PERFORMANCE EVALUATION OF STAND-ALONE WIND/PHOTOVOLTAIC GENERATING SYSTEMS

M.H. Nehrir, B.J. LaMeres, G. Venkataramanan, V. Gerez, and L.A. Alvarado*
Electrical & Computer Engineering Department
Montana State University
Bozeman, MT 59717

Abstract: This paper describes the development of a computer model for performance evaluation of stand-alone wind/photovoltaic generating systems. Models for different system components are developed, integrated, and used to predict the behavior of generating systems based on available wind/solar and load data. The model is useful for evaluating the performance of stand-alone generating systems and gaining a better insight in the component sizes needed before they are built. Simulation results are presented for performance evaluation of a stand-alone generating system that has been previously designed to supply the average power demand of a typical residential house [1].

An electric water heater model is used as a dump load, and the excess available wind/solar-generated power is used to heat the water. The heated water is used as the inlet water to the main house water heater, which is assumed to be non-electric.

Key Words: Wind/PV generation, Computer modeling, electric water heater dump load.

I. INTRODUCTION

The limited reserves of fossil fuels and global environmental concerns over their use for electric power generation have increased the interest in the utilization of renewable energy resources. In particular, rapid advances in wind-turbine generator and photovoltaic technologies have brought opportunities for the utilization of wind and solar resources for electric power generation world-wide. Moreover, the economic aspects of these technologies are now sufficiently promising to also justify their use in small-scale stand-alone applications for residential/ranch use.

This paper describes the development of a computer model for performance evaluation of stand-alone hybrid wind-PV generating systems. The model uses wind/solar radiation data from the sight for the generating unit and the anticipated load data to predict the generated power and the performance of the storage battery and back-up generator. Such performance evaluation can be useful to determine the component sizes actually needed for generating systems to supply power to loads reliably. It is also helpful in performing a detailed economical analysis (cost benefit study) for the generating unit. The computer model was developed using MATLAB/ SIMULINK.

Of particular interest is the model used for dump load. The excess wind/solar-generated power, when available, is used to heat water in an electric water heater. This heated water can be used for any purposes such as animal drinking water (in the winter). In this study the pre-heated water is used as inlet water to the main house water heater, which is assumed to be non-electric. This strategy can be an effective way of reducing the amount of fuel needed to heat water in the main house water heater.

II. SYSTEM CONFIGURATION

The block diagram for a typical stand-alone wind-PV generating system is shown in Fig. 1. The system consists of wind turbine generator(s), PV panels, storage batteries, back-up generator, and dump load. Provisions for the availability of both AC and DC buses are made using electronic converters. The generating system components can be selected, for the load to be supplied, based on a component sizing strategy [1-3]. However, this is not a requirement, and the model can be used to estimate the generation and storage battery sizes needed for a particular application.

Storage batteries are charged when wind/solar generation exceeds the demand until a specified upper limit for the battery voltage is reached. At this point the excess available power is diverted to the dump load, which in this study is assumed to be an electric water heater. The power absorbed by an electric water heater can be made variable by controlling the voltage applied to the water heater [4,5]. Batteries will discharge, supplying power to the load when demand exceeds generation. They will continue discharging until a specified lower limit for the battery voltage is reached. At that, point the batteries will stop supplying power to the load, and the back-up generator will come on to supply the required power to the load.

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* Presently at QUALCOMM Inc., Boulder, CO.

III. COMPONENT MODELING

Since in this study the steady-state operation of the generating system is of interest, simple steady-state models for the wind turbine generator (WTG), PV arrays, and the back-up generator are used. However, because the charge and discharge characteristics of the storage battery are of interest, a dynamic battery model is used. A dynamic model is also used for the electric water heater dump load because the variation of water temperature with time is of interest.

A. Wind Turbine and PV Array Models: The WTG was modeled using a simple look-up table, which converts the available wind speed to electric power, using the WTG's power curve provided by the manufacturer. In this study the power curve of a 10-kW Bergey WTG, shown in Fig.2, is used. The available insolation data (W/m^2) and the total number of PV panels used, together with the panel efficiency, provide the total available PV-generated electric power.

B. Back-Up Generator Model: The back-up generator is to provide the required power $|\Delta P|$ ($\Delta P = P_{wind}+P_{solar}-P_{demand}$) to the load when demand exceeds generation (i.e. when ΔP is negative) and the storage batteries can not provide the required power (i.e. when battery voltage falls to 85% of its rated value). This limitation will be explained in subsection C. The back-up generator is modeled as a variable power source (P_{bg}) with a fixed terminal voltage. The value of P_{bg} at any time (t) is given by equation (1).

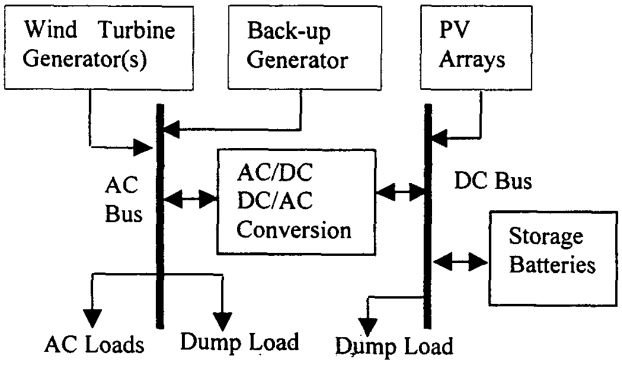


Fig. 1. Stand-alone wind-PV generating system configuration.

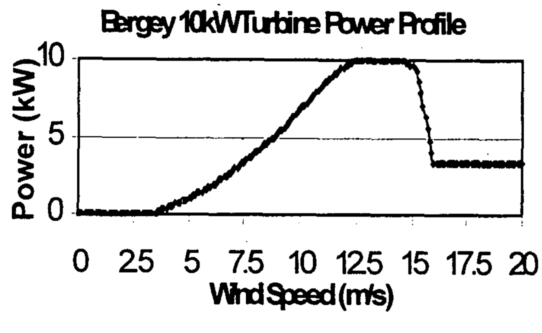
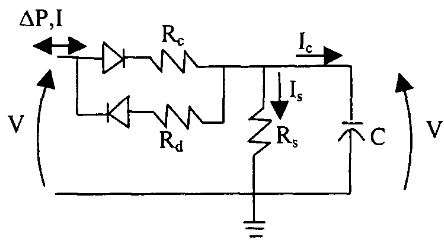


Fig. 2. Power curve of a 10-kW Bergey wind generator.

$$
\begin{aligned}
&P_{bg} = 0 \text{ when } \Delta P \geq 0, && (1)\\
&P_{bg} = 0 \text{ when } \Delta P < 0 \text{ and } V_{battery} > 85\% \text{ of rated,} &&\\
&P_{bg} = |\Delta P| \text{ when } \Delta P < 0 \text{ and } V_{battery} \leq 85\% \text{ of rated} &&
\end{aligned}
$$



ΔP, I = Input/output power, current

V_c, V = Battery nominal, output voltage

R_c,R_d,R_s= Charge, Discharge, Self-Discharge Resistance

C = Battery capacitance

Fig. 3. Battery equivalent circuit [6].

C. Storage Battery Model: A model for the storage battery is needed to predict the rate at which the battery is charged (discharged) when the generated power is more (less) than demand. It is assumed that lead acid batteries are used. The equivalent circuit used for these batteries, taken from [6], is shown in Fig. 3. The input power to this equivalent circuit is the charging/discharging power (ΔP). Power will flow into the batteries when the generated power exceeds demand (ΔP>0) and will flow out of the batteries when $\Delta P < 0$. The output signal is the battery voltage which will vary as a function of power flow into or out of the battery. Protection against overvoltage and undervoltage is provided to prevent battery overcharge and overdischarge. A minimum voltage is considered as the end of discharge (EOD) for the batteries to ensure their maximum life time [7]. In this study a nominal, battery voltage of 24 V is used, with V_{max}=26 V and V_{min}=20.4 V (85% of the nominal voltage). Therefore, batteries will stop charging when the voltage reaches 26 V and will stop supplying power to the load when voltages falls to 20.4 V. Series/parallel combination of the batteries may be needed to obtain the desired nominal output voltage. The mathematical development for obtaining the battery voltage as a function of the power flow into or out of the battery and the model parameter values used are given in Appendix A.

D. Dump Load Model: The dump load is a resistive load (R) which consumes any excess wind/solar-generated power (ΔP). Since ΔP varies with time, the dump load can be modeled with a variable resistor having a fixed voltage across it, or as a fixed resistor having a variable voltage. In either case, the variable power is $\Delta P = V^2/R$ or $V = (\Delta P.R)^{1/2}$. In this study a conventional residential electric water heater (with a 220-V, 4.5-kW heating element) is used as dump load, which is assumed to be the house auxiliary water heater. It will use any excess available power (ΔP) to heat the water. The power supplied to this water heater is varied by varying its voltage using an electronic voltage controller [4,5]. The water heated by this water heater can be used in any way the user wishes. In this study, it is assumed that the heated water is used as the incoming water to the main house water heater, which is assumed to be non-electric. This configuration can be beneficial to save on any type of fuel (such as propane) that the main house water heater uses. Because the inlet water to the water heater is pre-heated by the dump load electric water heater, less fuel would be needed to heat the water to the desired temperature in the main water heater.

The variation of hot water temperature in an electric water heater has been previously developed by the authors and can be expressed as follows [8,9].

$$T_h(t)=[T_h(\tau).e^{-(1.R'C)(t-\tau)}]+[GR'T_{out}+B(t).R'.T_{in}+Q(t)R'].\\ [1-e^{-(1.R'C)(t-\tau)}] \qquad (2)$$

The parameters in equation (2) are:

$T_h(t)=$ Mean tank water temperature at time t (°F),
$T_{out}=$ Ambient temperature of the area surrounding the water heater tank (70°F)
$T_{in}=$ Incoming cold water temperature (40°F)
$\tau=$ Initial time (sec.)
$Q=$ Water heater input power (BTU/hr),
$R'=$ $1/(G+B(t))$, $G=(SA)(1/R)$, $B(t)=8.3W_D(t)(C_p)$
8.3 = Specific mass of water (lbs/gallon of water),
$W_D(t)=$ Hot water demand (Gal./Hour),
$C_p=$ Specific heat of water (BTU/ (°F lb)),
$SA=$ Water heater tank surface area,
$R=$ Tank insulation thermal resistance (15 hour ft^2 °F/BTU)
$C=$ Tank equivalent thermal mass (BTU/°F) given by (gallons) . (8.3 lbs/gallon) . C_p.

In equation (2) hot water usage (W_D), and therefore $B=8.3W_D(C_p)$, are functions of time of day. Daily average household hot water usage has been used, taken from [10]. Using that equation, the temperature of hot water in the dump load electric water heater tank can be predicted as a function of the excess available wind/solar-generated power, which is supplied to the water heater, i.e. $Q(t)=\Delta P$ when $\Delta P>0$ and the batteries are fully charged.

IV. SIMULATION RESULTS

The component models presented above were integrated to evaluate the performance of a stand-alone Wind/PV generating system that was designed to supply the electrical power requirement of an average house assumed to be located in a remote area in south-central Montana [1]. The hourly average wind and solar power generation, average power demand, and the ΔP profiles for the house are given in Fig. 4. The component ratings used for the generating system, based on the design procedure given in [1], are listed in Table 1.

Note that in Fig. 4 ΔP is positive when the sum of wind and solar-generated power exceeds power demand, and it is negative otherwise. The battery voltage and power profiles are shown in Fig. 5. Batteries supply power to the load when ΔP is negative and the battery voltage is above 20.4 V.

Table 1. Component ratings chosen for the example stand-alone Wind/PV system [1].

Component	Rating	Number
Wind Turbine Generator	10 kW	1
Solar Panel	53 W	72
Back-up Generator	3.2 kW	1
Deep Cycle Battery	2.1 kWh (total)	

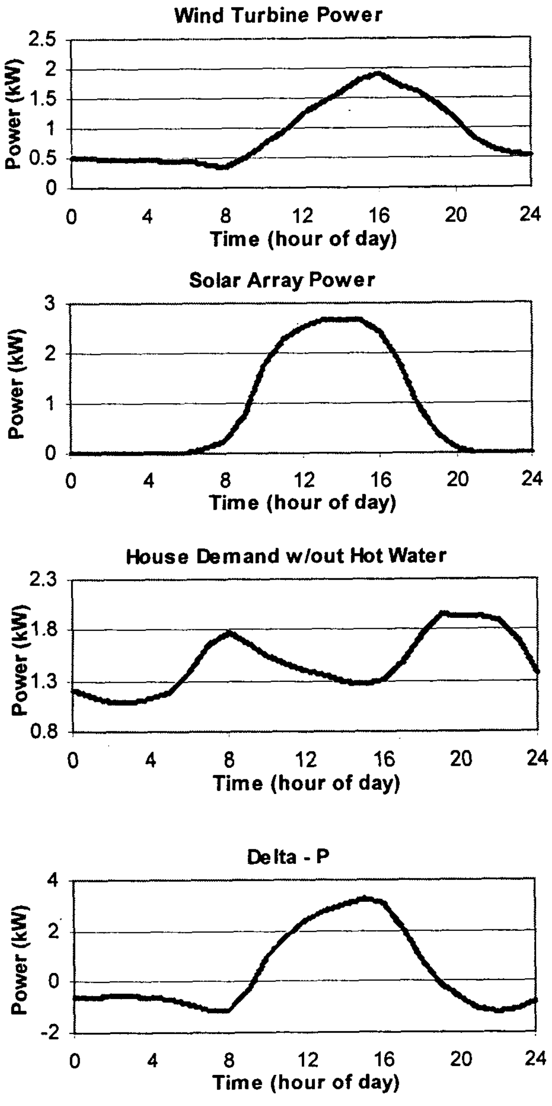


Fig. 4. Generation, power demand, and ΔP profiles.

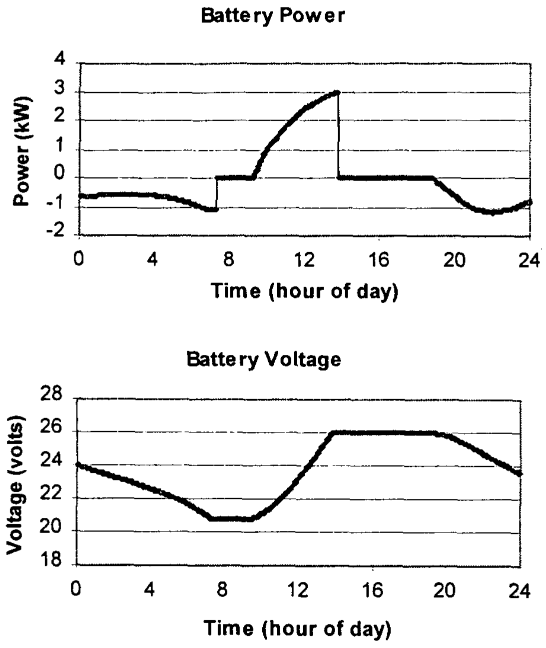


Fig. 5. Battery voltage and power profiles.

When the excess available power (ΔP) is positive, it is used to charge the batteries as long as the battery voltage is less than 26 V. The charge and discharge rate of the batteries depend on ΔP, which is a function of time, and on the battery resistance values. The resistance values used in the equivalent circuit of Fig. 3 are given in Appendix A.

Fig. 6 shows the power supplied to the load by the back-up generator. This unit comes on and supplies the required power to the load when $\Delta P < 0$ and the battery voltage is less than 20.4 V. Note from Fig. 5 that the battery discharges in the early morning hours (because of lack of sufficient wind and solar generation) until about 8:00 hours, where the battery voltage falls to its minimum level of 20.4 V. At that time the batteries stop supplying power to the load and the back-up generator comes on to supply the required power ($P_{bg} = P_{demand} - P_{gen}$) to the load. At 10:00 hours, generation exceeds the demand; the back-up generator is turned off, and the batteries begin and continue charging until 14:00 hours when the battery voltage reaches its upper limit of 26 V and stops charging. After that time, the excess wind/solar-generated power is supplied to a 50-gallon electric water heater used as a dump load. Power supplied to the water heater, as a function of hour of day, is shown in Fig. 7. At 19:00 hours ΔP goes negative (Fig. 5), and the power supplied to the water heater goes to zero. At this time the batteries start discharging to supply the required power to the load.

Fig. 8 shows the temperature profile of the water in the dump load water heater tank for 72 hours. It is assumed that the incoming cold water to the dump load water heater is at 40 °F, and its output (hot water) pipe is connected to the main house water heater cold water (input) pipe. Simulation has been performed for 72 hours to make sure water temperature comes to steady-state. Initially, the temperature of the water in the water heater tank is the same as that of the incoming cold water. Between 14:00 and 19:00 hours power is supplied to the water heater. Water temperature starts rising at 14:00 hours. However, at 18:00 hours it begins to fall because the power supplied to the water heater has decreased, and also because the hot water usage in the house hold has increased. Daily average hot water usage of an average house, taken from [10], was assumed to be taken out of the main house water heater and therefore from the dump load water heater. The rate at which water temperature in the dump load water heater rises and falls depends on the amount of power supplied to the water heater and the rate of water usage.

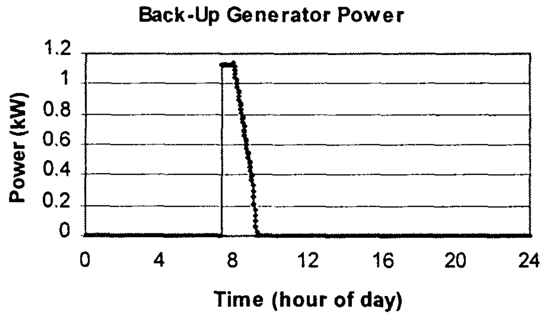


Fig. 6. Back-up generator power profile.

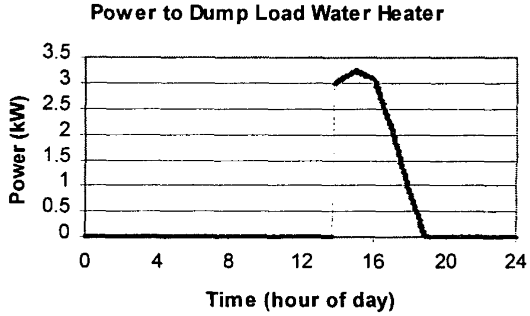


Fig. 7. Power supplied to the dump load water heater.

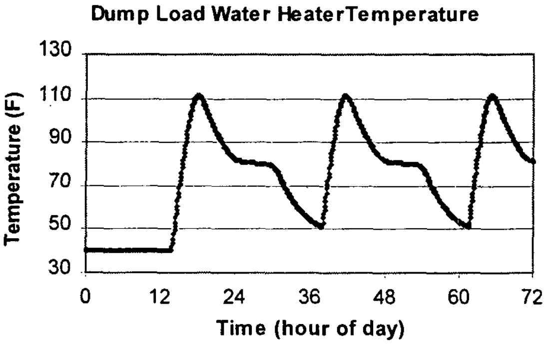


Fig. 8. Temperature profile of water in the dump load water heater.

V. CONCLUSIONS

This paper reported the development of a computer model for performance evaluation of stand-alone wind/PV generating systems. The model is a useful tool for predicting the performance of such generating systems before they are built. It can also be used to explore the cost versus benefits of increasing or decreasing the size (rating) or the number of each system component.

An electric water heater was used for the dump load to use the excess wind/solar-generated power to pre-heat the water flowing in the main house water heater. Simulation results were presented to predict the performance of a stand-alone wind/PV generating system supplying power to an average house assumed to be located in a rural area in south-central Montana.

Acknowledgment

This work was supported by the Montanans on a New Track for Science (MONTS) and DOE/EPSCoR programs at Montana State University.

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Appendix A: Storage Battery Input/Output Relationships

Here, we obtain the battery voltage as a function of power flow into or out of the battery. Assuming the initial battery capacitance voltage ($V_c(0)$) and the battery energy storage capacity (E) are known, the initial charge stored in the battery and the battery capacitance (C) can be obtained:

$C = (2\,E)/[V_c(0)]^2, \quad Q\,(0) = Cv_c(0)$

At any given time t, $i_c(t) = c\,d\,v_c(t)/dt$, $i_s(t) = v_c(t)/R_s$ and $i\,(t) = i_s\,(t) + i_c\,(t)$. Knowing i(t), the battery output voltage can be obtained as $v\,(t) = \Delta P(t)/i(t)$. During the charging periods, $\Delta P = (P_g - P_{demand}) > 0$, and $v(t) = v_c\,(t) + R_c.i(t)$. During the discharging periods $v(t) = v_c(t) - R_d.i(t)$.

The resistance values used in this study are: $R_s = 25\ M\Omega$, and $R_c = R_d = 1m\Omega$.

Biography

M. Hashem Nehrir (Senior Member, IEEE) received the B.S., M.S. and Ph.D. degrees from Oregon State University in 1969, 1971, and 1978 respectively, all in electrical engineering. From 1971 to 1986 he was with the Department of Electrical Engineering at Shiraz University in Iran, where he became department Chairman in 1984. He has been on the electrical engineering at Montana State University, where he is a full professor. His primary areas of interest are control and modeling of power systems and electrical machinery, Renewable power generation, and fuzzy logic control applications to power systems. Dr. Nehrir is a member of Eta Kappa Nu and Tau Beta Pi honor societies.

Brock J. LaMeres (Member, IEEE) received the B.S. degree in electrical engineering from Montana State University in December 1998 and joined the Hewlett Packard Co. in Colorado Springs, CO in January 1999. In 1996 he did an internship for VeriBest Inc., an EDA development company and during summer 1998 he did an internship for Micron Technology Inc. He received recognition and several scholarships for his participation and achievements in undergraduate research. His primary areas of interests are digital signal processing, fuzzy logic control, and microprocessor applications. He is a member of Eta Kappa Nu , Tau Beta Pi, Phi Kappa Phi, and Golden Key honor societies.

Giri Venkataramanan (Senior Member, IEEE) received the B.E. degree from the Government College of Technology, Coimbatore, of the University of Madras, India, the M.S. degree from the California Institute of Technology Pasadena, and the Ph.D. degree from the University of Wisconsin, Madison in 1986, 1987, and 1992, respectively, all in electrical engineering. He joined the Electrical Engineering Department at Montana State University in 1992, where he is currently an Associate Professor. His interests include modeling, design and control of power conversion systems and introduction of pragmatism education.

Victor Gerez (Senior Member, IEEE) received the engineering degree from the National University of Mexico and the M.S. and Ph.D. degrees from the University of California, at Berkeley in 1958, 69, and 72 respectively, all in electrical engineering. He started his engineering career in 1958. In 1973 he became chairman of the Mechanical-Electrical Engineering Department at the National University of Mexico. In 1977 he became the director of the power system division in Mexico's Electric Power Research Institute. He joined the Electrical Engineering Department at Montana State University in 1983, where he is currently a full professor; he was department head from 1984 to 1996.

INTERNATIONAL PRACTICES TO DRIVE TRANSMISSION AND DISTRIBUTION EFFICIENCY IN OPEN ACCESS / HIGH EFFICIENCY AND RENEWABLE GENERATION (PANEL)

WEDNESDAY, JULY 21/9:00 A. M.
WESTIN HOTEL/YUKON

Sponsor: Energy Development and Power Generation Committee, International Practices Subcommittee
Chair: T. HAMMONS, University of Glasgow, UK

The panel is intended to present viewpoints from different concerned jurisdictions and to elaborate on the various mechanisms and incentives, such as Performance Based Regulation (PBR), and other market drivers being used to achieve improved efficiencies in Transmission and Distribution systems.

FUEL CELL APPLICATION—UTILITY PERSPECTIVE (PANEL)

WEDNESDAY, JULY 21/2:00 P.M.
WESTIN HOTEL/ALBERTA

Sponsor: Energy Development and Power Generation Committee, Energy Development Subcommittee
Chair: C. H. SHIH, AEP

Advancement of fuel cell technologies in recent years has drawn serious attention in the electric power industry. Advanced fuel cells are environmentally attractive and have inherently high efficiencies. Fuel cells have potential to be adaptable to different operating conditions and may play an important role in future DR (Distributed Resources) deployment. The panel session will address major R&D programs sponsored by EPRI, status of few key utility organizations, initiatives, major results of pilot programs and experiences, and perspective of fuel cell application in the U.S. and abroad.

Panelists

A 200 kw ONSI Fuel Cell on Anaerobic Digester Gas
    Y KISHINEVSKY, New York Power Authority
Fuel Cells in Distributed Generation
    J. O'SULLIVAN, EPRI
Experience with a MCFC Power Plant at MCAS Miramar, San Diego and Perspective on Impact of Fuel Cells in the Market Place
    A. FIGUEROA, San Diego Gas & Electric Co.
Fuel Cell Technologies in Search of New Directions, Based on Over 20 Years Experience
    A. HAGIWARA, TEPCO
Fuel Cell MTG Hybrid: The Most Exciting Innovation in Power in the Next 10 Years
    S. L. HAMILTON, Edison Technologies Solutions