Power Quality Control of Hybrid Wind Power Generation with Battery Storage Using Fuzzy-LQR Controller

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Abstract --- This paper presents a modeling and control design for a wind-hybrid power system with a battery storage. The proposed control scheme is based on the Takagi-Sugeno fuzzy model and the linear quadratic regulator. The Takagi-Sugeno fuzzy model expresses the local dynamics of a nonlinear system through sub-systems partitioned by linguistic rules. The controllers for each sub-system are designed by the linear quadratic regulator. In the simulation study, the proposed controller is compared with the proportional-integral (PI) controller. The simulation results show that the proposed controller is more effective than the PI controller against disturbances caused by wind speed and load variation. Thus, better quality of the wind-hybrid power system is achieved.

Index Terms — Wind power generation, battery storage, converter, Takagi-Sugeno fuzzy model, linear quadratic regulator.

I. INTRODUCTION

In remote areas such as small islands, diesel generators are the main power supply. Diesel fuel has several drawbacks: it is quite expensive because transportation to remote areas adds extra cost, and it causes pollution via engine exhaust. Providing a feasible, economical, and environmental alternative to diesel generators is important. A hybrid system of wind power and diesel generators can benefit islands and other isolated communities and increase fuel savings. However, wind is a natural energy source that produces a fluctuating power output. An excessive fluctuation of power output negatively influences the quality of electricity in distribution systems, particularly frequency and voltage [1],[2].

A hybrid generation system is, in general, composed of a wind-turbine coupled with an induction generator, a diesel-synchronous unit, a dump load, and an energy storage system. Several modes of operation are possible, but in this paper, a wind-battery mode is considered. In this mode, a wind-turbine induction generator unit operates in parallel with the battery storage. When the wind-induction unit alone provides sufficient power, the diesel engine is disconnected from the synchronous generator, and the synchronous generator acts as a synchronous condenser to provide reactive power compensation [3].

Only a few publications are concerned with energy storage systems combined with wind power generation [4],[5], along side an analysis of the dynamic stability of wind-battery hybrid systems in remote areas [6]-[9]. These works do not provide a full dynamic model for stability analysis, nor for designing an effective controller. In this paper, a nonlinear mathematical model of a wind-battery hybrid system is developed to design more effective controller for power quality improvement. In addition, the battery storage model is used in both charge and discharge modes.

This paper proposes the fuzzy-LQR controller (FLQR), which is based on the Takagi-Sugeno (TS) fuzzy model [10] and linear quadratic regulator (LQR) [11]. The TS fuzzy model provides a simple and straightforward way to decompose the task of modeling and control design into a group of local tasks, which tend to be easier to handle and, in the end, the TS fuzzy model also provides the mechanism to blend these local tasks together to deliver the overall model and control design. Therefore, by employing the TS fuzzy model, a control methodology can be devised to take advantage of the advances of modern control for designing a nonlinear controller. A state-feedback by a linear quadratic regulator (LQR) is used to design controller for each sub-system. Since the final states in the target power system are not zero, extended state variables are used to design the LQR controller.

The paper is organized as follows: in Section II, the wind-battery hybrid system is modeled. Based on the reduced-order model, the proposed controller is developed in Section III, using the TS fuzzy model and the LQR. In Section IV, the controller is evaluated within various simulations, and conclusions are drawn in Section V.

II. SYSTEM MODEL

A wind-battery hybrid system consists of a wind turbine, induction generator (IG), a diesel engine (DE), synchronous generator (SG), a battery connected with a three-phase
the SG and the direct-current setpoint (u_2) of the battery system from the control point of view. The measurements are the voltage amplitude (v_1) and the frequency (v_2) of the AC bus. The wind speed (v_1) and the load (v_2) are considered to be disturbances. The wind turbine generator and the battery-converter unit run in parallel, serving the load. From the control point of view, this is a coupled 2×2 multi-input-multi-output nonlinear system.

III. FUZZY-LQR CONTROLLER DESIGN

Fig. 2 depicts the input and output relationship of the wind-battery system from the control point of view. The nonlinear mathematical model of the wind-battery system is described in detail in Appendices. The following considerations are taken into account to identify component models: the electrical system is assumed as a perfectly balanced three-phase system with pure sinusoidal voltage and frequency. High frequency transients in stator variables are neglected, which indicates that the stator voltage and currents are allowed to change instantly, because this paper is focused on the transient period instead of sub-transient period. Damper-winding models are ignored because their effect appears mainly in a grid-connected system or a system with several synchronous generators running in parallel. The different component models are of equal level of complexity. Finally, the models reflect the main dynamic characteristics that are important from control point of view. Thus, the models selected are suitable for analysis of relatively small-scale power systems in contrast to large grid-connected systems.

B. Reduced-order Model

The nonlinear mathematical model of the wind-battery system, described in detail in the Appendices, is reduced to the following second order model that is only to be used as a model to controller design purposes:

\[ \dot{\omega}_s = \frac{1}{J_s} (-D_s \omega_s - T_s) \]

\[ \dot{\psi}_f = \frac{1}{\tau_{do}} (-\psi_f + L_{md} i_{sd}) + E_{fd} \]

The reduced-order model is based on the following assumptions: the torsional modes of the mechanical drive trains are assumed to be outside of the desired bandwidth of the controlled system. There is no elasticity in the drive train. Electrical dynamics of the induction generator are not explicitly modeled.

A complete list of symbols is given in the Appendices. The reduced-order model (1) is slightly modified to represent the battery-converter unit effect in the system as shown below. The air gap torque of the synchronous generator \( T_s \) can be represented as

\[ T_s = \frac{P_s}{\omega_s} = \frac{P_{BC} + P_{load} - P_{ind}}{\omega_s} \]

where \( P_{BC} \), \( P_s \), and \( P_{ind} \) are the power for the battery-converter unit, the synchronous generator, and the induction generator, respectively, and \( \omega_s \) is the angular speed, which is proportional to frequency \( f \).

Applying (2) into (1), the reduced-order model becomes
\[
\dot{\omega}_k = \frac{1}{J_s} \left( -D_s \omega_k + \frac{P_{ind} - P_{load}}{\omega_k} - \frac{1}{\omega_k} P_{BC} \right) \\
\psi_f = \frac{1}{\epsilon_{do}} (-\psi_f + L_{md} l_{sd}) + E_{fd}
\]

(3)

The targets considered to be stable are the bus voltage and the frequency. Therefore, at a local operating point, flux linkage \( \psi \) in (3) can be modified in terms of the bus voltage and the frequency based on the assumption that the rate of change of voltage is a linear combination of rate of change of rotor flux and angular speed of the SG:

\[
\dot{V}_b = \eta_1 \psi_f + \eta_2 \dot{\omega}_k
\]

(4)

where \( \eta_1 = \frac{\partial V_b}{\partial \psi_f} \) and \( \eta_2 = \frac{\partial V_b}{\partial \omega_k} \). Here, \( \eta_1, \eta_2 \) can be approximated as 1 [p.u.]. In addition, \( P_{BC} = V_c I_{ref} \) where \( V_c \) is the AC side voltage of the converter. Therefore, from (3) and (4) the final reduced-order model is derived as

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(5)

where

\[
x(t) = [V_b \ \omega_k]^T, \ u(t) = [E_{fd} \ \ I_{ref}]^T
\]

\[
A = \begin{bmatrix}
1 & 1 \\
0 & 1
\end{bmatrix} - \begin{bmatrix}
-\frac{L_f}{T_d o} - \frac{L_f}{T_d o} \frac{L_{md}}{J_s o} l_{sd} + \frac{E_{fd}}{J_s o} \\
\frac{P_{ind} - P_{load}}{J_s o} - \frac{D_s}{J_s}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
1 & -\frac{V_c}{J_s o} \\
0 & -\frac{V_c}{J_s o}
\end{bmatrix}, \ C = \begin{bmatrix}
1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Note that the model (5) is in the linear form for fixed matrices \( A, B \) and \( C \). However, matrices \( A \) and \( B \) are not fixed, but changes as functions of state variables, thus making the model nonlinear. Also, the model (5) is only used as a tool for controller design purposes. Based on the reduced-order model, the proposed controller is designed in the following sub-sections.

C. Fuzzy-LQR Controller

The Takagi-Sugeno fuzzy model represents a nonlinear system by partitioning the system into several sub-systems and then combining them with linguistic rules. In this paper, three linear sub-systems are considered for the nonlinear state-space model (6) as

\[
\begin{align*}
\dot{x}(t) &= A_i x(t) + B_i u(t) \\
y(t) &= C_i x(t)
\end{align*}
\]

(6)

where \( A_i \in \mathbb{R}^{n \times n}, B_i \in \mathbb{R}^{n \times m}, \) and \( C_i \in \mathbb{R}^{l \times n} \). Here, \( n, m, \) and \( p \) are the number of states, inputs, and outputs, respectively. The sub-systems are obtained by partitioning the state-space into overlapping ranges of low, medium, and high states. For each sub-space, different model \((i=1, 2, 3)\) is applied. The degree of membership function for each state-space is depicted in Fig.3.

![Fig. 3. The membership function for states.](image)

Here, \( LP(i=1), BP(i=2), \) and \( HP(i=3) \) stand for low possible, most possible, and high possible membership functions, respectively. Each membership function also represents model uncertainty for each sub-system. The implicit rule is to apply corresponding sub-systems according to the degree of belonging to the sub-space measured by the membership functions. Therefore, even if the sub-systems are linear model, the composite system represents the nonlinear system. Membership functions can be optimized by the observed data.

Three controllers are designed for three linear sub-systems, and then the total control output is obtained by defuzzification. Hence, the fuzzy-LQR controller output is

\[
u_{FR}(t) = \frac{1}{3} \sum_{i=1}^{3} \bar{h}_i(x(t)) u_i(t)
\]

(7)

where \( u_{FR}(t) \) is the fuzzy-LQR controller output, \( u_i(t) \) is the controller output for each linear sub-system, and \( \bar{h}_i(x(t)) \) is the membership value of each linear sub-system.

D. Non-zero Final-state Based Linear Quadratic Regulator

For simplicity in notation, the suffix \( i \) in (6) is dropped below, such that

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(8)

Conventional state-feedback control methods are for zero final states. However, the final states may not be zero but constants such as the system under study. Therefore, it is necessary to consider such non-zero final state, leading to, so-called, tracking problem [11],[14].

Here, an additional state is introduced to address the tracking problem as
\[ \dot{x}_r(t) = r(t) - y(t) \]  

(9)

where \( x_r(t) \in \mathbb{R}^p \) is the additional state vector and the signal \( r(t) \) satisfies

\[ \dot{r}(t) = \eta (r(t) - r_{ref}) \]

(10)

with \( \eta \in \mathbb{R}^{nxp} \), a positive definite design matrix, and a constant reference signal \( r_{ref} = 1 \).

Equation (9) utilizes the integral action in (10) that makes steady-state error zero. Therefore, whenever the initial state \( x(0) \) is constant, the signal \( r(t) \) makes the state \( x_r(t) \) to be zero. Hence, the non-zero final state problem can be solved.

Including the additional state, the states can be defined as

\[ \tilde{x}(t) = \begin{bmatrix} x_r(t) & x(t) \end{bmatrix}^T \]

(11)

where \( \tilde{x}(t) \in \mathbb{R}^{p+n} \) and the associated system and input matrices for the augmented system are represented as

\[ \dot{\tilde{x}}(t) = \tilde{A}\tilde{x}(t) + \tilde{B}u(t) \]

(12)

where \( \tilde{A} \in \mathbb{R}^{(p+n)\times(p+n)} \), \( \tilde{B} \in \mathbb{R}^{(p+n)\times m} \), and

\[ \tilde{A} = \begin{bmatrix} 0 & -C \\ 0 & A \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} 0 \\ B \end{bmatrix}. \]

The proposed controller is derived from the augmented matrices in (12). The signal \( r(t) \) will be added in the final control structure.

The LQR is designed for each linear sub-system by minimizing the quadratic performance index [11]

\[ J = \frac{1}{2} \int_0^\infty \dot{x}(t)^T Q\dot{x}(t) + u(t)^T Ru(t) dt \]

(13)

where \( Q \) is a positive-semidefinite, real, symmetric matrix and \( R \) is a positive-definite, real, symmetric matrix.

The overall proposed control scheme is given in Fig. 4. Here, \( u_F(t) \) is the final control input in the form

\[ u_F(t) = r(t) + u_{FL}(t) \]

(14)

### IV. Evaluation by Simulation

#### A. System Parameters

The wind-battery system consists of a horizontal axis, 3-bladed, stall regulated wind turbine with a rotor of 16.6m diameter, that runs an induction generator (IG) rated at 55kW. The IG is connected to an AC bus in parallel with a diesel-synchronous generator unit. This unit consists of a 50kW turbocharged diesel engine (DE) driving a 65kVA brushless synchronous generator (SG). Nominal system frequency is 50Hz, and the rated line AC voltage is 230V [15]. However, in the simulation, DE is disconnected, and SG is used as a synchronous condenser. The battery storage is connected to the AC bus through a thyristor-bridge controlled current source converter rated at 55kW. A load is rated at 40kW. The inertia of the induction generator is 1.40kgm², and the inertia of the synchronous generator is 1.11kgm².

The system state (12) is defined as

\[ \tilde{x}(t) = \begin{bmatrix} x_{r,1}(t) & x_{r,2}(t) & x_1(t) & x_2(t) \end{bmatrix}^T \]

(15)

where \( x_1 \) and \( x_2 \) stand for voltage and frequency, respectively.

From the observed data, the membership functions \( LP, BP, \) and \( HP \) are obtained as \( [L_L, L_M, L_h] = [0.9074, 0.9810, 1.0287] \), \( [B_L, B_M, B_h] = [0.9257, 1.0489] \), and \( [H_L, H_M, H_h] = [0.9431, 1.0191, 1.0685] \) for voltage and for frequency \( [L_L, L_M, L_h] = [0.9640, 0.9927, 1.0236] \), \( [B_L, B_M, B_h] = [0.9716, 1.0316] \), and \( [H_L, H_M, H_h] = [0.9792, 1.0083, 1.0396] \). For the LQR controllers, the diagonal terms of \( Q \) are \( Q_{11} = Q_{22} = Q_{33} = Q_{44} = 2000 \), and the diagonal terms of \( R \) are \( R_{11} = R_{22} = 5 \). The rest of the terms are zero. The tuned PI controller gains for the governor and the excitation system are \( P_{gov} = 20, I_{gov} = 60 \), and \( P_{efd} = 30, I_{efd} = 90 \), respectively.

#### B. Wind-battery System Control

A wind-battery system can be simulated by two modes: a charge mode and a discharge mode. Fig. 5 shows the high wind speed for the charge mode, and Fig. 6 shows low wind speed for the discharge mode. Figs. 7 and 8 show the response in power distribution. In both cases, load power is fixed at 28kW. The response in bus voltage and frequency is shown in Figs. 9 and 10, respectively. In addition, the charge mode is tested with a sudden decrease in load demand from 33kW to 23kW at \( t = 15 \) sec. Fig. 11 shows the response in power distribution. The response in bus voltage and frequency is shown in Fig. 12.
The fuzzy-LQR controller achieves better performance. The criteria considered for bus voltage and frequency deviation is less than 1%. The voltage performance of the PI controller shows slow damping and fluctuation that goes beyond the criteria. Such poor performance is caused by the PI controller design, based on a single-input-single-output model. Clearly, a proper control method is required that handles a multi-input-multi-output system. With the proposed controller, all performances are smooth and damped. The charge mode seems to be more challenging than the discharge mode, as shown in Fig. 9 to have larger voltage deviation. This may be a consequence of a strong coupling between input (direct-current setpoint) and output (voltage) in the charge mode.
V. CONCLUSION

In this paper, a wind-battery hybrid system is modeled to analyze the power quality problem, and a control scheme is developed based on the Takagi-Sugeno (TS) fuzzy model and the linear quadratic regulator (LQR). An alternative state-space model to represent a nonlinear system is presented based on the Takagi-Sugeno fuzzy model. The proposed state space model provides a new means for controller design, especially when system states are not fully measurable and there is a non-zero final state. With the advantage of the TS fuzzy model, the proposed controller provides more effective control for the system that achieves good power quality, represented by fast damping of bus voltage and frequency.

VI. APPENDIX

A. Converter-battery Energy Storage System

The model of the three-phase thyristor current converter and the battery storage system emphasizes the input-output relationship between voltage and current and the connection to the overall electrical system. The DC-side of the converter is connected to battery storage. Thyristor is assumed ideal but with constant losses and harmonic current ratio between AC- and DC-current is constant as 0.955 with a large value of $I_b$ [16].

The ideal no-load maximum DC voltage of the six-pulse converter $V_{co}$ is

$$V_{co} = \frac{3\sqrt{2}}{\pi} V_c$$

and the terminal voltage of the equivalent battery is

$$V_{bc} = V_{co} \cos(\alpha_r)$$

where

- $V_c$: AC side line-to-line voltage
- $V_{co}$: communicating voltage drop of the six-pulse converter
- $\alpha_r$: firing angle
- $I_{bes}$: DC current flowing into battery.

The current $I_{bes}$ is

$$\frac{dI_{bes}}{dt} = \frac{1}{L_b} [V_{bc} - R_b I_{bes} + V_{bc}]$$

where

- $R_b$: total resistance of battery internal and DC line
- $L_b$: DC line inductance
- $V_{bc}$: open circuit DC voltage.

In connecting battery energy storage to the AC bus, $P_{BC} \cdot Q_{BC}$ can be described as

$$P_{BC} = V_{cd} I_{bes,d} + V_{q} I_{bes,q} \quad Q_{BC} = V_{cd} I_{bes,q} - V_{q} I_{bes,d}$$

where the power factor on the AC side of the converter is $\cos(\phi) = 0.955 \cos(\alpha_r)$. $P_{BC} = V_{bc} I_{bes} + P_{c,loss}$, and $Q_{BC} = P_{BC} \tan(\phi)$. Therefore, the currents, $I_{bes,d}$ and $I_{bes,q}$ can be obtained. Here, $P_{c,loss}$ is the constant power loss in the thyristor.

In Fig. 2, the control scheme of the converter system is depicted, and $u_c$ is the internal PI controller output of the converter where $k_c$ is the proportional gain and $k_c/J_C$ is the integral gain.

Fig. A2. The control scheme of the converter.

B. Wind-diesel Mechanical and Electrical Model

The modeling of the SG and the IG generator is carried out based on [13].

**Synchronous generator: (salient pole)**

$$\dot{\omega}_g = \frac{1}{J_g} (-D_\phi \omega_g - T_I)$$

$$\dot{\psi}_f = \frac{1}{T_{bo}} (-\psi_f + L_{mlq} i_{jq}) + E_{id}$$

$$\begin{bmatrix}
  r_a & -\omega_L L_a & 1 & 0 & i_{sq} \\
  \omega L_q & r_a & 0 & 1 & i_{dq} \\
  r_i & -\omega_L L_i & -1 & 0 & v_{sq} \\
  \omega L_i & r_i & 0 & -1 & v_{dq} \\
\end{bmatrix}
\begin{bmatrix}
  i_{sq} \\
  i_{dq} \\
  v_{sq} \\
  v_{dq} \\
\end{bmatrix}
= \begin{bmatrix}
  0 \\
  0 \\
  0 \\
  0 \\
\end{bmatrix}$$

where $T_I = \frac{L_{mlq} \psi_f}{L_f} i_{jq} - (L_q - L_i) V_{d,q}$

**Induction generator: (cylindrical with short circuited rotor winding)**

$$\dot{\psi}_{iq} = \frac{1}{r_q} (-\psi_{iq} + L_{aq} i_{aq}) + \omega_{d,bus}(\omega_e - \omega_a)\psi_{id}$$

$$\dot{\psi}_{id} = \frac{1}{r_q} (-\psi_{id} + L_{ad} i_{ad}) - \omega_{d,bus}(\omega_e - \omega_a)\psi_{iq}$$

$$\begin{bmatrix}
  r_e & -\omega_L L_e & 1 & 0 & i_{sq} \\
  \omega L_q & r_e & 0 & 1 & i_{dq} \\
  r_i & -\omega_L L_i & -1 & 0 & v_{sq} \\
  \omega L_i & r_i & 0 & -1 & v_{dq} \\
\end{bmatrix}
\begin{bmatrix}
  i_{sq} \\
  i_{dq} \\
  v_{sq} \\
  v_{dq} \\
\end{bmatrix}
= \begin{bmatrix}
  0 \\
  0 \\
  0 \\
  0 \\
\end{bmatrix}$$

where $T_I = \frac{L_{mlq} \psi_f}{L_f} i_{jq} - (L_q - L_i) V_{d,q}$

**Drive train model**

$$\dot{\theta}_e = \omega_{a,ref} (\omega_e - \omega_a)$$

$$\dot{\omega}_e = \frac{1}{J_e} \left( \frac{1}{2} C_p \rho A_e \frac{V_c^2}{\omega_a} - C_L \theta_e - (D_e + \omega_{a,ref} D_e) \omega_a + \omega_{a,ref} \dot{D}_e \omega_a \right)$$

$$\dot{\omega}_a = \frac{1}{J_a} \left( C_L \omega_e + \omega_{a,ref} D_e \omega_e - (D_e + \omega_{a,ref} D_e) \omega_a - T_a \right)$$

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Current balance form for electrical model

\[ i_{aq} + i_{dq} - i_{ac,d} = 0, \quad i_{ad} + i_{id} - i_{bd,d} = 0 \]  \hspace{1cm} (B.6)

where

\[ i_{aq} = \frac{\omega_s}{n_1} V_{aq} + \frac{x_1}{r_2 + x_2} V_{ad}, \quad i_{dq} = -\frac{\omega_s}{n_1} V_{d} + \frac{x_1}{r_2 + x_2} V_{aq} \]

\[ i_{ac,d} = \frac{-\alpha_t C_{qilt}}{1 - \omega_s^2 C_{qilt}^2} V_{aq} + \frac{1}{1 - \omega_s^2 C_{qilt}^2} i_{aq,d}, \quad \alpha_t = i_{aq} + \alpha_t C_{qad} \]

\[ i_{ad,d} = \frac{\alpha_t C_{qilt}}{1 - \omega_s^2 C_{qilt}^2} V_{aq} + \frac{1}{1 - \omega_s^2 C_{qilt}^2} i_{aq,d}, \quad \alpha_t = i_{bd} - \alpha_t C_{qad} \]

where

C, \alpha_t : capacitor bank and angular speed of wind turbine
L_{q}, L_{d} : d-axis field mutual inductance and transient inductance.
L_{aq}, L_{d} : current component of the load
V_{aq}, V_{ad} : AC side voltage of the converter
V_{aq}, V_{ad} : stator terminal voltage components of SG
E_{q}, E_{d} : filed voltage and filed flux linkage of SG
\omega_s, \omega_t : bus frequency (or angular speed of SG) and IG rotor
e_{d}, e_{q} : transient open circuit time constant
T_{i}, T_{o} : air gap torques of SG and IG
J_{s}, J_{d} : inertia and frictional damping of SG
\nu_{q}, \nu_{d} : rotor flux linkage components of SG
I_{ac}, I_{ad} : AC side current of the converter
r_{s}, r_{d}, L_{d}, L_{q} : stator and rotor resistance and inductance of SG
r_{t}, r_{d}, L_{d}, L_{q} : resistance and reactance between SG and IG and bus
i_{aq}, i_{ad} : current component of IG and into the bus
i_{aq}, i_{ad} : stator terminal current and voltage of IG
L_{aq}, L_{d}, \nu_{aq}, \nu_{d} : q, d-axis, field, and mutual inductance of SG.

VII. REFERENCES


VIII. BIOGRAPHIES

Hee-Sang Ko (St.M’98) received his B.S. degree in Electrical Engineering from Cheju National University, Korea, in 1996, and his M.S. degree in Electrical Engineering from the Pennsylvania State University in 2000. He has been working toward a Ph.D. in Electrical and Computer Engineering at the University of British Columbia since 2001. His research interests include electricity quality analysis of alternative energy systems and the estimation of electrical system data.

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Kwang Y. Lee (F’10) received the B.S. degree in Electrical Engineering from Seoul National University, Korea, in 1964, the M.S. degree in Electrical Engineering from North Dakota State, Fargo in 1968, and the Ph.D. degree in Systems Science from Michigan State, East Lansing in 1971. He has been with Michigan State, Oregon State, Univ. of Houston, and the Pennsylvania State University, where he is a Professor of Electrical Engineering. His interests are power systems operation and planning, and intelligent control of power plants and power systems. He is a Fellow of IEEE, Editor of IEEE Transactions on Energy Conversion, and Associate Editor of IEEE Transactions on Neural Networks.