JPE 3-1-6

A Study on Photovoltaic/Wind/Diesel Hybrid Power System

[1]Byung-Hwan Jeong, [1]Jun-Seok Cho, [1]Jae-Seok Gho, [1]Gyu-Ha Choe*, [2]Eung-Sang Kim, and [3]Chang-Sung Lee

[1]Dept. of Power Electronics Engineering, Konkuk Univ., Seoul Korea
[2]FACTS & PQ Div., KERI, Daejon Korea, [3]Wooridle Co., Kangnung Korea

ABSTRACT

In this paper, a hybrid power system with photovoltaic/wind/diesel generators is proposed to solve the defect of stand-alone type power system in a remote area. A hybrid power system has a power-balanced controller to equilibrate generation power with a given load demand and which is composed of common DC power system. To execute a power-balanced control, a hybrid power system is assumed that all of power generators have the characteristics of an equivalent current-source and load sharing control technique must be needed at the same time. So this paper discusses the structure of power-balance control for hybrid power system. And through the results of simulation, the proposed scheme was verified.

Keywords: photovoltaic/wind/diesel hybrid power system, power balance control

1. Introduction

The stand-alone photovoltaic generation system or diesel generation system has been operated in islands or remote areas for power supplies. However, a stand-alone power system has a defect to extend more energy storage device than hybrid system and a generation power fluctuates as weather condition. Therefore it is required that an interactive photovoltaic/wind/diesel hybrid generation system for mutual compensation of meteorological and regional conditions between individual power generators. When PV/wind hybrid system generates a sufficient power than a load demand, the surplus power is charged to battery bank. On the contrary, in case of an insufficient power, battery system discharges a storage-energy to load. Also, the diesel generator operates on the peak load demand while PV/wind/battery power capacities are insufficient. There are many control methods in hybrid power system. Among several types, control method to guarantee a stable power generation must be adopted, though the fluctuation of the generation with atmospheric changes. In particular, to connect hybrid generators on DC link, it is needed that the technique to convert an individual power system into equivalent current-source. If the controller of current-source type is applied, it has a merit to solve the matter of unbalanced power-sharing in the hybrid system by a conventional voltage-source method. And because this system has a common DC link, it can guarantee the stability of control system without the compensation of phase and magnitude in AC type hybrid system[1]. In this paper, it is proposed

Manuscript received April 1, 2002; revised Nov. 30, 2002.
Corresponding Author: ghchoe@konkuk.ac.kr Tel: +82-2-450-3486, Fax: +82-2-447-9186

that a hybrid generation system has a power-balance controller to equilibrate generation power with a load demand and it is composed of DC bus-type power systems. And all of power generators in hybrid power system can be equivalent to current-source characteristics. So this paper discusses the structure of power converter and power-balance control for photovoltaic/wind/diesel hybrid power system. And through the results of simulation, the proposed scheme was verified.

2. Hybrid Power System Description

In this paper, a proposed hybrid power system consists of photovoltaic/wind/diesel generation system, battery bank, inverter system and dump-load for emergency as shown Fig. 1. A hybrid power system needs the algorithm to convert all of generation systems into equivalent current-source for common DC link. As a load demand is varied, whether the surplus power is charged into battery bank or the insufficient power is transferred from battery bank to a load. Therefore battery bank is able to become a base-load or a base-generator as generation-load status. Because battery system must be charged or discharged, so two-quadrant converter is applied for such an operation. On the other hand, wind/diesel system uses AC generator and it needs power-conversion system for rectifying AC into a common DC. Converter that is applied in wind/diesel system must be controlled to keep a maximum power factor operation in input-terminal. And it has a good current control characteristics in order to operate as an ideal DC current-source in output-terminal. The output of solar cell array is a DC power, so a boost converter is used in photovoltaic system. Photovoltaic system must be done MPPT (Maximum Power Point Tracking) for maximum output power of solar cell array. To execute MPPT, it performs both of input voltage control and the averaging-current control at the same time. Then photovoltaic system that is connected on common DC link can be assumed an equivalent current-source.

The power of alternator systems is transferred to common DC link through power conversion device. In case the control method with DC voltage-source is applied DC voltage of output-terminal in converter must be equal between generator systems for parallel operation exactly. Efficiency of system decreases in a parallel operation of common voltage-source mode, as output fluctuations are exceeded. According to weather condition, photovoltaic /wind system has a fluctuant output-power characteristics each other. So DC/DC converter in hybrid system needs another algorithm for parallel operation. Improving a defect of voltage-source DC system, this paper proposes a hybrid power system with current–source. In Fig. 1, each current-source I_{wind}, I_{diesel}, I_{solar}, I_{batt} means the modeling of PV/wind/diesel and battery output current. Also, because a load power must be transferred by AC voltage-source, a voltage type inverter is adopted for DC/AC conversion. Therefore hybrid system is divided into DC current-source and AC voltage-source. Eq. (1)

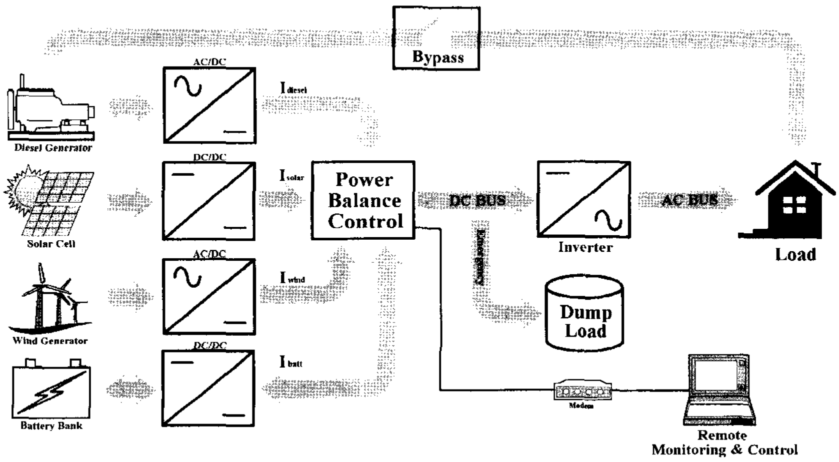

Fig. 1. Configuration of hybrid power system with common DC bus.

shows the relation of power flow when a balanced-power operates.

$$V_{inv} \cdot I_L = V_C \cdot (I_{diesel} + I_{wind} + I_{solar} + I_{batt}) \quad (1)$$

When an unbalanced-power deviation occurs in a hybrid system, it brings a common DC voltage to fluctuation, because a common DC system is controlled by current- source as Eq. (1). To equilibrate generation power with a given load demand, the capacity of generator must be controlled to compensate the deviation rapidly. But the response time of generators is so slower than a load variation. So battery system operates as a buffer between generators and load. Especially, battery system operates as not only a current-source but also a load by two-quadrant operation. But when emergency occurs in static inverter system, it is impossible that all powers from generators can't be charged into battery bank. To prevent DC link voltage rising, the limit value of voltage was set up. And then if the voltage increases rapidly by an unbalanced power, battery system breaks the rising voltage with a connecting dump-load in the common DC link. Because proposed hybrid power system controls the output of generator with a demanded-value of current sharing each other. The parallel algorithm in voltage-source mode controller and power deviation compensating controller for regulating voltage phase and its magnitude in the AC parallel operation are not needed. Therefore it has an advantage to be consistent in control structure regardless of varied-generation output and varied-load demand through overall hybrid system.

3. Control Method of Hybrid Power System

Fig. 2 shows overall circuit of proposed hybrid power system. PV system uses boost converter to control the input-voltage for MPPT operation. Wind generation system is composed of induction generator, converter for AC to DC conversion and maximum power generation, boost converter for maximum power transfer operation. 3-phase converter is employed for input current control in diesel generation system. And this converter has a rectifying operation characteristics without DC voltage control. To perform the charge and discharge current control of battery charge/discharge system,

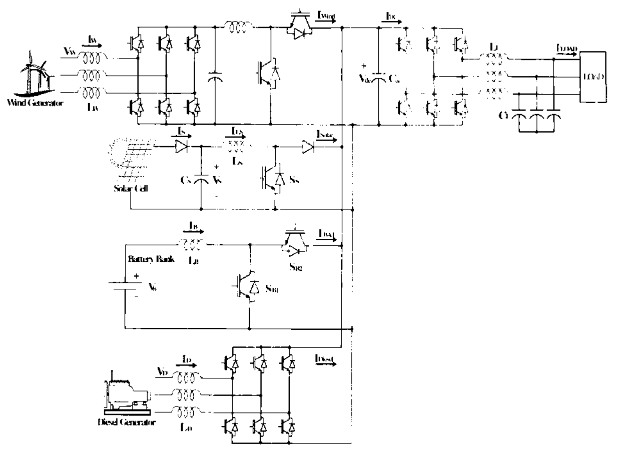

Fig. 2. Overall circuit of hybrid power system.

it is adopted that two-quadrant converter with DC voltage control. Also, the battery system has the characteristics of bi-directional power flow, it has an ability to perform a balanced-power between generation systems and a given load on common DC bus.

3.1 Control of Photovoltaic Power System

In the case of DC/DC converter in PV system, MPPT algorithm is adopted to derive a maximum output from PV cells. Due to the characteristics of solar cell, as a maximum power is varied by illumination and temperature. the maximum power point voltage of solar cells are fluctuated simultaneously. Therefore output voltage of solar cells must be controlled through current-control of inductor by switching. For such an operation, it is needed that input voltage varied-control of boost converter and this voltage is in inverse-proportion to flowing current in inductor. The solar cell, it has a characteristics of current-source, so if it is controlled by MPPT method in input stage of converter, it can transfers maximum power to load regardless of output-terminal voltage of boost converter.

Also Perturbation and Observation (P&O) method and Incremental Conductance (IncCond) method are applied for MPPT algorithm of PV system generally. In this paper, to execute maximum power tracking, it is adopted perturbation and observation method. The perturbation and observation method has been widely used because of its simple feedback structure and fewer measured parameters. The maximum power tracker operates by periodically incrementing or decrementing the solar array voltage. If a given perturbation leads to an increase (decrease) in array power, the subsequent perturbation is made in the same (opposite) direction. In this manner, the maximum power track continuous hunts or seek the maximum power conditions. Maximum power control is achieved by forcing the derivative (dP/dV) to be equal to zero under power feedback control[3].

$$\frac{dP_s(k)}{dV_l(k)} = \frac{P_s(k)-P_s(k-1)}{V_s(k)-V_s(k-1)} = \frac{V_s(k)I_l(k)-V_s(k-1)I_s(k-1)}{V_s(k)-V_s(k-1)} = I_s(k)+V_s(k-1)\frac{I_s(k)-I_s(k-1)}{V_s(k)-V_s(k-1)} \quad (2)$$

In practical, to control the input-terminal of converter, it is needed that the method of control with negative closed-transfer function in inverse-proportion to inductor current. And as Fig. 3, an averaging current-mode control method is employed. Assuming that converter consists of major voltage and minor current controller, these equations can be represented as following.

$$V_{con\_S} = (I_{Ls}^{*} - I_{Ls})\cdot(K_{pi} + \frac{K_{ii}}{s}) + V_S \quad (3)$$

where, V_{con_S} : Switching-voltage in converter (Solar)

V_S : Converter input voltage

I_{Ls}^{*} : Reference inductor current

I_{Ls} : Inductor current

$$I_{Ls}^{*} = -(V_S^{*} - V_S)\cdot(K_{pv} + \frac{K_{iv}}{s}) + I_S \quad (4)$$

where, V_S^{*} : MPPT reference voltage point

I_S : Solar cell output current

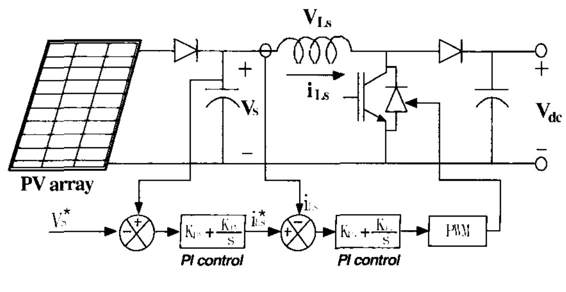

Fig. 3. Control block diagram of PV system.

3.2 Control of Wind Power System

Wind power system consists of vector control converter and boost converter for maximum power generation. It is needed that the algorithm to estimate generation capacity for maximum power transfer operation of wind generation system, regardless of variation of load demand or fluctuation of wind-generator. Power equation of wind generator is followed as Eq. (5) and C_P is a function of tip-speed ratio λ, which is defined by Eq. (6). Their relationship is graphically shown in Fig. 4.

$$P_{wind} = 0.5\rho C_P \pi R^2 V^3 \quad (5)$$

$$\lambda = \frac{\omega_m R}{V} \quad (6)$$

where, ρ : air density (kg/m^3)

R : radius of the wind turbine rotor (m)

C_P : rotor power coefficient

V : wind speed (m/s)

λ : tip speed ratio

P_{wind} : mechanical power at wind turbine

If wind generator operates on $C_{P\max}$, wind power system would generate maximum power. So, speed reference for maximum power is followed as Eq. (7)

$$\omega_m^{*} = \frac{\lambda_{opt} \times V}{R} \quad (7)$$

where, ω_m : angular speed (rad/s)

Therefore, maximum output power and torque by wind velocity is followed as Eq. (8) and Eq. (9).

$$P_{target} = 0.5\rho\pi R^5 \frac{C_{P\max}}{\lambda_{opt}^3}\omega_m^{*3} \quad (8)$$

$$T_{target} = \frac{P_{target}}{\omega_m^{*}} = 0.5\rho\pi R^5 \frac{C_{P\max}}{\lambda_{opt}^3}\omega_m^{*2} \quad (9)$$

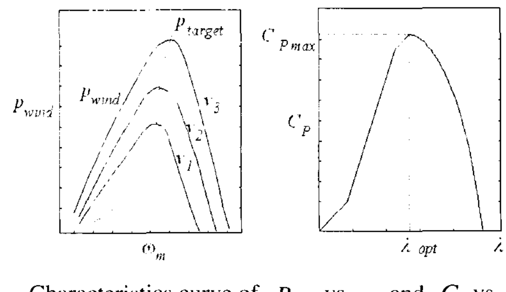

Fig. 4. Characteristics curve of P_{wind} vs ω_m and C_P vs λ .

Maximum power control method is to keep wind turbines operating at their optimal tip-speed ratios, where the maximum energy conversion efficiency of wind turbines can be reached[4]-[7].

To generate maximum power, wind generator must keep track of P_{target} curve on Fig. 4. This operation can be obtained through speed control by using indirect field-oriented control method of induction generator. So, speed reference in Eq. (7) is employed for speed control block in Fig. 5. And excitation current must be injected into induction generator for voltage settlement initially. Therefore first it operates on motor control mode for flux settlement and then it operates on generator control mode to transfer generation power from wind turbine to converter. And boost converter is applied for maximum power transfer operation similar to PV system. To control induction generator by indirect field-oriented method, d-q model equation must be adopted as followings.

$$V_{ds}^e = (R_s + R_r \frac{L_m^2}{L_r^2}) i_{ds}^e + \rho\sigma L_s i_{ds}^e - \omega_e \sigma L_s i_{qs}^e - R_r \frac{L_m}{L_r^2} \lambda_{dr}^e \qquad (10)$$

$$V_{qs}^e = (R_s + R_r \frac{L_m^2}{L_r^2}) i_{qs}^e + \rho\sigma L_s i_{qs}^e - \omega_e \sigma L_s i_{ds}^e - \varpi_r \frac{L_m}{L_r} \lambda_{dr}^e \qquad (11)$$

where, R_s : Stator resistance, R_r : Rotor resistance

λ_{dr}^e, λ_{qr}^e : flux linkage of rotor

V_{ds}^e, V_{qs}^e : Induction generator stator of d-q shaft voltage

σ : leakage coefficient, ω_e : angular velocity

Eq. (10) and (11) show stator voltage equations of induction generator and Fig. 5 shows control block diagram of indirect field-oriented control method in wind power system.

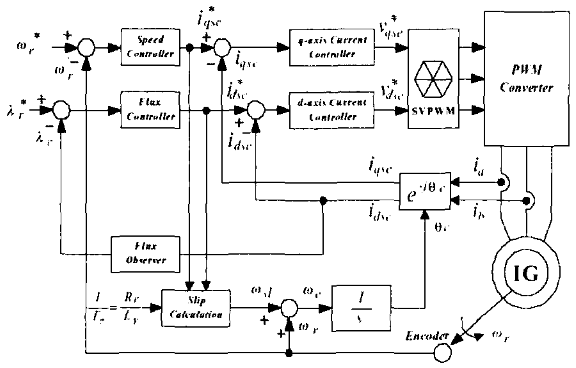

Fig. 5. Control block diagram of wind power system.

3.3 Control of Battery Charge/Discharge System

Hybrid power system was composed of two power conversion device in side of topology, it is current source system and voltage source system. Current source system indicates each generation system and voltage source system indicate battery charge/discharge system in hybrid power system. Current source type of hybrid power system is difficult common DC bus voltage stabilization. Therefore it is required that peripheral system to support a balanced power between load and generation systems. In this system, it is applied battery charge/discharge system to use the two-quadrant converter like Fig. 2. Because the battery system has the characteristics of bi-directional power flow, it has a ability to perform a balanced-power between generation systems and a given load in DC bus. A balanced-power equation of battery system is given by,

$$V_{dc} \cdot I_{Load} = V_{dc} \cdot (I_{Solar} + I_{Wind} + I_{BAT} + I_{Diesel}) \qquad (12)$$

$$V_B \cdot I_B = V_{dc} \cdot I_{BAT} \qquad (13)$$

In special, this system is composed of a current controller and the voltage controller of output-terminal. The control-equation structure is followed as below. Fig. 6 shows Control block diagram of battery charge/discharge system.

$$V_{con\_B} = (I_B^* - I_B) \cdot (K_{pi} + \frac{K_{ii}}{s}) + V_B \qquad (14)$$

where, V_{con_B} : Switching-voltage in converter (Battery)

V_B : Battery-cell voltage

I_B^* : Reference inductor current

I_B : Inductor current

$$I_B^* = (V_{dc}^* - V_{dc}) \cdot (K_{pv} + \frac{K_{iv}}{s}) + \frac{V_{dc}}{V_B}(I_{Load} - I_{Wind} - I_{Solar} - I_{Disel}) \qquad (15)$$

where, V_{dc}^* : DC bus reference voltage

V_{dc} : DC bus voltage

I_{Load} : Load current

I_{Wind} : Wind system current

I_{Solar} : PV system current

I_{Disel} : Diesel system current

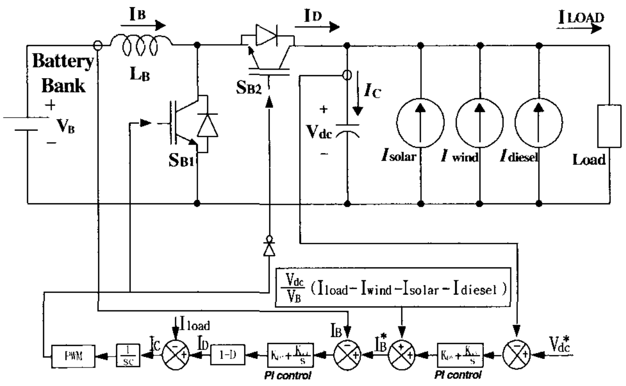

Fig. 6. Control block diagram of battery charge/discharge system.

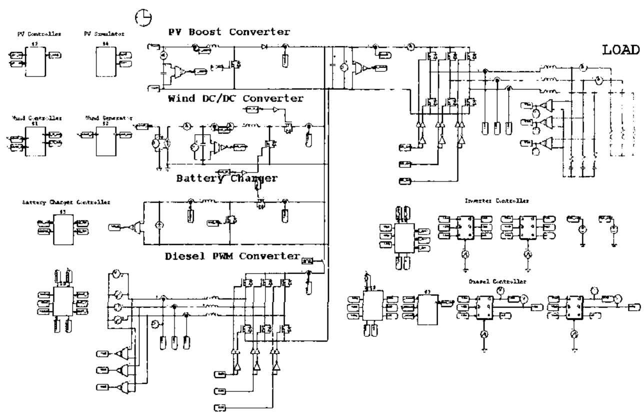

Fig. 7. Simulation schematic of hybrid power system.

Assuming that the battery system operates with the value of reference DC voltage for balanced-power control, if there is an unbalanced-power between generation power and required-power in load, so that the error of dc voltage occurs. Therefore battery system is able to compensate an unbalanced-power by charging or discharging with current in proportion to DC voltage's error.

4. Simulation

The proposed algorithm of hybrid power system is verified through computer simulation. Simulation parameters are shown as Table 1, and simulation modes for transient characteristics of systems are shown as Table 2. Fig. 7 is shown that simulation schematic for hybrid power system.

Fig. 8 shows the result of simulation mode 1. Filtered-output current waveforms of output-terminal in hybrid system are shown, when load is changed from 10[kW] to 50[kW] and from 50[kW] to 10[kW]. When the load is a 10[kW] capacity, it is shown that battery system operates on charge-mode. Also when hybrid system operates on a rated-load, PV/Wind system has an insufficient generation capacities than load demand. So the battery system is changed charge-mode into discharge-mode to compensate lacking power.

Fig. 9 represents that DC bus voltage has a fast transient response, when load is changed suddenly. And it is shown that although the load is varied, PV/wind generation systems carry on maximum power transfer operation, due to the current-source control method. Assumed fixed-load

Table 1. Simulation parameters.

Parameters	Value
C_{dc}	9900 [uF]
C_S	9900 [uF]
L_S	3.7 [mH]
L_W	2 [mH]
L_B	2 [mH]
V_{dc}	600 [V]
V_B	230 [V]
T_S	100 [us]
Rated-load	50 [kW]
Solar cell maximum output	10 [kW]
Solar MPPT voltage	252 [V]
Solar MPPT current	41.6 [A]
Wind-Gen. maximum output	40 [kVA]
Wind-Gen. Rated voltage	380 [V]

Table 2. Simulation modes.

Generation power	Mode 1	Mode 2	Mode 3
P_{solar} [kW]	10	$5 \rightarrow 10$	0
P_{wind} [kW]	20	$30 \rightarrow 5$	30
P_{bat} [kW]	$-20 \rightarrow 20 \rightarrow -20$	$5 \rightarrow 15$	$20 \rightarrow -35$
P_{diesel} [kW]	0	0	$0 \rightarrow 55$
P_{load} [kW]	$10 \rightarrow 50 \rightarrow 10$	30	50

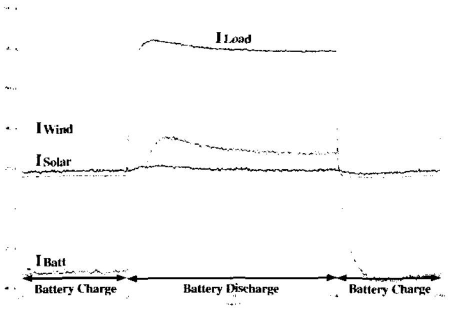

Fig. 8. Current waveforms when load is varied.

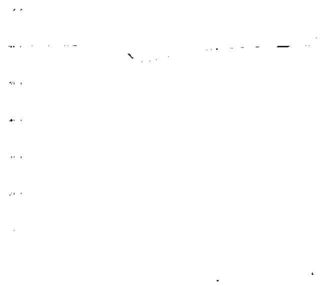

Fig. 9. DC bus voltage when load is varied.

30[kW], Fig. 10 shows the current waveforms of hybrid system, while the output-power of PV generation system is increased from 5[kW] to 10[kW] and output-power of wind generation system is decreased from 30[kW] to 5[kW]. As the output current of PV/wind system is varied, battery system is reversed from charge to discharge mode.

Also Fig. 11 is shown that a stable output characteristics of DC bus voltage on previous condition. Fig. 12 shows the result of simulation mode 3. Output current waveforms of output-terminal in hybrid system are shown, when diesel generator is operated. When the load is a 50[kW] capacity, photovoltaic power 10[kW] and wind power 30[kW], PV/Wind system has an insufficient generation capacities than load demand. So the battery system is changed into discharge-mode to compensate lacking power. And when battery system was on low voltage condition, diesel generator operates to compensate lacking power between PV/wind generation power and load. At the same time, battery system is changed from discharge-mode to charge-mode by diesel system.

Fig. 13 is shown DC bus voltage when diesel generator is operated. Fig. 14 shows the output-current and voltage waveforms of diesel generation system and Fig 15. shows phase voltage and current waveform of three phase PWM inverter.

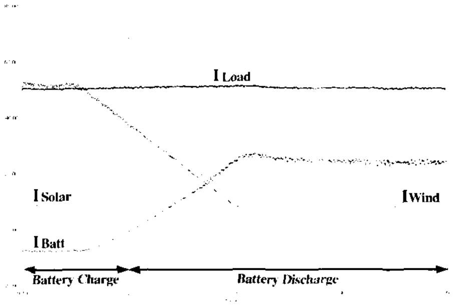

Fig. 10. Current waveforms when wind generation output is varied.

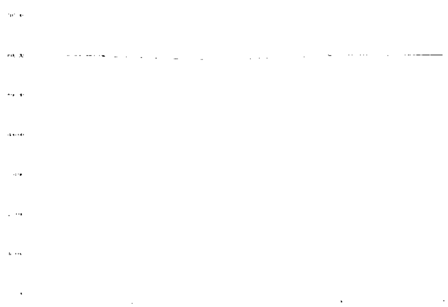

Fig. 11. DC bus voltage when wind generation output is varied.

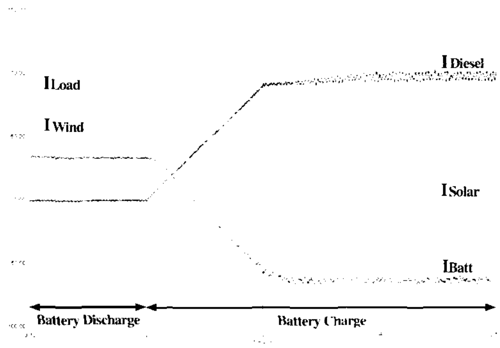

Fig. 12. Current waveforms when diesel generator is operated.

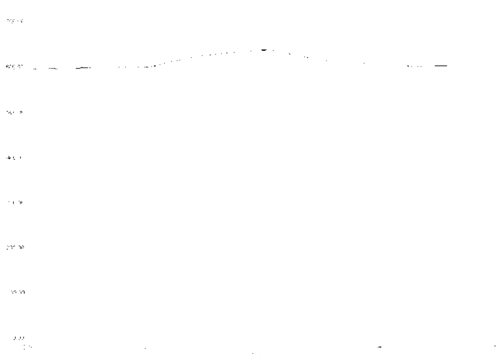

Fig. 13. DC bus voltage when diesel generator is operated.

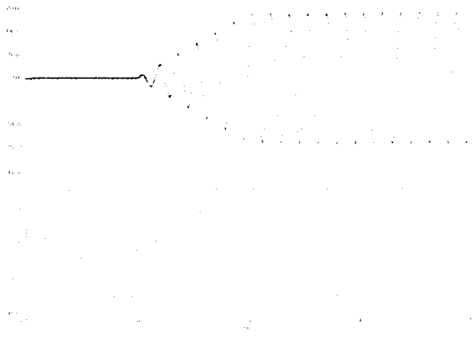

Fig. 14. Current & voltage waveform when diesel generator operated.

Fig. 15. Phase voltage & current waveform of three phase PWM inverter.

5. Conclusion

In this paper, it deals with an overall basic-configuration and a power balance control for photovoltaic/wind/diesel hybrid power system. Also, though the results of simulation, the proposed scheme was verified. To execute a stable power-balanced control, a hybrid power system is assumed that all of power generators are an equivalent current-source with a common DC link. And PV/wind generation system is controlled to transfer maximum power into a load respectively, and it has a fast transient response with a stable operation. From now on, the algorithm of proposed hybrid power system will be verified through an experiment.

Acknowledgments

This work was supported by a grant from the KEMCO Korea Energy Management Corporation).

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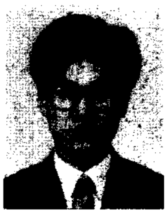
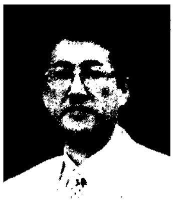
Byung-Hwan Jeong was born in Phohang, Korea on November 1, 1978. He received B.S degree in the electrical engineering from Kyungsung University, Pusan, Korea where he is currently working toward M.S. degree in Konkuk University, Seoul, Korea. His research interest is photovoltaic/wind/diesel hybrid power system.

Jun-Seok Cho was born in Seoul, Korea, on May 4, 1974. He received B.S., M.S. degree in the electrical engineering from Konkuk University, where he is currently working toward the Ph.D. degree. Since 2002, he has been with ENSYS Ltd., where he is currently a senior researcher in R&D center. His current research interests are parallel operation of inverter system and FACTS.

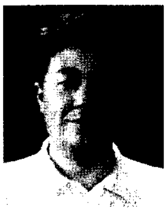


Jae-Seok Gho received B.S., M.S. and Ph.D. degree in the electrical engineering from Konkuk University. Since 2003, he has been with Xilon Ltd., where he is currently a managing director in R&D center. His current research interests are high performance SMPS for household electric appliance.



Gyu-Ha Choe was born in Pusan, Korea. He received the B.S., M.S. and Ph.D. degrees from Seoul National University, Seoul, Korea, in 1978, 1980 and 1986, respectively. Since 1980, he has been with the Department of Electrical Engineering, Konkuk University, Seoul, Korea, where he is a Professor and Dean of Academic Affairs. From 1987 to 1988, he was a Visiting Scholar in the Department of Electrical Engineering, Oregon State University, Covallis. His research interests are in the fields of active power filters, PWM control, ac voltage regulator, inverter welding machines and photovoltaic system.

Eung-Sang Kim was born in Yeosu, Korea, in 1962. He received the B.S. degree from Seoul Industrial University, Seoul, Korea, in 1988 and M.S., Ph.D. degrees in electrical engineering from Soongsil University, Seoul, Korea, in 1991 and 1997, respectively. Since 1991, he has been with the Department of Power Distribution System, Korea, Electro-technology Research Institute (KERI), Changwon, Korea, where he is currently a Principle of Researcher. His primary areas of interest are interconnection to power system of dispersed generation and storage system. He is a member of IEEE.



Chang-Sung Lee was born in Daegu, Korea, on 1958. Since 1999, he has been with Wooridle Co., Kangnung, Korea, where he is currently a representative director. His current research interests are photovoltaic power system, wind power system, and photovoltaic/wind/diesel hybrid power system.