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Abstract

Due to the intermittent nature of wind, a wind turbine generator alone cannot supply all the active and reactive power required by the load at all times in a standalone environment. As a close relationship exists between reactive power and voltage magnitude, reactive power support is the mean used to maintain the desired voltage profile, both during normal and contingency conditions. In this paper, a synchronous condenser is integrated into the AC bus of a wind turbine generator based hybrid Remote Area Power Supply (RAPS) system where a Permanent Magnet Synchronous Generator (PMSG) is used to satisfy the active power load demand of the system. In this regard, the reactive power provision from the wind turbine generator is maintained to be zero. A battery storage is used to stabilise the DC link of the converter/inverter arrangement.

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Enhanced Reactive Power Support of a PMSG based Wind Turbine for a Remote Area Power System

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Abstract— **Due to the intermittent nature of wind, a wind turbine generator alone cannot supply all the active and reactive power required by the load at all times in a standalone environment. As a close relationship exists between reactive power and voltage magnitude, reactive power support is the mean used to maintain the desired voltage profile, both during normal and contingency conditions. In this paper, a synchronous condenser is integrated into the AC bus of a wind turbine generator based hybrid Remote Area Power Supply (RAPS) system where a Permanent Magnet Synchronous Generator (PMSG) is used to satisfy the active power load demand of the system. In this regard, the reactive power provision from the wind turbine generator is maintained to be zero. A battery storage is used to stabilise the DC link of the converter/inverter arrangement.**

Keywords- remote area power supply; reactive power; wind; permanent magnet generator.

I. INTRODUCTION

Remote Area Power Supply (RAPS) systems are installed mainly due to the unavailability of electricity grids in rural and regional communities. Other reasons include the desire to use renewable energy, or for independence, and in some instances the lower running costs of a RAPS system. A RAPS system can be operated solely using a diesel or petrol generator. However, in recent years, there has been an increasing trend towards combining the traditional diesel or petrol generator with one or more renewable energy generating sources such as PV modules, wind turbines, fuel cells or micro hydro-generation in a hybrid system.

A fundamental requirement to the supply of electricity is to ensure that the voltage magnitude is within a specified range at each bus. Consequently, voltage control is an inherent part of power system operations [1]. Due to the tight coupling between reactive power and voltage magnitude, reactive power support is the mean used to maintain the desired voltage profile, both during normal and contingency conditions. The main challenges in a RAPS system are to maintain the voltage and frequency levels within acceptable limits as these are the most important parameters to be controlled from the customers' perspective.

Wind is identified as one of the fastest growing renewable energy technology in the energy industry. The operation of wind generator based power systems, however, is challenging due to the variable and intermittent nature of wind. When a wind generator operates in grid connected mode, power smoothing/conditioning and other power quality aspects (i.e. harmonics and flicker) are the most important aspects to be examined whereas in the standalone mode, the highest emphasis is given to minimise the demand-generation mismatch to overcome unexpected voltage and frequency excursions [2]. If the reactive power variations are large, voltage variations that are outside acceptable levels are inevitable.

Full Converter Wind Turbine (FCWT) concept with Permanent Magnet Synchronous Generator (PMSG) is considered to be one of the most suitable methods for low and medium power level applications [3]. PMSG based wind turbines offer many advantages as well. The self excitation capability, low excitation losses, high torque density and low maintenance are some of the attractive features of PMSG. The decoupling between the load and the generator minimises the effects of a grid fault and thus provides a better fault response. Also, PMSG allows low speed operation and gearless direct drive connection. Most modern wind turbines have some capability to control reactive output at the machine terminals either as a function of the machine design or with the help of small, internal switched shunt capacitors. However, additional reactive power support is required in the presence of large inductive or capacitive loads for the purpose of voltage regulation, both during transient and steady-state operation.

A wind turbine based RAPS system where the PMSG acts as the main source of energy is shown in Fig. 1. Unlike an induction generator, the PMSG does not need separate excitation for the rotor. The PMSG shown in Fig. 1 consists of a Line Side Converter (LSC) to control the system voltage and frequency. Vector control strategy has been employed for the LSC controls. The machine side is connected to an uncontrolled rectifier. It is identified that the PMSG alone is not capable of regulating the voltage and frequency in a standalone environment. Therefore, a battery storage system has been incorporated into the DC link of the rectifier-inverter system via a bi-directional buck boost converter. The battery storage system absorbs excess power during over-generation scenarios and discharges it into the system when there is a power deficit during under-generation. The frequency of the

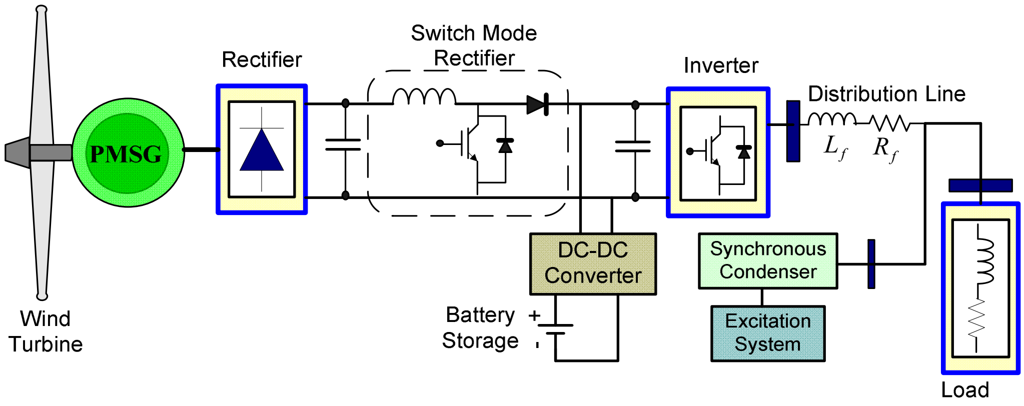

Fig.1 A wind-battery based hybrid RAPS system with a synchronous condenser integrated

system is controlled by maintaining the power balance of the entire system.

The PMSG alone cannot supply all the reactive power of the system demand when it operates in a standalone environment. The system voltage control in a RAPS system is achieved by maintaining the reactive power balance of the system. Reactive power compensation in a RAPS system can be done either by synchronous condensers, Static VAR Compensators (SVC) which utilise power electronics, or Flexible AC Transmission System (FACTS) devices. In this paper, a synchronous condenser is connected to the load side AC bus of the RAPS system, as shown in Fig. 1, which is used to support the reactive power demand of the load in order to maintain the system voltage within acceptable limits. Section II and III provide brief descriptions of the wind turbine model and the implemented control strategy, respectively. Section IV outlines the characteristics of synchronous condensers and an explanation of the power sharing scheme, both active and reactive, among the various RAPS system modules is given in section V. Section VI discusses the voltage regulator and exciter system implemented in this paper and section VII discusses the adopted battery control strategy. The simulated behaviour of the RAPS system under variable wind and changing load conditions is discussed and illustrated in Section VIII.

II. WIND TURBINE MODEL

The amount of power captured by the wind turbine, which is the power delivered by the rotor, is given by (1) [4].

$$P_t = 0.5\rho A C_p(\lambda,\beta).v_\omega^3 = 0.5\rho A C_p\left(\frac{\omega_m R}{\lambda}\right)^3 \qquad (1)$$

where ρ is the air density (kg/m^3), v_w is wind speed in m/s, A is the blades swept area, C_p is the turbine rotor power coefficient which is a function of the tip speed ratio, λ, and pitch angle, β, ω_m is the rotational speed of turbine rotor in rad/s, and R is the radius of the turbine.

III. CONTROL OF PMSG

The vector control scheme implemented in the LSC controls is based on a synchronously rotating reference frame. The angular velocity of the rotating axis system, ω, is set in the controller and defines the electrical frequency of the load. The voltage balance across the filter inductance is given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_f \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix} \qquad (2)$$

where L_f and R_f are the filter inductance and resistance respectively, v_{a1}, v_{b1} and v_{c1} represent the voltages at the inverter output, and i_a, i_b and i_c are the line currents.

The vector representation of a balanced three-phase system and their equivalent vectors in a rotating *dq* reference frame is shown in Fig. 2. Transforming the voltage equations using *dq* transformation in the rotating reference frame results in (3) and (4) [4].

$$v_d = v_{d1} - R_f i_d - L_f \frac{di_d}{dt} + \omega L_f i_q \qquad (3)$$

$$v_q = v_{q1} - R_f i_q - L_f \frac{di_q}{dt} - \omega L_f i_d \qquad (4)$$

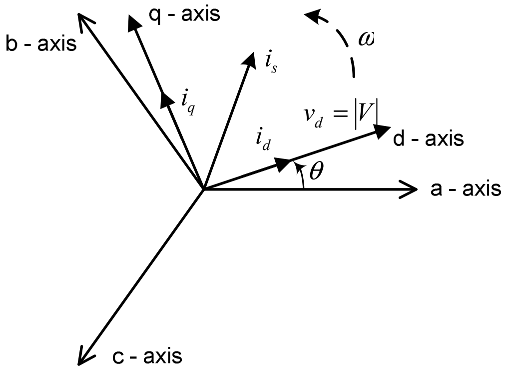

Fig. 2 *abc* axes and the rotating reference frame *dq*

The instantaneous power in a three-phase system is given by

$$P(t) = v_a i_a + v_b i_b + v_c i_c \tag{5}$$

Using *dq* transformation, the active and reactive powers are given by

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \tag{6}$$

$$Q = \frac{3}{2}(v_d i_q + v_q i_d) \tag{7}$$

If the v_q reference is set to zero, and $v_d=|V|$, the equations for the active and reactive power become

$$P = \frac{3}{2}(v_d i_d) = \frac{3}{2}|V| i_d \tag{8}$$

$$Q = \frac{3}{2}(v_d i_q) = \frac{3}{2}|V| i_q \tag{9}$$

Therefore, the active and reactive power can be controlled by controlling the direct and quadrature currents respectively. However, in the presence of large inductive, or capacitive, loads, an additional source of reactive power is required to avoid generation-demand mismatch of reactive power to maintain the system voltage within acceptable limits.

IV. CHARACTERISTICS OF SYNCHRONOUS CONDENSERS

A synchronous condenser is a synchronous motor without any mechanical load [5]. Its field is controlled by a voltage regulator to generate or absorb reactive power to support a system's voltage or to keep the system power factor at a specified level. Synchronous condensers installation and operation are identical to large electric machines. A major advantage of the synchronous condenser from an operating point of view, when compared to other means of supplying reactive power, is the flexibility of its control [6]. Once the machine is connected to the system, the reactive power that it supplies can be varied continuously over the entire range from 50 per cent or more lagging to full leading kVA by simple adjustment of its field current. Another advantage of the synchronous condenser over other rotating machines is that it neither drives nor is driven by any other apparatus [6].

V. POWER SHARING AMONG SYSTEM COMPONENTS

To achieve voltage and frequency regulation, proper control coordination among all the system components need to be established. In this regard, the inverter system of the wind energy system is identified as the main source of reactive power in the hybrid RAPS system implying that the entire reactive power requirement of the system has to be met by the wind energy system. The frequency regulation of the system is achieved by controlling the active power flow control among the PMSG, battery and dummy load. The system frequency and voltage control is achieved by maintaining the active power and reactive power balance of the system respectively. This can be expressed mathematically using equations (1)–(3).

$$\sum P_{sources} - \sum P_{\sin ks} = \frac{d(K.E)}{dt} = \frac{d(\sum J\omega^2)}{dt} = 0 \tag{10}$$

$$P_w \pm P_b = P_L \tag{11}$$

$$\sum Q_{sources} - \sum Q_{\sin ks} = 0 \tag{12}$$

where P is active power, $K.E$ is kinetic energy of the system, J is moment of inertia of the rotating machine, ω is angular velocity of the rotating machine, P_w is wind power, P_b is battery storage power, P_L is load demand, and Q is reactive power of the system.

The adopted control coordination strategy is shown in Fig. 3. The details of the proposed control coordination strategy are as follows. If the power output of the wind generator, P_w, is greater than the load power demand, P_L, the battery absorbs the additional power (i.e. $P_w - P_L$). Otherwise, the battery enters into its discharge mode of operation. If the excess power (i.e. P_w-P_L) is greater than the maximum capacity of the battery, $(P_b)_{max}$, the dummy load has to consume the additional power associated with the RAPS system. It is assumed that P_w and P_b are sufficient to supply the system load demand at all times.

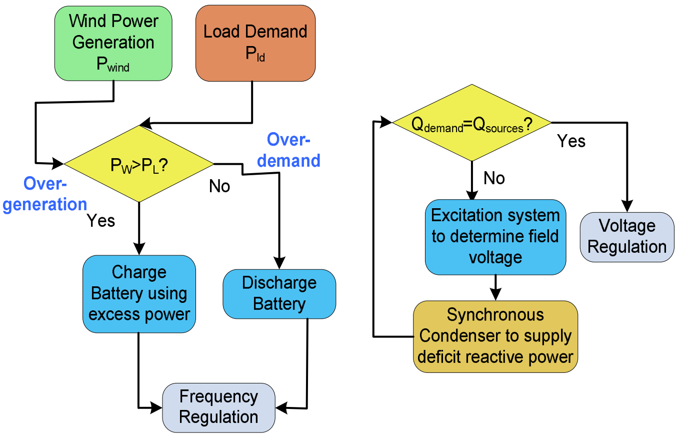

Fig. 3 Control coordination strategy

The synchronous condenser, connected to the load side AC bus, acts as the reactive power compensator to ensure the regulation of the load side voltage. An excitation system used to determine the field voltage of the synchronous condenser is discussed in the next section.

VI. EXCITATION SYSTEM

An IEEE type 1 voltage regulator and exciter system is used to control the field voltage of the synchronous condenser. The control functions of an exciter include the voltage and reactive power flow control and enhance the stability of a system. The protective functions of an exciter ensure that the required voltage and reactive power flow do not exceed the capability limit of the synchronous machine, excitation system and other equipment [7]. The performance requirements of an excitation system are mainly determined by the status of the synchronous generator and power system. The excitation system should also respond rapidly to any disturbance and minimise the transient instability [8]. A block diagram of the exciter system used in this paper is shown in Fig. 4. The excitation system consists of an exciter, a regulator, a lead lag compensator and a power system stabiliser. The regulator processes and amplifies the input control signals to a desired level and generates appropriate control signals for the exciter. The exciter provides power to the synchronous machine field winding.

The reference voltage input of the excitation system is set to 1 pu which corresponds to the desired system voltage on the load side. The load side voltage is broken down into its *d* and *q* components and fed into the voltage regulator and exciter system. The excitation system determines the field voltage to be applied to the synchronous condenser based on the difference between the system and reference voltages in order to maintain the system voltage at 1 pu both during transient and steady-state conditions.

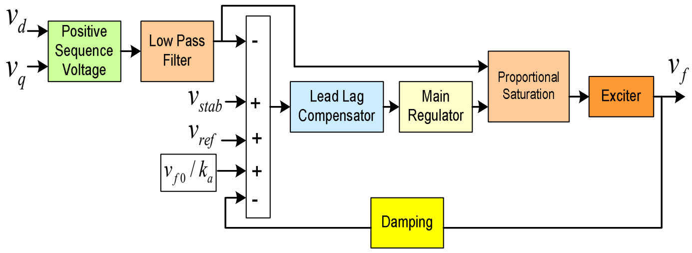

Fig. 4 IEEE Type 1 voltage regulator and exciter system

VII. BATTERY CONTROLLER

Energy storage elements play an important role in standalone systems to minimise generation-demand mismatch, especially during the following conditions:

- Reduced power generation due to low wind speed and high load demand,
- Increased power generation due to high wind speed and low load demand.

In the proposed RAPS system, a battery bank is chosen as the energy storage element and is connected to the DC link of the system through a DC-DC bidirectional buck-boost converter. The control strategy used for the operation of the battery is shown in Fig. 5. Any change in the power generated from wind or a variation in the load demand is reflected by a fluctuation in the DC link voltage. Therefore, the control strategy for the battery storage was based on the DC link voltage. The reference DC link voltage, V^*_{dc}, is compared with the actual DC voltage, V_{dc}, and the error is passed fed into a Proportional + Integral (PI) controller to produce the reference battery current, I^*_{bat}. The actual battery current, I_{bat}, is then compared with its reference value and the error in the battery current is passed through a hysteresis block which produces the control signals (gate pulses), Q_1 and Q_2, for the IGBT devices of the DC-DC converter. The battery storage system absorbs and stores power during over-generation situations when there is excess power in the system. When the load demand exceeds the power generated by the wind, the battery storage provides the deficit power required to maintain system power balance.

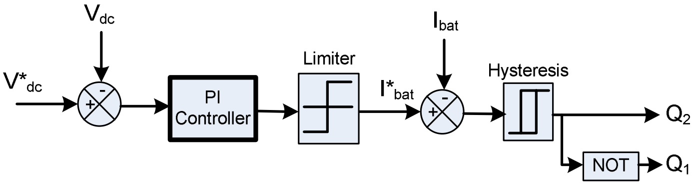

Fig. 5 Battery controller

VIII. RESULTS AND DISCUSSIONS

The RAPS system shown in Fig. 1 with a synchronous condenser integrated for reactive power support was simulated under variable wind and load conditions. The conditions under which the system was simulated are as follows:

(1) At t = 1.5s, the load is increased from 0.33 pu to 0.5 pu,
(2) At t = 2.5s, the wind speed increases from 9 m/s to 11 m/s,
(3) At t = 3.5s, a 10 kW pump load is started.

The RAPS system voltage in the absence of reactive power support under the abovementioned conditions is shown in Fig. 6. It can be seen that the magnitude of system voltage varies when load changes at both t = 1.5s and 3.5s. The system voltages and frequency when the synchronous condenser is implemented for reactive power support of the RAPS system is shown in Fig. 7. The magnitude of the system voltage is seen to be unaffected by the wind speed and load changes including during the starting of the pump load at t = 3.5s. Fig. 8 shows the real and reactive power of the system. The spike seen at t = 3.5s in the reactive power (bottom subplot of Fig. 8) is due to the starting of the pump load which demands a huge amount of reactive power. This sudden demand for large amount of reactive power is satisfied by the synchronous condenser, thus minimising the effect on the system voltage during such transient conditions.

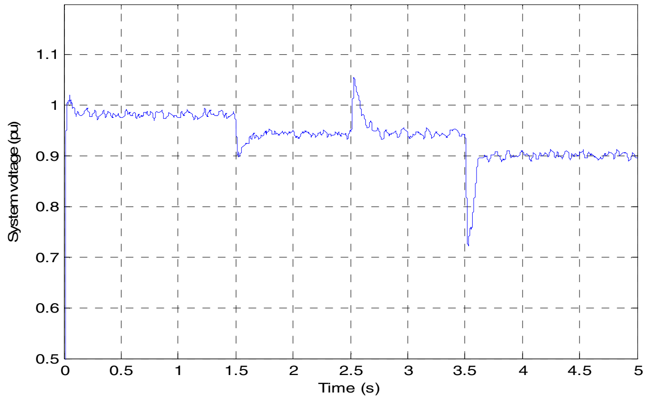

Fig. 6 System voltage under varying wind and load conditions with no reactive power support.

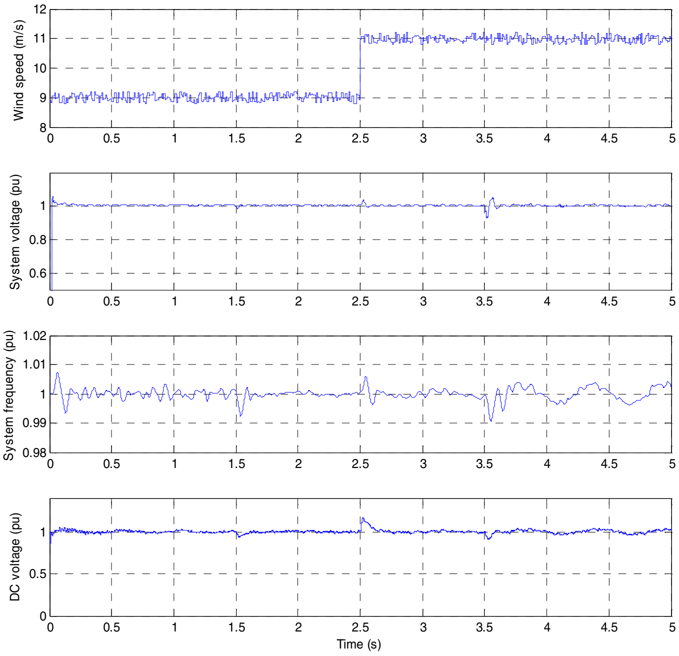

Fig. 7 Wind speed, system voltage and frequency, and DC link voltage under variable wind and load conditions with reactive power support from synchronous condenser.

IX. CONCLUSIONS

The RAPS system studied in this paper consists of a wind turbine, electric load, a battery bank and a synchronous generator for reactive power support. Vector control is implemented for the LSC controls to control the system voltage and frequency. The PMSG alone cannot supply all the reactive power of the system demand when it operates in a standalone environment in the presence of large inductive, or capacitive loads. In order to maintain the reactive power balance of the system in such scenarios, a synchronous condenser is connected to the load side AC bus of the proposed RAPS system to maintain the system voltage within acceptable limits. The frequency of the system is controlled by maintaining the active power balance of the entire system. A battery storage system has been incorporated into the DC link of the rectifier-inverter system to minimize generation-demand mismatch. The behaviour of the proposed RAPS system with a synchronous condenser integrated was simulated under variable wind and load conditions. A pump load was also introduced to observe the performance of the proposed RAPS system when a large amount of reactive power is demanded. The system voltage and frequency are seen to be well regulated within the acceptable limits and not affected by the changes in wind speed and load changes.

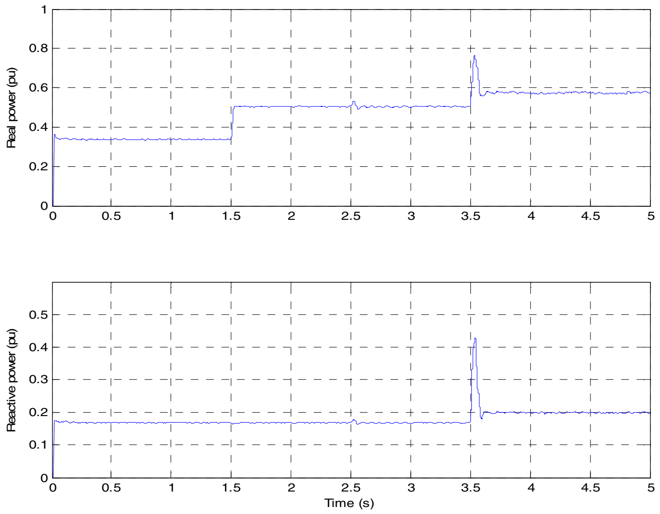

Fig. 8 Real and reactive power under varying wind and load conditions.

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REFERENCES

[1] T. Van Cutsem and C. Vournas, Voltage Stability of Electric Power Systems, Kluwer, 1998.

[2] C. A. Abbey and G. Joos, “Short-term energy storage for wind energy applications”, *Industry Application Conference,* Hong Kong, vol. 3, 2-6 Oct. 2005, pp. 2035-2042.

[3] S. Li and T.A Haskew, “Analysis of Decoupled d-q Vector Control in DFIG Back-to-Back PWM Converter”, *Power Engineering Society General Meeting*, Tampa, Florida, 24-28 Jun 2007, pp. 1 -7.

[4] M. E. Haque, M. Negnevitsky and K. M. Muttaqi, “A Novel Control Strategy for a Variable-Speed Wind Turbine With a Permanent-Magnet Synchronous Generator”, *IEEE Transactions on Industry Application,* vol. 46, issue 1, Jan/Feb 2010, pp. 331-339.

[5] C. Corvin, “SLAC synchronous condenser”, *in Proceedings of Particle Accelerator Conference,* Dallas, TX, May 1-5, 1995, vol. 4, pp. 2114-2116.

[6] P. L. Alger, “Synchronous Condensers”, *Transactions of the American Institute of Electrical Engineers,* vol. 47, issue 1, 1928, pp. 124-133.

[7] P. Kundur, “Power System Stability and Control,” *ISBN 0-07-03598-X,* New York, McGraw-Hill, 1994, Chapter 7.

[8] IEEE Std 421.5^{TM}-2005, “IEE Recommended Practice for Excitation System Models for Power System Stability Studies”, *IEEE Power Engineering Society*, 21 April 2006.