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Utility integration of PV-wind-fuel cell hybrid distributed generation systems under variable load demands

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ABSTRACT

This paper presents modeling, control and performance of a DC micro-grid connected to the utility under variable load demand and different environmental conditions. This micro-grid consists of 60 kW wind turbine (WT) energy conversion system, 40 kW photovoltaic (PV) panel and 40 kW fuel cell (FC) module, in addition to, DC and AC loads. The WT energy conversion system is controlled by the indirect field orientation control (FOC) method to extract maximum power from the wind. The PV module is controlled to generate the available maximum power using P&O MPPT control considering environmental conditions. The fuel cell, with a current controlled DC/DC boost converter, supplies power only when the load demand exceeds the total power of the WT and PV systems. A bidirectional 6-pulse PWM converter connects the micro-grid to utility using the natural frame control (NFC) technique. It controls the DC bus voltage, power and reactive power transfer to/from the utility according to the available power from the DG units and the total load demand. The various control algorithms are presented to harness the maximum power from the renewable energy sources at different operating modes. In addition, voltage stability and smooth power transfer between the micro-grid and utility are maintained.

1. Introduction

Electrical power systems are being more stressed due to the increase in the power demand, limitation on power delivery capability of the grid, complications in building new transmission - distribution infrastructures and finally all these may lead to blackouts. Distributed Generation (DG) technology have been gaining interest due to its benefits such as high reliability, high power quality, efficiency, reduced emissions, security, and load management [1,2]. Development of power electronic converters along with its high-performance controllers makes it possible to integrate different types of DGs to the utility.

The majority of DG units are interfaced to the utility via DC/AC inverter systems. However, the uncontrolled use of individual DG can cause various problems thereby compromising their benefits [3,4]. These problems include difficulties in connecting these units directly to the AC system due to their variable and intermittent power generation, voltage oscillation and protection issues. Connecting the renewable energy resources to a common DC bus provides several advantages as higher efficiency and reliability, absence of frequency and phase control requirements, when compared to the AC micro-grid [5]. Moreover, it has low losses, low cost, the possibility to operate across long distances, and it does not use transformers, in turn leading to volume and cost reduction [2].

Grid-connected three-phase inverters are well documented in literature [6–9] to connect the DGs to the utility grid. The current-controlled voltage source inverter is normally used to control the active and reactive power flow of the micro-grid. The controllers are implemented in synchronously rotating reference frame using proportional-integral (PI) controller or stationary reference frame using proportional-resonant (PR) controller or in Natural Frame Control (NFC) or sometimes called a–b–c frame using hysteresis or deadbeat controllers. A predictive controller-based current control scheme implemented in synchronously rotating reference frame is proposed in [10]. Predictive controller is also proposed in [11] for balanced grid-connected active filter application.

These advantages of simplicity, low cost, ruggedness, high efficiency make the SCIG very attractive for wind power applications both for fixed and variable speed operation [12,13]. Different control methods such as direct/indirect Field-Oriented Control (FOC) and direct torque are used for controlling the converter of the induction machine. The FOC method [14–16] has the ability to control the frequency, amplitude and phase of the motor drive

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Nomenclature

A	swept area of turbine rotor (m^2)
A_i	ideality factor
C_p	power coefficient
E_g	band energy gap (eV)
E_{nst}	Nernst voltage (V)
F	Faraday constant (9.648e4C/mol)
Gr	gear ratio
i_{ai}, i_{bi}, i_{ci}	inverter output currents (A)
I_{au}	utility phase current (A)
i_c	FC current density (A/m^2)
i_c	inverter d-axis line current (A)
i_{dr}	rotor d-axis current (A)
i_{ds}	stator d-axis current (A)
i_m	FC maximum current density (A/m^2)
i_n	FC internal current density (A/m^2)
i_o	FC exchange current density (A/m^2)
I_{ph}	photon-current of PV (A)
I_{pv}	rated output current of PV (V)
i_{qi}	inverter q-axis line current (A)
i_{qr}	rotor q-axis current (A)
i_{qs}	stator q-axis current (A)
I_{rr}	rated saturation current (A)
I_{sat}	reverse saturation current (A)
I_{sc}	PV rated short circuit current (A)
J_m	moment of inertia ($kg\ m^2$)
k	Boltzmann constant (1.38e−23 $m^2\ kg/s^2$ K)
k_i	temperature coefficient of I_{sc}
k_t	torque constant
L_{lr}	rotor leakage inductance (H)
L_{ls}	stator leakage inductance (H)
L_m	magnetizing inductance (H)
m	fitting constant (3e−5 V)
n	fitting constant (8e−3 cm^2/mA)
n_p	parallel PV modules
n_s	series connected cells in PV module
N_t	rated turbine speed (rpm)
P	pole pairs
p	differential operator
P_{AC}	AC load power (W)
P_{DC}	DC load power (W)
P_{fc}	FC output power (W)
P_{H2}	hydrogen pressure (bar)
P_{H2O}	water pressure (bar)
P_i	inverter output power (W)
P_m	wind turbine mechanical power (W)
P_{O2}	oxygen pressure (bar)
P_{PV}	PV output power (W)
P_u	utility output power (W)
P_w	WECS output power (W)
P_{wt}	turbine output power (W)
q	electron charge (C)
Q_i	inverter reactive power (Var)
Q_L	AC load reactive power (Var)
Q_t	AC side reactive power of micro-grid (Var)
Q_u	utility reactive power (Var)
R	ideal gas constant (8.314 J/K mol)
R_r	rotor resistance (Ω)
r_s	PV internal series resistance (Ω)
R_s	stator resistance (Ω)
r_{sh}	PV internal shunt resistance (Ω)
R_t	rotor radius of wind turbine (m)
S	reference solar irradiance (W/m^2)
T	cell absolute temperature (K)
T_{em}	electromagnetic torque (N m)
T_r	reference temperature (K)
v_{act}	FC activation loss voltage (V)
v_{ai}, v_{bi}, v_{ci}	inverter AC output voltages (V)
V_{au}	utility phase voltage (V)
V_c	FC terminal voltage (V)
v_{con}	FC concentration loss voltage (V)
V_{dc}	DC bus voltage (V)
v_{di}	inverter d-axis voltage (V)
v_{dr}	rotor d-axis voltage (V)
v_{ds}	stator d-axis voltage (V)
V_{oc}	PV rated open-circuit voltage (V)
v_{ohm}	FC ohmic loss voltage (V)
V_{pv}	rated output voltage of PV (V)
v_{qi}	inverter q-axis voltage (V)
v_{qr}	rotor q-axis voltage (V)
v_{qs}	stator q-axis voltage (V)
V_w	wind speed (m/s)
w_g	generator synchronous speed (rpm)
α	charge transfer coefficient
ρ	air density (kg/m^3)
λ	tip-speed ratio
β	pitch angle (°)
ω	rotor speed (rad/s)
λ_{dr}	rotor d-axis flux linkage (Wb)
λ_{ds}	stator d-axis flux linkage (Wb)
θ_f	rotor flux angle (rad)
λ_{opt}	optimum tip speed ratio
λ_{qr}	rotor q-axis flux linkage (Wb)
λ_{qs}	stator q-axis flux linkage (Wb)
ω_r	rotor mechanical reference speed (rad/s)
τ_r	rotor time constant (H/Ω)
ω_{sl}	slip frequency speed (rpm)

voltage. The key to field oriented control is to control the rotor flux vector and the rotor current. In this case, the stator currents of the SCIG are separated into flux and torque producing components by utilizing transformation to the d–q coordinate system. The maximum power point tracking (MPPT) technique is usually an essential part of photovoltaic or wind power generation systems to capture the available maximum power from the sun or wind, respectively.

In most of the published papers, the main problematic issue in micro-grids is the coordination control between the different distributed generations and the utility where one or two of DG units are typically studied. The contributions of this work can be summarized in the following points: (1) The coordination control between three different sources; wind turbine, photovoltaic and fuel cell. Both the renewable energy resources are operated at MPPT, while, the fuel cell is used to supply the shortage of power amount exceeding the total output power from renewable sources needed by AC and DC loads. (2) The control of grid-side converter is bidirectional to facilitate the flow of power from the micro-grid to utility and vice versa instead of one way operation as indicated in [5]. The ability and fast response of grid-side converter to control both the active and reactive power and hence, operations of lead/lag/unity PF are possible. (3) Simplicity of abc control coupled with hysteresis band implementation provides a harmonic-free three-phase output voltages from the grid-side converter to feed the AC load.