Power-Management Strategies for a Grid-Connected PV-FC Hybrid System

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***Abstract*—This paper presents a method to operate a grid connected hybrid system. The hybrid system composed of a Photovoltaic (PV) array and a Proton exchange membrane fuel cell (PEMFC) is considered. The PV array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when variations in irradiation and temperature occur, which make it become an uncontrollable source. In coordination with PEMFC, the hybrid system output power becomes controllable. Two operation modes, the unit-power control (UPC) mode and the feeder-flow control (FFC) mode, can be applied to the hybrid system. The coordination of two control modes, the coordination of the PV array and the PEMFC in the hybrid system, and the determination of reference parameters are presented. The proposed operating strategy with a flexible operation mode change always operates the PV array at maximum output power and the PEMFC in its high efficiency performance band, thus improving the performance of system operation, enhancing system stability, and decreasing the number of operating mode changes.**

***Index Terms*—Distributed generation, fuel cell, hybrid system, microgrid, photovoltaic, power management.**

NOMENCLATURE

A	A dimensionless factor.
D	Duty cycle.
f	Switching frequency.
F	Faraday constant (96487 coulombs per mol).
G_a	Irradiation (W/m^2).
G_{as}	Standard irradiation (1000 W/m^2).
$I_{\rm sc}$	Short-circuit current.
$I_{\rm ph}$	Photo current.
$I_{\rm sat}$	Reverse saturation current.
$I_{\rm limit}$	Limitation current (in amperes).
K	Boltzmann constant.
$P_{\rm PV}$	Photovoltaic output power.
P_{MPP}	PV maximum output power.
$P_{\rm FC}$	PEMFC output power.
$P_{\rm FC}^{\rm low}$	PEMFC lower limit of high efficiency band.
$P_{\rm FC}^{\rm up}$	PEMFC upper limit of high efficiency band.
$P_{\rm FC}^{\rm max}$	PEMFC maximum output power.
$P_{\rm Feeder}$	Feeder power flow.
$P_{\rm Feeder}^{\rm ref}$	Feeder reference power.
$P_{\rm Feeder}^{\rm max}$	Feeder maximum power.
$P_{\rm MS}^{\rm ref}$	Hybrid source reference power.
$P_{\rm Load}$	Load demand.
q	Electronic charge.
R	Gas constant, 8.3143 J/(mol.K).
R_s	Series resistance.
T	Temperature (in Kelvin).
T_s	Standard temperature (298 K).
V_t	Thermal voltage.
$V_{\rm op}$	Open-circuit voltage.
Z	Number of participating electrons.
$\Delta I_{\rm sc}$	Temperature coefficient.
$\Delta V/V_0$	Voltage ripples.

Manuscript received July 13, 2009; revised December 10, 2009, March 10, 2010. First published May 18, 2010; current version published June 23, 2010. This work was supported by an INHA University Research Grant. Paper no. TPWRD-00523-2009.

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Digital Object Identifier 10.1109/TPWRD.2010.2047735

I. INTRODUCTION

RENEWABLE energy is currently widely used. One of these resources is solar energy. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source. Furthermore, it is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC, should be installed in the hybrid system. By changing the FC output power, the hybrid source output becomes controllable. However, PEMFC, in its turn, works only at a high efficiency within a specific power range ($P_{\rm FC}^{\rm low} \div P_{\rm FC}^{\rm up}$) [1], [2].

The hybrid system can either be connected to the main grid or work autonomously with respect to the grid-connected mode or islanded mode, respectively. In the grid-connected mode, the hybrid source is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. When load demand changes, the power supplied by the main grid and hybrid system must be properly changed. The power delivered from the main grid and PV array as well as PEMFC must be coordinated to meet load demand. The hybrid source has two control modes: 1) unit-power control (UPC) mode and feeder-flow control (FFC) mode. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Therefore, the reference value of the hybrid source output $P_{\rm MS}^{\rm ref}$ must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by the hybrid source, and, hence, the feeder reference power $P_{\rm feeder}^{\rm ref}$ must be known.

The proposed operating strategy is to coordinate the two control modes and determine the reference values of the UPC mode and FFC mode so that all constraints are satisfied. This operating strategy will minimize the number of operating mode changes, improve performance of the system operation, and enhance system stability.

II. System Description

A. Structure of Grid-Connected Hybrid Power System

The system consists of a PV-FC hybrid source with the main grid connecting to loads at the PCC as shown in Fig. 1. The photovoltaic [3], [4] and the PEMFC [5], [6] are modeled as nonlinear voltage sources. These sources are connected to dc–dc converters which are coupled at the dc side of a dc/ac inverter. The dc/dc connected to the PV array works as an MPPT controller. Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O). The P&O method has been widely used because of its simple feedback structure and fewer measured parameters [7]. The P&O algorithm with power feedback control [8]–[10] is shown in Fig. 2. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative (dP/dV) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of $\Delta V_{\rm ref}$.

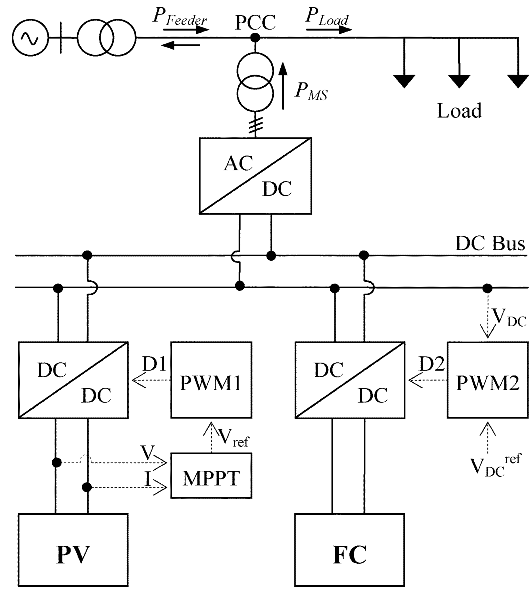

Fig. 1. Grid-connected PV-FC hybrid system.

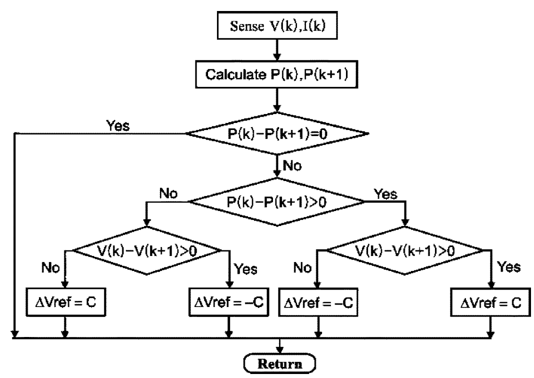

Fig. 2. P&O MPPT algorithm.

B. PV Array Model

The mathematical model [3], [4] can be expressed as

$$I = I_{\rm ph} - I_{\rm sat}\left\{\exp\left[\frac{q}{AKT}(V+IR_s)\right]-1\right\}. \qquad (1)$$

Equation (1) shows that the output characteristic of a solar cell is nonlinear and vitally affected by solar radiation, temperature, and load condition.

Photocurrent $I_{\rm ph}$ is directly proportional to solar radiation $\rm G_a$

$$I_{\rm ph}(G_a) = I_{\rm sc}\frac{G_a}{G_{\rm as}}. \qquad (2)$$

The short-circuit current of solar cell $I_{\rm sc}$ depends linearly on cell temperature

$$I_{\rm sc}(T) = I_{scs}[1+\Delta I_{\rm sc}(T-T_s)]. \qquad (3)$$

Thus, $I_{\rm ph}$ depends on solar irradiance and cell temperature

$$I_{\rm ph}(G_a,T) = I_{scs}\frac{G_a}{G_{\rm as}}[1+\Delta I_{\rm sc}(T-T_s)]. \qquad (4)$$

$I_{\rm sat}$ also depends on solar irradiation and cell temperature and can be mathematically expressed as follows:

$$I_{\rm sat}(G_a,T) = \frac{I_{\rm ph}(G_a,T)}{e^{\left(\frac{V_{\rm oc}(T)}{V_t(T)}\right)}-1}. \qquad (5)$$

C. PEMFC Model

The PEMFC steady-state feature of a PEMFC source is assessed by means of a polarization curve, which shows the nonlinear relationship between the voltage and current density. The PEMFC output voltage is as follows [5]:

$$V_{\rm out} = E_{\rm Nerst} - V_{\rm act} - V_{\rm ohm} - V_{\rm conc} \qquad (6)$$

where $E_{\rm Nerst}$ is the "thermodynamic potential" of Nerst, which represents the reversible (or open-circuit) voltage of the fuel