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Research Article

Integrating STATCOM and Battery Energy Storage System for Power System Transient Stability: A Review and Application

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Integration of STATCOM with energy storage devices plays an imperative role in improving the power system operation and control. Significant research has been done in this area for practical realization of benefits of the integration. This paper, however, pays particular importance to the performance improvement for the transients as is achievable by STATCOM with battery-powered storage systems. Application of STATCOM with storage in regard to intermittent renewable energy sources such as wind power generation is also discussed in the paper. At the beginning of this paper, an overall review of the STATCOM and energy storage systems are elaborated. A brief overview of the advantages of using STATCOM in conjunction to energy storage systems in achieving power system stability is presented. In the second part of the paper, a typical transient stability model of a STATCOM is presented. The dynamics of real and reactive power responses of the integrated system to transients is studied. The study is aimed at showing that the combination of STATCOM and battery energy storage significantly improves the performance of the system. The final results show that the STATCOM reactive power/voltage control helps in transient stability enhancement.

1. Introduction

The principal benefit of the STATCOM for transient stability enhancement is direct through rapid bus voltage control. In particular, the STATCOM may be used to enhance power transfer during low-voltage conditions, which typically predominate during faults, decreasing the acceleration of local generators. An additional benefit is the reduction of the demagnetizing effects of faults on local generation. STATCOMs behave analogously to synchronous compensators, except that STATCOMs have no mechanical inertia and are therefore capable of responding much more rapidly to changing system conditions. When compared to synchronous machines, they do not contribute to short circuit currents and have no moving parts. However, the system has a symmetric lead-lag capability and can theoretically go from full lag to full lead in fraction of cycles [1, 2].

In Many research papers, it has been shown that an energy storage system (ESS) plays an important role in power system control. In practice, by integrating an ESS with STATCOM (STATCOM + ESS) significant improvements over traditional STATCOM performance are achievable. Some of the advantages of battery technologies are of higher energy storage densities, greater cycling capabilities, better reliability, and lower cost. This combined system is capable of mitigating majority of the stability and voltage fluctuation problems in the power system as discussed in detail in Section 2, with comprehensive literature review.

A STATCOM, connected in shunt, with the system is capable of improving transient stability by compensating the reactive power at the point of common connection. The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power during transients. This is achieved by increasing (decreasing) the power transfer capability when the machine angle increases (decreases). In Figure 1, which shows the single line diagram of a STATCOM, if the DC capacitor voltage, V_{dc}, is increased from its nominal value, the STATCOM is “overexcited” (capacitive mode) and generates reactive power. If the voltage of the DC capacitor bank is decreased below the nominal value, the STATCOM is “under excited” (inductive mode) and absorbs reactive power from the system. This is completely analogous to increasing or decreasing the field voltage of a synchronous compensator [2].

In this paper, review and application of using STATCOM in network with BESS are presented. Next section provides review in greater details and Sections 3–5 provide application demonstration of STATCOM + BESS. For test cases, a power transmission system with a single machine generator connected to an infinite bus is considered. For simplification purpose the classical model of a generator is assumed with an infinite bus as a constant voltage source. The model is implemented in MATLAB/Simulink and computer simulation results under different fault (3-phase to ground fault) clearing times are analyzed for transient stability. The results are then compared with STATCOM placed in the system. The analysis is then extended by adding an energy storage device (battery) to the STATCOM. The final results show that the addition of energy storage allows the STATCOM to inject and/or absorb active and reactive power simultaneously and, therefore, provides additional benefits and improvements in the system.

The paper is organized as follows. Section 2 gives a comprehensive review and brief introduction of STATCOM and battery, applications as well as financial aspects. Sections 3, 4, and 5 provide modeling and a practical case study of STATCOM being used in interface with BESS and the corresponding results based on the transient analysis of such system are discussed. Finally, in Section 6 conclusions are drawn.

2. STATCOM, BESS, and FACTS

2.1. Basics of FACTS. In power transmission and distribution systems, power electronics-based controllers are commonly named as flexible AC transmission system (FACTS) devices. By facilitating bulk power transfers, these FACTS networks help to build more transmission lines and power generation plants and thereby enhance neighboring utilities and regions to economically and reliably exchange power.

Continual advancements in power electronic technologies are acting to improve the stature of FACTS devices within the bulk power system. This in turn is restructuring the electric utility industry by moving steadily towards a more competitive scenario, in which power is bought and sold as a commodity. However, usually due to cost and lack of systematic control, although several FACTS topologies have been proposed to mitigate these potential problems, transmission service providers are reluctant to install them. The utility providers need to incorporate means of local control to address a number of potential utility problems such as uneven power flow through the system, transient and dynamic instability, subsynchronous oscillations, dynamic overvoltages, and undervoltages [3].

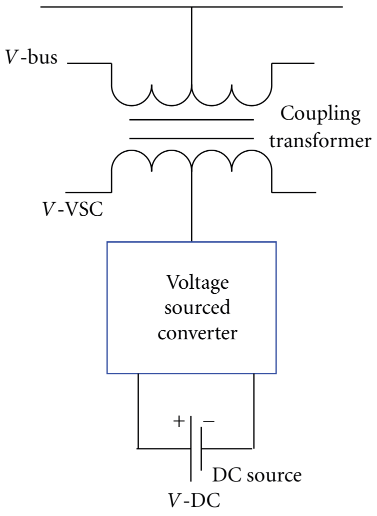

Figure 1: STATCOM connected to a transmission line.

There are numerous topologies of FACTS devices that are discussed in the literature [4–6]. All of them have certain advantages as well as disadvantages. Among them multilevel-converter-based FACTS has an added advantage of offering improved power quality, decreased switching frequencies, decreased power losses, and minimized stress on individual power-electronics devices. In addition, multilevel-converter-based FACTS enable more effective use of BESS. Several multilevel power-electronics topologies have been proposed for FACTS devices [6]. FACTS control scheme for several different types of applications and evaluation has been proposed in the literature [7, 8]. Comparison of several FACTS devices for stability enhancement has been discussed in [9]. Applications of STATCOM for voltage regulation/control [10–12] and stability [13–16] have been discussed in several papers.

2.2. Integration of Energy Storage Systems into FACTS Devices. An energy storage system (ESS) can play an important role in power system control [17] and provide significant improvements over traditional STATCOM performance. Battery energy storage systems (BESS) in conjunction with STATCOM have recently emerged as one of the most promising near-term storage technologies for power applications [18, 19]. By the addition of an energy storage system to the STATCOM it has been possible to control the active power flow between the STATCOM and the point of common coupling (PCC). Thus, the STATCOM compensates the reactive power and, in addition, stores energy in the storage-system when the generated power exceeds the power limits that could be injected to the distribution grid. In addition, this solution provides promotes control of the power flow at the PCC, by adjusting the direction of power injection, such as downwards or upwards.

Recently, a considerable amount of attention has been given to developing control strategies for a variety of FACTS devices, such as static synchronous compensator

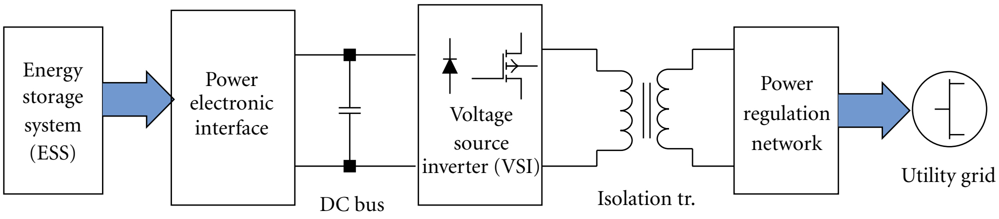

FIGURE 2: STATCOM + ESS connected to power utility system.

(STATCOM), the static synchronous series compensator (SSSC), and the unified power flow controller (UPFC), to be able to address and mitigate a wide range of potential bulk power transmission problems [20–22].

In the absence of energy storage, FACTS devices are limited in the degree of freedom and sustained action in which they can help the power grid. By the method of integration of energy storage system (ESS) into FACTS devices, an independent real and reactive power absorption or injection into and from the grid is possible. This integrated system leads to a more economical and flexible power transmission controller for the power system. When a transmission line experiences significant power transfer variations in an intermittent manner, a FACTS + BESS combination can be installed to regulate and adjust the power flow within the loaded transmission line. The enhanced superior performance of combined FACTS + ESS will have greater appeal to transmission service providers. Performance indices were proposed for FACTS dynamic performance with energy storage in [23] and control schemes have been discussed in [24–26].

Power system deregulation, along with transmission limitations and generation shortage, has changed the power of grid conditions by creating situations where energy storage technology can play a very vital role in maintaining system reliability and power quality. There are multiple benefits of energy storage devices such as the ability to rapidly damp oscillations, respond to sudden load transients, and continue to supply the load during transmission or distribution interruptions. In addition, this system can correct load voltage profiles with rapid reactive power control, and still allow the generators to balance with the system load at their normal speed. Figure 2 presents typical architecture of connected STATCOM with ESS to electric utility system.

The static synchronous compensator, or STATCOM, is a shunt-connected power electronic converter-based FACTS device. Unlike static var compensator (SVC), the STATCOM does not employ capacitor or reactor banks to produce reactive power. The major disadvantage of a traditional STATCOM (with no energy storage) is that it has only two possible steady-state operating modes, namely, inductive (lagging) and capacitive (leading). Even though both the traditional STATCOM output voltage magnitude and phase angle can be controlled, they cannot be independently adjusted in steady state due to the lack of significant active power capability of STATCOM. Typically, the STATCOM converter voltage is maintained in phase with the PCC voltage, thus ensuring that only reactive power flows from the STATCOM to the system. However, owing to some losses in the coupling transformer and converter, the converter voltage is generally maintained with a small phase shift with the PCC voltage. Thus, practically, a small amount of real power flows through the system from PCC to DC bus, to compensate for the losses. However, the real power capability of the STATCOM is very limited due to the absence of any energy storage the DC bus. Compared with the traditional STATCOM, the STATCOM + BESS offer more flexibility.

In case of STATCOM + BESS, the number of steady-state operating modes is extended to various situations such as inductive mode with DC charge and DC discharge, capacitive mode with DC charge and discharge. Thus, in steady state, the STATCOM + BESS has four operating modes and can operate at every point in the steady-state characteristic circle. In addition, depending on the energy output of the battery or other ESS, the discharge/charge profile is generally sufficient to provide enough energy to stabilize the power regulation in the system and maintain operation until other long-term energy sources are brought into operation. Architecture of connecting BESS with STACOM and control architecture have been shown in Figures 3 and 4.

One of the drawbacks of FACTS + ESS is that for FACTS integration, the size of the storage systems, particularly battery energy storage (BESS), may be too large for practical use in large-scale transmission-level applications. On certain occasions, large battery systems tend to exhibit voltage instability when numerous cells are placed in series. However, typically it is seen that even large oscillations can be mitigated with modest power injection from a storage system. The ability to independently control both active and reactive powers in STATCOM + BESS makes them ideal controllers for various types of power regulation system applications, including voltage fluctuation mitigation and oscillation damping. Among them, the most important use of the STATCOM + BESS is to stabilize any disturbances occurring in the power system.

2.3. Application of STATCOM with BESS. STATCOM with storage have several advantages for operation and control of power system [17]. Some of these applications include reactive and active power control, stability enhancement, system security enhancement, integration of renewable generation, avoidance of new transmission line construction, power flow congestion management, and providing control mechanism for remedial action schemes.

Wind power generation is one of the important renewable energy, which need to be controlled given inherent

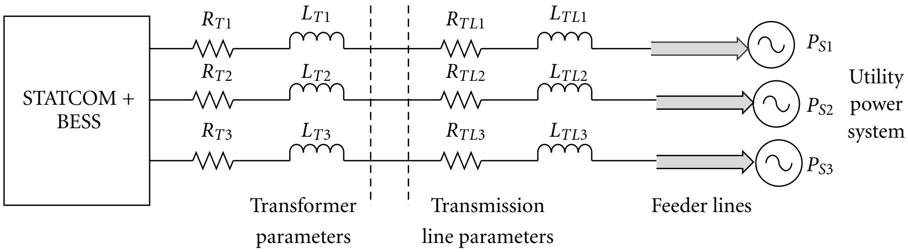

Figure 3: STATCOM + BESS connected to power transmission system.

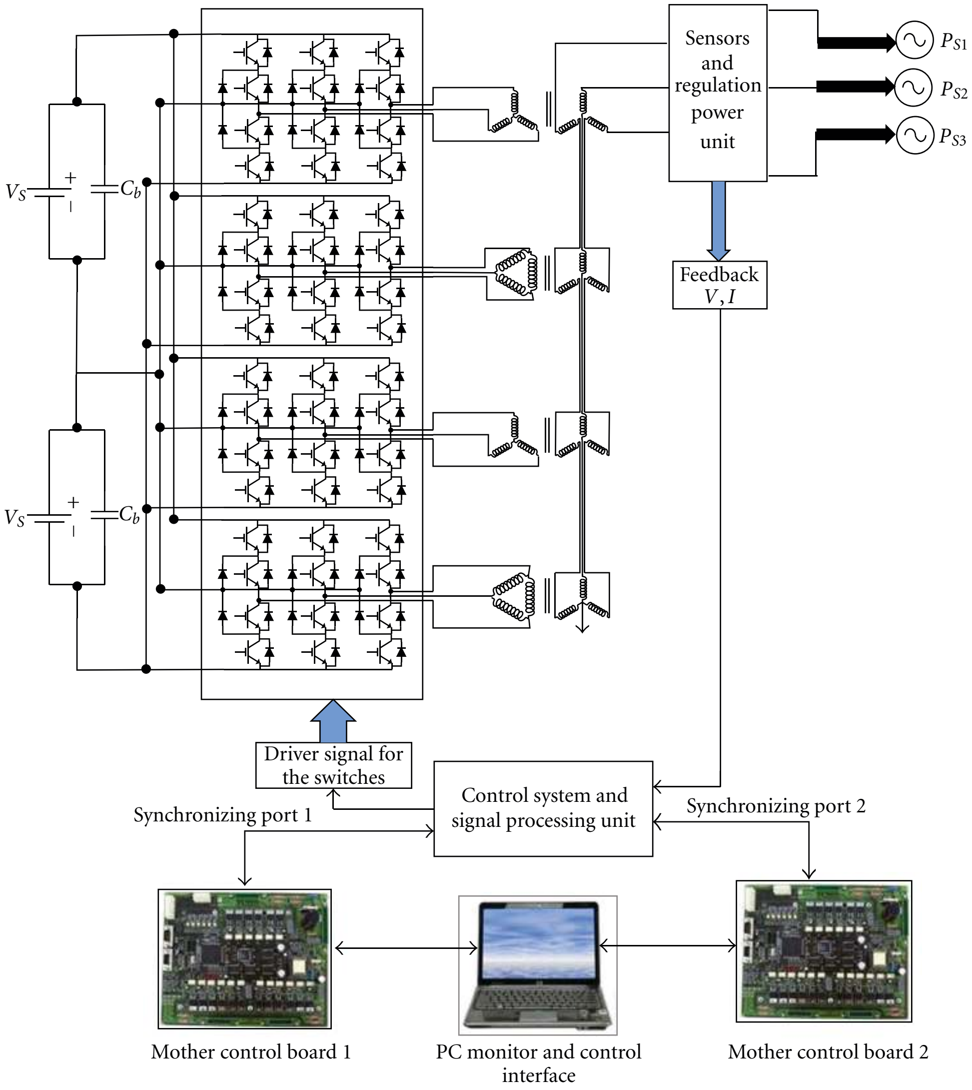

Figure 4: Structure of a BESS connected FACTS in a complete control interface for maintaining stability.

intermittency [27]. Power electronic interface have proven an important facilitator in integrating renewable energy [28, 29]. Due to the high wind power generation penetration into the grid network, the power quality of the wind generator and their continuous long-term operation becomes significantly important. The pulsating nature of the wind turbine torque produces oscillatory active and reactive power outputs at blade-passing frequencies. This oscillatory nature worsens the power quality of the wind farm in terms of voltage fluctuation at the PCC and sometimes causes damage the generators connected to the network.

During sudden severe disturbances, such as line sag or other fault situations, turbine would transmit less power to the grid. However, due to the imbalance created between the mechanical and electrical power, the speed of the turbine would eventually increase. This increase in speed of the induction generator would result in consumption of more reactive power, which causes the voltage to dip. In such situations, stability can only be retained if the increased generator speed is below the prescribed critical speed limit. Thus, in order to sustain stable operation in the event of such fault conditions of the wind farm, reactive power must be supplied externally [30]. Also, with the increasing amount of wind power generation, the wind systems cannot disconnect from the power system in case of any faults but needs to support the grid in case of faults. As a result, many countries are developing grid code requirements to have fault ride through of the wind power systems.

The benefit of using a battery in parallel to the wind turbine is that it gives the chance to produce always as much power as possible and store the energy that cannot be injected to the grid. A battery connected to the STATCOM can be the best solution to maximize the power that can be injected in a weak network in a distributed generator (DG) system [31]. The generator can be sized to produce more power than the maximum power because the excessive power can be absorbed by the battery. For a case where this situation will be possible but not probable, the BESS can be used as a dump load to absorb the power.

STATCOM can be used for stability enhancement even in offshore wind farms as they are weakly connected [32]. If there is an excess of DG power than the maximum power that can be injected to the power system, then the battery will act to absorb the extra surplus power. On the other hand, if the power consumption is excessive as well, the battery will provide the necessary power. If the battery is fully charged, then a dump load can be used to absorb this excessive power production, while the only solution for excessive consumption will be the limitation of the power. STACOM with storage can be used for low voltage ridethrough capability [33] and reactive power compensation [34]. There are number of additional examples for using STATCOM with storage for stability enhancement in [35].

Generally BESS units are designed and installed in existing systems for the purposes of load leveling, stabilizing, and load frequency control. Depending upon the specific application in conjunction with the power system, the optimal installation site and capacity of BESS can be determined. This is widely implemented for load-leveling applications. In addition, the integration of battery energy storage with a FACTS power flow controller can improve the power system operation, regulation, and control. It is quite natural that due to the intermittent nature of wind the active power P-wind generated by the wind power generator always fluctuates. Since active and reactive power is directly related hence the reactive power Q-wind absorbed by the wind power generator unit also fluctuates.

In the aftermath of disturbance, low-frequency oscillations in the AC system can be damped by either real or reactive power injection/absorption. In certain cases, the reactive power injected to the system is dependent on the STATCOM terminal voltage while the ESS is ordered according to the variation in the real power flow in the system. The approach of damping power oscillations with real power is more effective than reactive power since it does not compromise the voltage quality of the system. In terms of dynamic performance for damping oscillations, it is observed in practical cases that if ESS is connected to the AC system, it would provide better performance for a series-connected voltage source inverter (static synchronous series compensator) compared to a shunt-connected voltage source inverter. However, this is not a pragmatic solution due to the additional cost involved.

The pulsating torque at blade-passing frequency varies the slip of the wind power generator about the normal operating point. Terminal voltage of the wind turbine varies significantly with its slip. There is also a variation in the terminal voltage with active power output of the wind turbine. The large variation is due to the power flow, causing a change in voltage drop in the distribution circuit. The voltage drop can be separated into a “horizontal” and a “vertical” component of the voltage drop across the grid impedance. These voltages are the components in phase and in quadrature with the network voltage, respectively.

In summary, STATCOM + BESS unit can be applied to load leveling, saving energy at peak demand, minimizing subsynchronous oscillations, enhancing transient and dynamic stability. Another advantage of using STATCOM + BESS is that the DC link capacitor value can be reduced enormously. For certain applications, only a small capacitor would be sufficient to smooth the battery DC current which is an eminent feature of integrating battery energy storage system (BESS) with STATCOM.

2.4. Economic Aspect of the ESS System Connected to STATCOM. The cost of such an integrated system can be broken down into three major segments, namely, the energy storage system, the supporting systems such as “refrigeration for SMES,” and the power conversion system. The amount of energy to be stored primarily determines the cost of the energy storage system. For the high-power low-energy storage applications, the configuration and the size of the power conversion system may become a dominant component.

In order to establish a realistic cost estimate, the following steps must be considered.

(i) Identification of the system issue(s) to be addressed.

(ii) Study of preliminary system characteristics.

(iii) Define basic energy storage, power, voltage, and current requirements.

(iv) Define utility financial benefits from the integration of the systems to determine adequacy of utility’s return on investment.

(v) Model system performance in response to system demands to establish effectiveness of the BESS.

(vi) Optimize integrated system specifications and determine system cost.

(vii) Study and compare various energy storage systems performance and costs.

In terms of per unit active or reactive power, the cost of energy storage in feasible range is possible to be achieved by

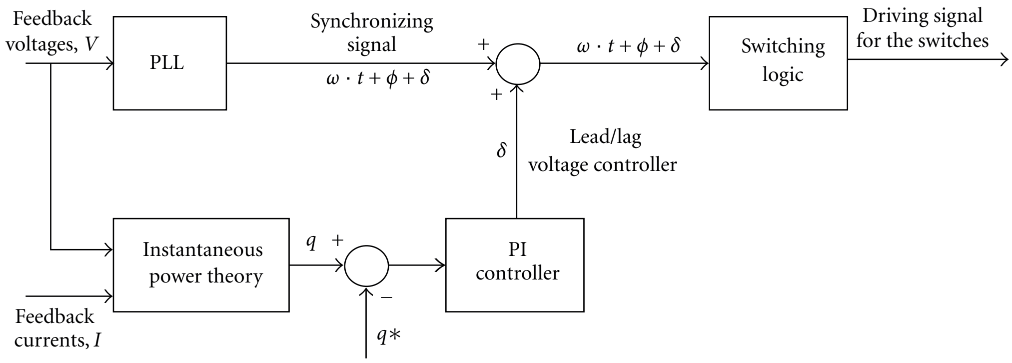

Figure 5: STATCOM control design.

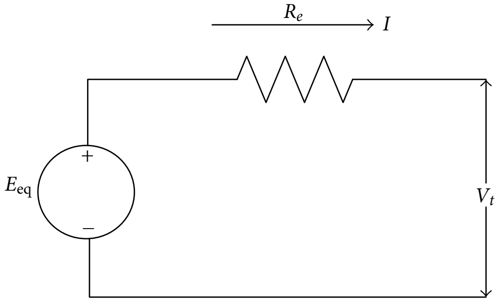

Figure 6: Equivalent model of battery.

a FACTS + BESS system. While each system will be tailored to individual utility needs, target costs for a basic energy storage system on a per-kilowatt basis are less than the costs on a per-kilowatt basis of the lowest cost generation units. With advancement in utility scale battery storage system, cost has been going down and bigger battery size is practical.

3. System Modeling

3.1. STATCOM Modeling. A STATCOM regulates voltage on a three-bus system. It is modeled as 48-pulse power converter which uses a voltage-sourced converter (VSC) built of four 12-pulse three-level GTO inverters. During steady-state operation the STATCOM control system keeps the fundamental component of the VSC voltage in phase with the system voltage. If the voltage generated by the VSC is higher (or lower) than the system voltage, the STATCOM generates (or absorbs) reactive power. The amount of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance.

The fundamental component of VSC voltage is controlled by varying the DC bus voltage. In order to vary the DC voltage, and therefore the reactive power, the VSC voltage angle (alpha) which is normally kept close to zero is temporarily phase shifted. This VSC voltage lag or lead produces a temporary flow of active power which results in an increase or decrease of capacitor voltages. The control used for this model of STATCOM is a very simple one. It uses measurements of voltages and currents at the point where the STATCOM is connected to the AC system bus.

These measured signals are worked in two ways as shown in Figure 2. In one way, the voltages are fed to the PLL (phase-locked loop) block in order to detect the frequency and phase angle and to generate the synchronizing signal to the switching logic. Control scheme is shown in Figure 5.

3.1.1. Battery Modeling. The governing equation for a simple battery model as shown in Figure 6 is given by [36] as follows:

$$V_t = E_{\text{eq}} - iR. \tag{1}$$

Here the equilibrium potential of the battery is a function of the state of charge (SOC) of the battery and can be fitted directly from the experimental data

$$E_{\text{eq}} = f(\text{SOC}). \tag{2}$$

If the following assumptions are valid: (i) the Nernst equation is a valid description of the equilibrium potential of the relevant electrochemical reactions; (ii) the main electrochemical reactions on positive and negative electrodes have fast kinetics; (iii) the capacity of the positive electrode roughly matches that of the negative electrode, we have

$$E_{\text{eq}} = E_0 + \frac{RT}{nF}\ln\left(\frac{\text{SOC}}{1-\text{SOC}}\right). \tag{3}$$

Assuming no side reactions, then the relationship between SOC and charge/discharge rate is given by

$$\frac{d\text{SOC}}{dt} = \frac{i}{3600C_{\text{bat}}}. \tag{4}$$

4. Test Case

The test case system is considered as two-area system, area-1 and area-2 as shown in Figure 7. The two areas are connected by two parallel connected long transmission lines. The direction of real power flow is from area-1 to area-2. The STATCOM is placed on one of the transmission lines and near to the generator being analyzed (area-1).

For a long transmission line, having a series impedance of z ohm/km and shunt admittance of y mho/km, the relationship between the sending end and the receiving end

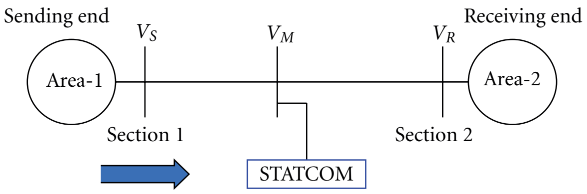

Figure 7: Two-area system with STATCOM device.

quantities with A, B, C, and D constants of the line can be written as follows:

$$\begin{aligned} V_S &= AV_R + BI_R, \\ I_S &= CV_R + DI_R. \end{aligned} \tag{5}$$

For the simplified model, where the line resistance and capacitance are neglected, both sending end power (P_S) and receiving end power (P_R) become maximum at power angle $\delta = 90^\circ$. When a STATCOM is connected to a long line to increase the power transfer capability, the above simplifications may provide erroneous results.

The active power flows at the sending end and the receiving end for a long transmission line with distributed parameters can be written as follows:

$$\begin{aligned} P_S &= K_1 \cos(\theta_B - \theta_A) - K_2 \cos(\theta_B + \delta), \\ P_R &= K_2 \cos(\theta_B - \delta) - K_3 \cos(\theta_B - \theta_A), \end{aligned} \tag{6}$$

where $K_1 = AV_S^2/B$, $K_2 = AV_SV_R/B$, $K_3 = AV_R/B$, $A = |A|\angle\theta_A$, $B = |B|\angle\theta_B$, $V_R = |V_R|\angle 0$, $V_S = |V_S|\angle\delta$.

Parameters for MatLab/Simulink Model. Figure 8 shows the MatLab/Simulink [37] model for the test case described above. The generator controller will provide the mechanical input P_m, and the field voltage V_f, depending on the electrical load of the system. The controller will also provide damping to the rotor angle during transient condition of the system. The data for various components used in the simulation are as follows (the values are in pu unless stated).

Synchronous generator parameters: 200 MVA, V = 13.8 KV, f = 60 Hz, X_d = 1.305, X_d^1 = 0.296, X_d'' = 0.255, X_q = 0.474, X_q'' = 0.243, $X1$ = 0.18.

Transformer parameters: 210 MVA 13.8 kV/500 kV, R_2 = 0.0027, L_2 = 0.08, R_m = 500, X_m = 500.

Transmission line parameters (per km): R_1 = 0.01273, R_0 = 0.3864, L_1 = 0.9337 mH, L_0 = 4.1263 mH, C_1 = 12.74 nF, C_0 = 7.751 nF.

STATCOM parameters: 500 KV, 100 MVAR, V_{ds} = 9 KV, Cdc = 600 mF, V_{ref} = 1.0, K_p = 12, K_i = 40.

Loads: generator side load—5 MW, 13.8 KV, 60 Hz; infinite bus side load—10 MW, 500 KV, 60 Hz.

Receiving end source (infinite bus): 500 KV, 5000 MVA, L = 0.0140 H, R = 0.529 ohms.

5. Simulation Analysis

5.1. Wind Energy Integration. Simulation analysis is performed in order to investigate the impact of STATCOM on the performance of a wind farm connected to the grid when a two-phase-to-line ground fault is applied to the system at time t = 12 seconds and the fault is cleared at time t = 12.2 seconds. Figure 9 shows the results of bus voltage, active and reactive power at the bus where wind farm is connected and Figure 10 shows the results with STATCOM connected to the bus. It can be clearly seen from results, that when the STATCOM is not used, the bus voltage drops to 0.5 pu. However, with STATCOM the bus voltage returns to 1 pu after the fault is cleared.

STATCOM + BESS are suggested to be the prominent device, which responds quickly during these fault conditions while improving the power quality and the stability of the wind farms. So far, the studies on this were limited to only the control of the reactive power. However, with the addition of energy storage systems (ESS), STATCOM can provide added benefit to the wind farm and the power generator systems. Among the ESS, battery-based storage systems, BESS is a highly recommended storage technology due to the advantage of having lower losses and cost.

During the occurrence of voltage fluctuations, BESS units act to balance the power fluctuation by alternately doing charging and discharging operations. In the instance of line sag or other fault situations, BESS can be used to enhance the stability margin by absorbing the active power from the wind farm. For the improvement of stability, very large amount of energy absorption may be needed intermittently. The terminal voltage and the current of the wind farm are measured and recorded to the control circuit. A simple and fast responding real as well as reactive power control is used to sense the error signal and STATCOM + BESS is used to inject real and reactive power to nullify the disturbances or oscillations created, in order to recommence normal operation of the farm.

The combined STATCOM + BESS inject fluctuating real power and the full reactive power absorbed by the wind turbine together with the bus capacitor bank as shown in Figure 11. This in turn results in the elimination of the voltage fluctuation while minimizing the reactive power flow in the grid by STATCOM + BESS.

5.2. Stability Enhancement. In order to demonstrate the effectiveness of the STATCOM-battery combination for stability enhancement, several cases are simulated. These cases are given as subsections here. To simulate dynamic oscillations in each case, a 3-phase fault is introduced at time = 27 sec and different fault-clearing times were generated at bus-B2. The plot step is 1E-5 sec for all the figures given in these cases.

Case I (system with no compensators). A two-machine AC system is simulated. When there is no STATCOM-battery combination connected to the system, the system response is depicted in Figure 12.

The system response for fault-clearing times 0.23 sec, 0.235 sec is plotted and compared with faultless system. For the fault clearing time 0.23 sec, which is less than the critical clearing time 0.2315 sec, the rotor angle of the generator will

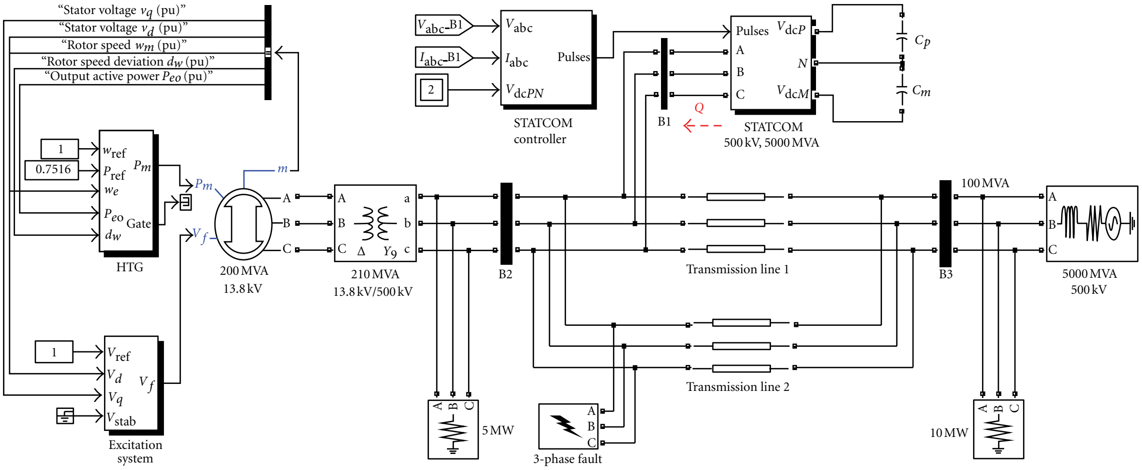

FIGURE 8: MATLAB/SIMULINK simulation model for test case system with STATCOM.

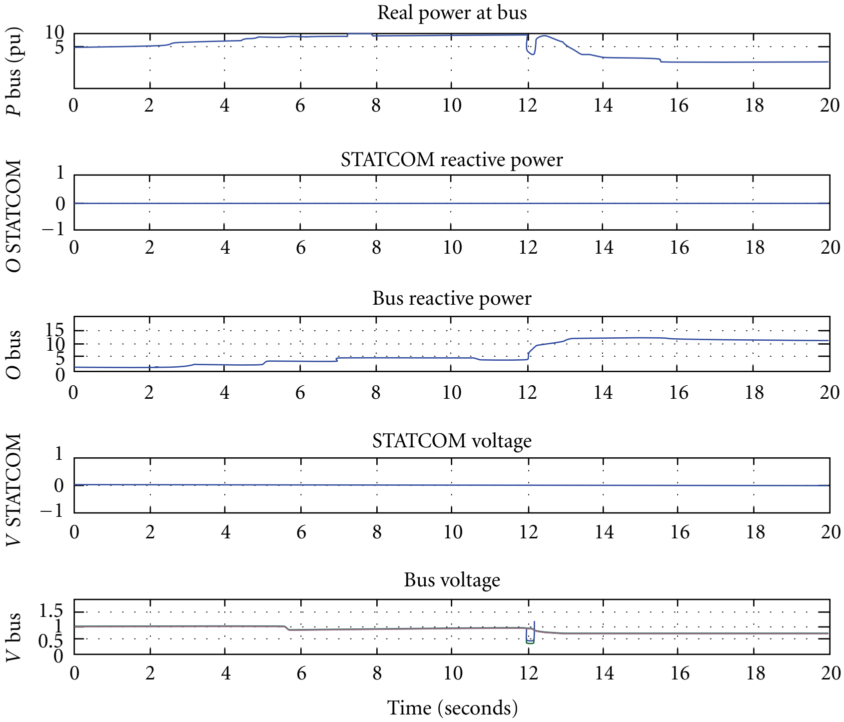

FIGURE 9: Wind Farm simulation without STATCOM connected to power transmission system.

remain stable after the fault is cleared. For the fault clearing time 0.235 sec, which is greater than the critical clearing time 0.2315 sec, the rotor angle of the generator becomes unstable after the fault is cleared. Since this case does not have any compensator attached to the AC system, STATCOM real and reactive powers are zero.

Case II (system with STATCOM). Now, the 500 KV, 100 MVAR STATCOM is connected to bus-B2. When only the STATCOM is connected, the response of the system is given in Figures 13 and 14.

Figure 13 shows the plots for the fault clearing of 0.23 sec with and without STATCOM. It is observed that the system with STATCOM will have faster rotor angle damping than compared to the system without STATCOM.

Figure 14 shows the plots for the fault clearing of 0.235 sec, which is more than the original critical clearing time, with and without STATCOM. It is observed that the generator rotor angle with STATCOM becomes stable. Whereas the generator rotor angle without STATCOM is unstable.

Case III (system with STATCOM-battery combination). Now a battery model attached to the STATCOM and this STATCOM-battery combination is then attached to bus-B2. The dynamic response of the combined device to AC

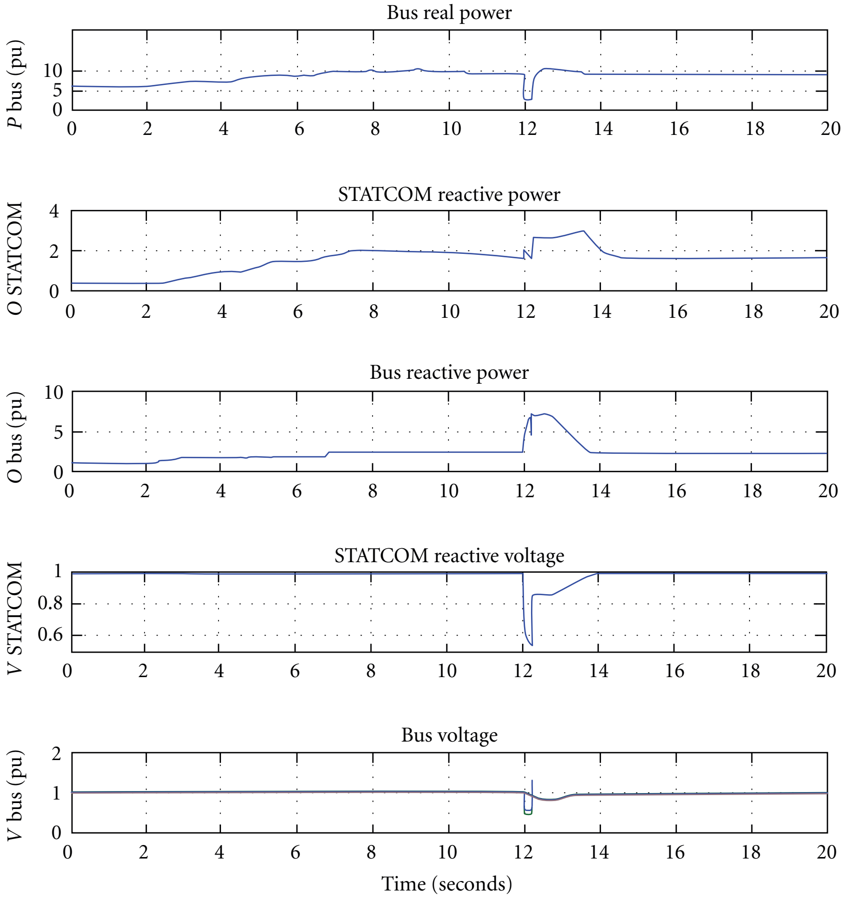

Figure 10: Wind Farm simulation with STATCOM connected to power transmission system.

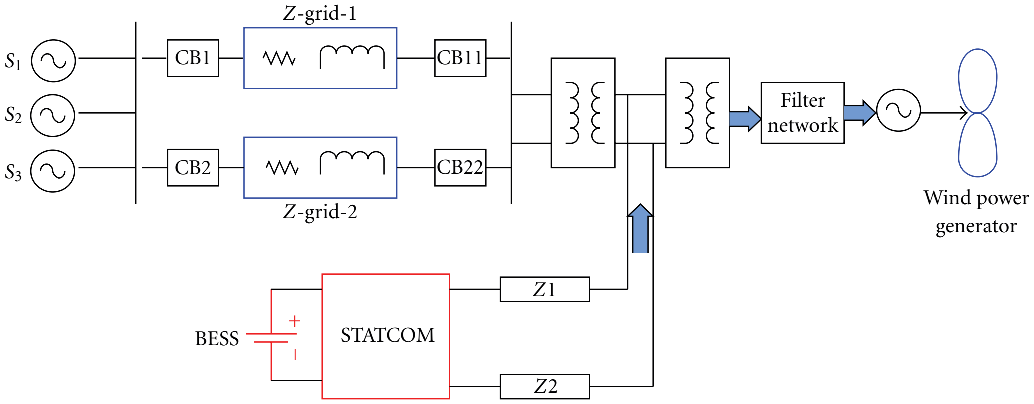

Figure 11: STACOM + BESS connected to wind power generator.

system oscillations is depicted in Figure 15. Figure shows the plots for the fault clearing of 0.235 sec, which is more than the original critical clearing time, with STATCOM and with STATCOM-battery combination. It is observed that the system with STATCOM-battery combination will have faster rotor angle damping than compared to the system with only STATCOM and the system is stable.

Figures 16 and 17 show comparison of the real and the reactive power injected or absorbed by the STATCOM and STATCOM-battery combination. In these figures, negative real and/or reactive power values represent the injected power from the device to the AC system. In this case study the reactive power injected to the system is dependent on the STATCOM terminal voltage, which is the voltage at bus-B1. During the fault, the real power injection into the system with STATCOM-battery combination is higher in magnitude when compared to the system with only STATCOM which can be observed in Figure 10. Damping

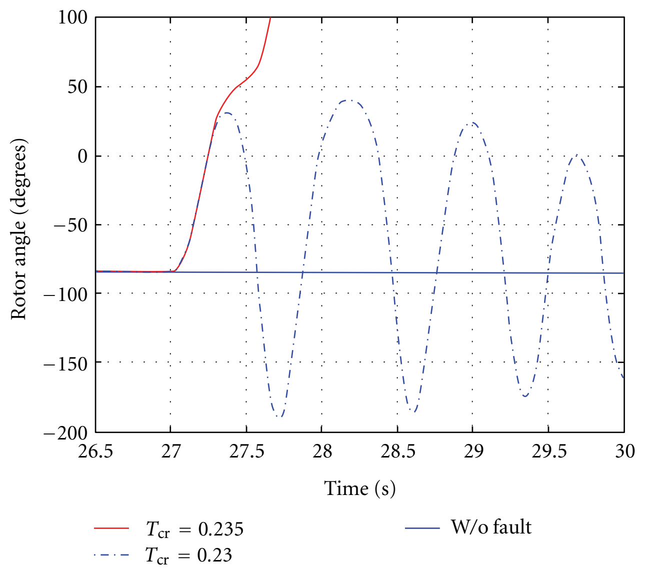

Figure 12: Rotor angle response for different values of fault-clearing time (fault applied at $t = 27$ sec).

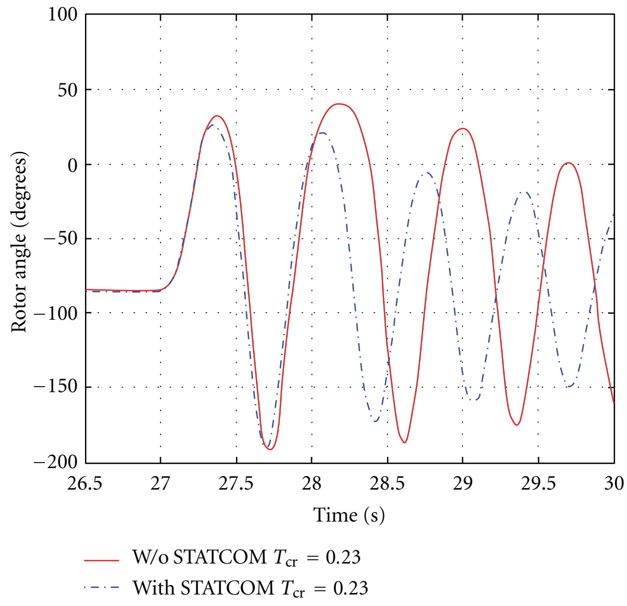

Figure 13: Rotor angle response with and without STATCOM at fault clearing time $T_{cr} = 0.23$ sec.

rotor angle oscillations with increase of real power is more effective than reactive power since it does not compromise the voltage quality of the system.

6. Conclusions

This paper is majorly divided into two sections. In the first section, thorough reviews of the benefits of using STATCOM in conjunction with battery energy storage systems are discussed. The importance and technical significance of BESS with STATCOM is elaborated here. Advantages of using BESS in connection to STATCOM in the power system for

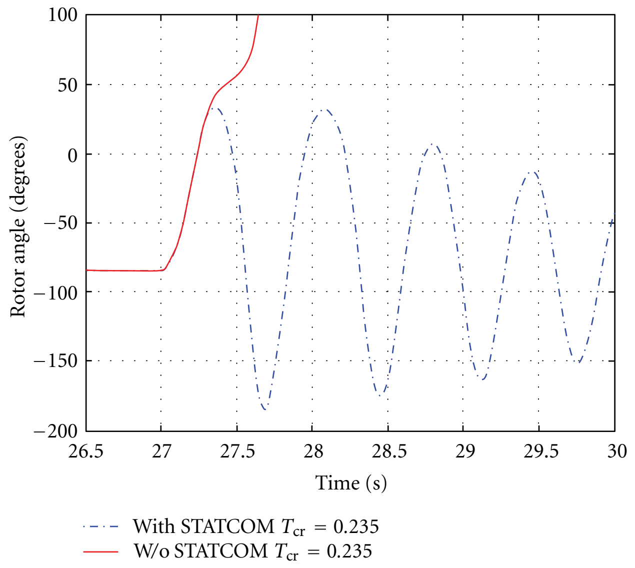

Figure 14: Rotor angle response with and without STATCOM at fault clearing time $T_{cr} = 0.235$ sec.

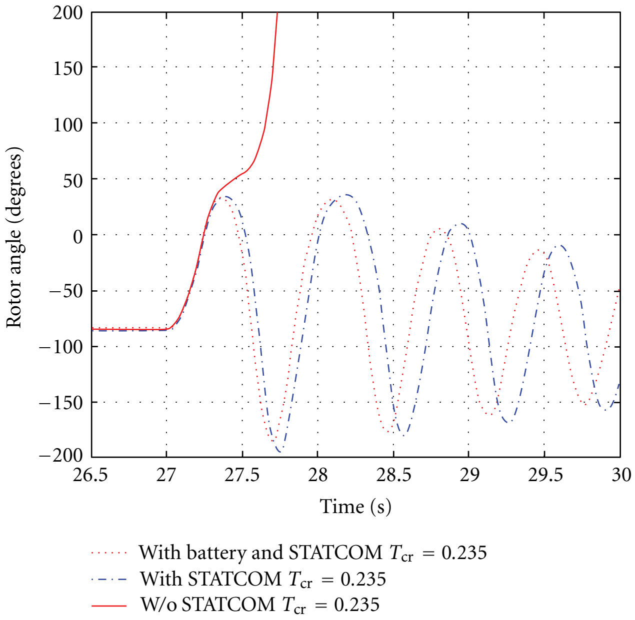

Figure 15: Rotor angle response with STATCOM and battery at fault clearing time $T_{cr} = 0.235$ sec.

minimizing the transient dynamics of the power system with practical application is discussed in the latter half of the paper. Detailed MATLAB/Simulink modeling and control of the integration of a STATCOM with a battery, and its dynamic response to generator rotor angle oscillations caused by a 3-phase fault as well as for integration of renewable energy are presented and discussed. It has been observed that the STATCOM-battery combination can be very effective in compensating generator rotor angle oscillations and thus well suited for improving transient stability and the dynamic behavior of the power system. It should also be noted that in this study the STATCOM provides a real

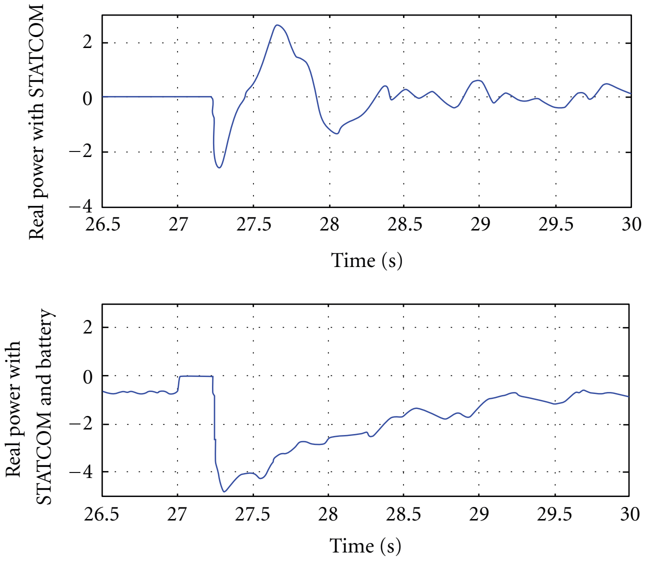

FIGURE 16: Real power comparison with STATCOM and STATCOM with a battery at $T_{\mathrm{cr}} = 0.235$ sec.

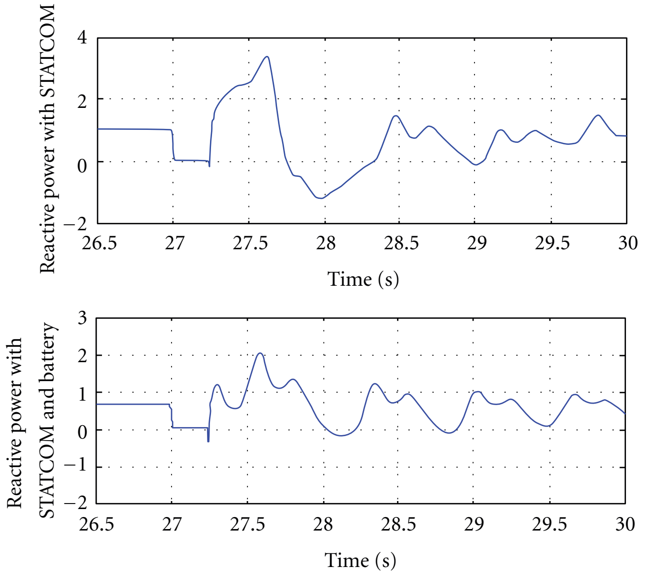

FIGURE 17: Reactive power comparison with STATCOM and STATCOM with a battery at $T_{\mathrm{cr}} = 0.235$ sec.

power flow path for battery, but the operation of the battery is independent of the STATCOM controller. While the STATCOM is controlled to absorb or inject reactive power, the battery is controlled to absorb or inject real power.

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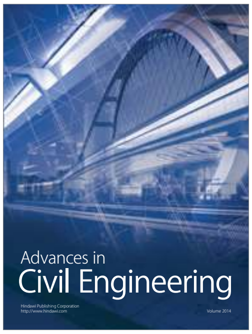
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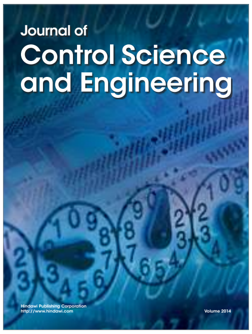
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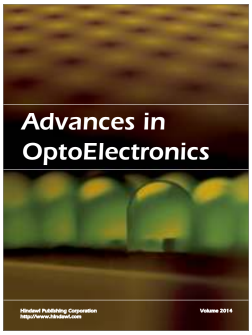
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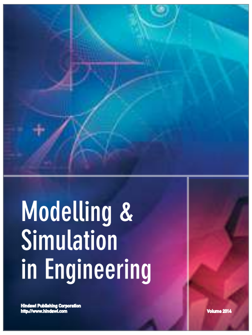
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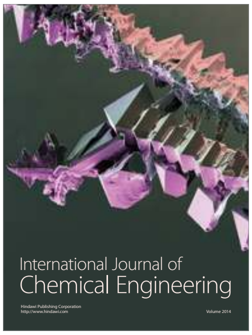
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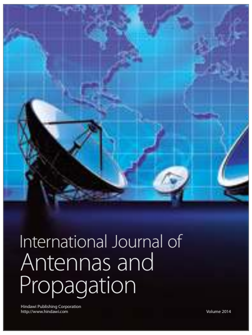
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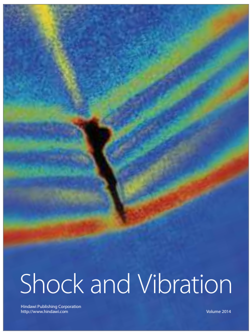
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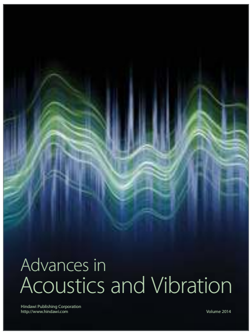
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