the increase in reactive ratingprovides the additional benefits to the system.

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