Supervisory Controller for Power Management of AC/DC Microgrid

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***Abstract*—This paper proposes a hybrid AC/DC micro grid to reduce the processes of multiple conversions in an individual AC or DC micro-grid. The hybrid grid consists of both AC and DC networks connected together by a bidirectional AC/DC converter. Wind generator, AC loads, and utility are connected to the AC bus whereas PV system and DC loads are tied to the DC bus. The coordination control algorithms of supervisor controller are proposed for smooth power transfer between AC and DC links and for stable system operation under various generation and load conditions. In this paper, a flexible supervisor controller is developed for a hybrid AC/DC micro-grid, where the power flow in the micro-grid is supervised based on demanded power with maximum utilization of renewable resources. A small hybrid micro-grid has been modeled and simulated using the Simulink in the MATLAB. The simulation results show that the system can maintain stable under load variations.**

Keywords-Hybrid AC/DC micro-grid; supervisor controller; BIC; MPPT; PV system; wind generation

I. INTRODUCTION

THREE PHASE AC power systems have existed for over 100 years due to their efficient transformation of AC power at different voltage levels and over long distance as well as the inherent characteristic from fossil energy driven rotating machines. Recently more renewable power conversion systems are connected in low voltage AC distribution systems as distributed generators or AC microgrids due to environmental issues caused by conventional fossil fueled power plants [1]. Previous research topics mainly focus on AC micro-grid applications [2]–[5]. Recently, The penetration of DC loads including LED, communication and computation devices, motors with DC drives, etc. is increasing dramatically nowadays [6]. So DC microgrids have recently emerged for their benefits in terms of efficiency, cost, and system that can eliminate the DC-AC or AC-DC power conversion stages and their accompanied energy losses. However, since the majority of the power grids are presently AC type, AC micro-grids are still dominant and purely DC microgrids are not expected to emerge exclusively in power grids [7]. Therefore, The concept of hybrid AC/DC systems is, therefore, emerging to combine the benefits of both AC and DC micro-grid [8].The main advantages of the hybrid AC/DC micro-grid are as follows: 1) the elimination of unnecessary multi-conversion processes, which results in conversion loss reduction and 2) the elimination of embedded rectifiers for DC loads in the current AC grids, which results in simplified equipment and cost reduction in electronic products [9].

The idea is to merge the AC and DC microgrids through a bidirectional AC/DC converter (BIC)and establishing a hybrid AC/DC micro-grid in which AC or DC type energy sources and loads can flexibly integrate into the micro-grids and power can smoothly flow between the two micro-grids. In this paper, a proposed microgridconsists of two renewable energy sources, Photovoltaic and wind energy systems. There are many papers that propose different topologies to connect these renewable energy systems to the AC and DC buses [10]–[13]. Nevertheless, forcing the micro-grids to work independently, may lead to not utilizing maximum available wind or solar power and may hamper the efficiency of the system [14]. The idea is that if there is a building have a DC and AC loads and these loads connected to the proposed microgrid. It is accepted that for the excellent operation of the microgrid, a supervisory controller to manage the power split between different energy sources is essential, which is called power management system.

This paper is organized as follows; Section II gives a brief overview of the renewable power source models and their corresponding converters, where the model of wind turbine as power source of the AC microgrid is given in Section II.A, and a model of PV panel as a source of the DC micro-grid is given in Section II.B. In Section III, a supervisory controller to coordinating between the AC and DC microgrids is proposed, in which different operating modes are programmed in order to manage the power split between the AC and DC microgrids. Coordinated control strategies and MPPT for the converters for all the circuit in the grid- connected mode are presented in Section IV. Simulation results obtained with the proposed supervisory controller are reported in Section V. Finally, conclusion section summarizes the main outcome of this paper.

II. SYSTEM MODELING

The grid-connectedmicrogrid is connected as shown in Fig. 1 where the PV source connected to DC bus and wind source with utility connected to AC bus.

A. AC Microgrid Modeling

As seen in Fig. 1, the AC microgrid based Wind turbine. The PMSG is connected to the grid (AC bus) at the point of common coupling (PCC) via an AC–DC–AC back-to-back converter set. Permanent magnet synchronous generator (PMSG) based variable speed wind turbines are considered appropriate and feasible technology in wind generation industry since PMSGs are self-excited, and thus allows operation at high power factor and high efficiency [15].

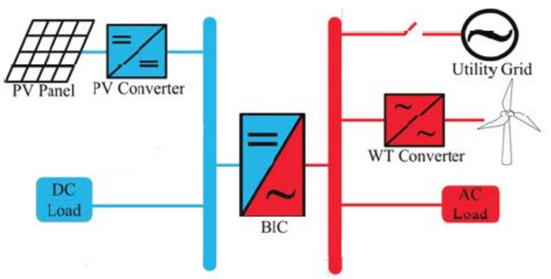


Figure 1. Schematic diagram of hybrid AC/DC micro-grid.

Wind Energy Conversion System (WECS) converts kinetic energy of the wind to mechanical energy by means of wind turbine rotor blades then the generator converts the mechanical power to electrical power. The WECS described in Fig. 1, consists of two main parts:

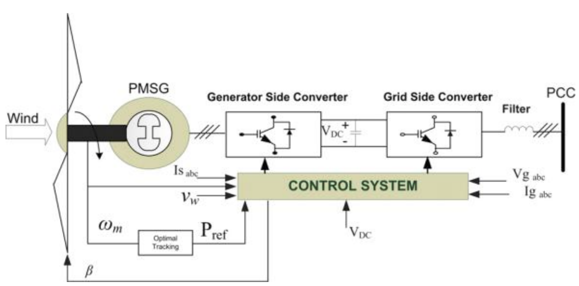


Figure 2. PMSG based wind turbine configuration.

1) Mechanical parts representation

A Wind Turbine (WT) cannot fully capture wind energy. Then, the output power of the windturbine is described as [16]:

$$P_{Turbine} = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)v^3 \quad (1)$$

where, ρ is the air density (kg/m3), R is the blade radius (m), CP is the performance coefficient of the turbine which is a function of the pitch angle of rotor blades β (in degrees) and the tip-speed ratio λ. v is the wind speed (in m/s). The tip-speed ratio $\lambda$is given by:

$$\lambda = \frac{\omega_m R}{v} \quad (2)$$

where ω_m is the wind turbine rotor speed (in rad/sec), respectively. The wind turbine mechanical torque output T_m given as:

$$T_m = \rho A C_P(\lambda,\beta)v^3\frac{1}{\omega_m} \quad (3)$$

$$C_P = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \quad (4)$$

The coefficient of power conversion and the power are maximums at a certain value of tip speed ratio called optimum tip speed ratio λ_{opt}. Therefore, the maximum value of $C_P(\lambda, \beta)$, (that is max C_P= 0.41), is achieved for λ_{opt}= 8.1 and for $\beta = 0^o$. Besides, any change in the wind velocity or the generator speed induces achange in the tip speed ratio leading to power coefficient variation[16].

2) Electrical parts representation

PMSG converts the mechanical power from the aerodynamic system to AC electrical power, which is then converted to DC power converter connected with DC link at its DC port. The power is transferred to the grid (AC bus) through ani nverter.

The stator voltage equations of the PMSG in direct and quadrature axes, V_{sd} and V_{sq}, are given as follows.

$$V_{sd} = -R_s I_{sd} - L_s\frac{d}{dt}I_{sd} + L_s\omega_e I_{sq} \quad (5)$$

$$V_{sq} = -R_s I_{sq} - L_s\frac{d}{dt}I_{sq} + L_s\omega_e I_{sd} + \omega_e\emptyset \quad (6)$$

where L_S, and R_S respectively represent the inductance and resistance of the PMSG winding, represents the magnet flux, ω_e is the electrical rotational speed of generator, and I_{sd}, I_{sq} are the direct and quadrature components of the machine currents respectively. In surface mounted PMSGs, $L_d = L_q = L_s$ So the electromagnetic torque T_e is

$$T_e = \frac{3}{2}P.I_{sq}.\emptyset \quad (7)$$

B. DC Micro-Grid Modeling

The DC micro-grid, as shown in Fig. 1, comprises a PV array connected to the DC bus through a DC/DC boost converter, which controls the operating point of the array. The generated current by the PV array is calculated based on the following equation [17].

$$I = I_{PV} - I_0\left[exp\left(\frac{V+R_sI}{V_ta}\right) - 1\right] - \frac{V+R_sI}{R_P} \quad (8)$$

$$I_{PV} = \left(I_{PV,n} + K_I\Delta T\right)\frac{G}{G_n} \quad (9)$$

$$I_0 = \frac{I_{sc,n}+K_I\Delta T}{exp\left(\left(V_{oc,n}+K_V\Delta T\right)/aV_t\right)-1} \quad (10)$$

where I_{pv} and I_0 are the photovoltaic (PV) and saturation currents, respectively, of the array and $V_t = N_s kT/q$ is the thermal voltage of the array with Ns cells connected in series. R_s is the equivalent series resistance of the array and R_P is the equivalent parallel resistance. where $I_{PV,n}$ (in amperes) is the light-generated current at the nominal condition (usually

25^{O}C and 1000 W/m^2), $\Delta T = T - T_n$ (T and T_n being the actual and nominal temperatures [in Kelvin], respectively), G (watts per square meters) is the irradiation on the device surface, G_n is the nominal irradiation and the current and voltage coefficients K_I and K_V. Similar to the AC micro-grid, DC bus delivers the energy generated by solar subsystem to the DC load.

III. Supervisory Power Management System

The proposed program, as shown in Fig. 3, consists of a central unit, fed with the data collected from all microgrid components, in order to determine efficient strategies for power flow between energy resources.

The input variables to the supervisor controller are generation forecast (P_{WG}^{Max}, P_{PV}^{Max}), demanded power (P_L^{ac}, P_L^{dc}). Also, output commands of the proposed program are set-points for the amount of power which should be exchanged between the micro-grids (P_{ac2dc}^{ref}, P_{dc2ac}^{ref}). The output commands are sent to the bidirectional converter to force the micro-grid components to track the obtained set-points.

Operating modes of the microgrid are divided into two groups. The first group consisted of three different modes with no power exchange between the AC and DC microgrids, the other group consisted of six modes with power exchange between the micro-grids, as shown in Fig. 4. This will be explained in details as follows. When the DC micro-grid injects power to the AC microgrid, the AC power is obtained from DC/AC inverter. Also, when the AC microgrid injects power to the DC micro-grid, the main converter acts as an AC/DC converter.

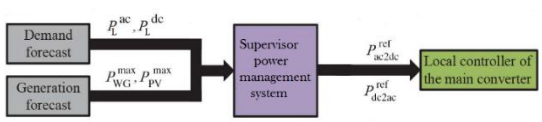


Figure 3. Power management architecture for hybrid AC/DC micro-grid.

1) Modes1, 2 and 3

In these modes, the power does not exchange between the AC and DC microgrids. In mode 1 the DC load power (P_L^{dc}) is equal to the PV power (P_{PV}^{Max}) so no power exchange from DC to AC (P_{dc2ac}=0) or from AC to DC (P_{ac2dc}=0). On the other hand AC load power (P_L^{ac}) is equal to wind power (P_{WG}^{Max}) so the grid power equal zero(P_{grid} = 0). In mode 2 the DC load power(P_L^{dc}) is equal to the PV power (P_{PV}^{Max}) so no power exchange from DC to AC (P_{dc2ac}=0) and from AC to DC (P_{ac2dc}=0). On the other hand AC load power (P_L^{ac}) is greater than wind power (P_{WG}^{Max}) so the residual power demanded is supplied from the grid ($P_{grid} = P_L^{ac} - P_{WG}^{Max}$).Mode 3 is the same as mode 2 but P_L^{ac} is lower than P_{WG}^{Max} so the excess of power supplied to the grid ($P_{grid} = P_{WG}^{Max} - P_L^{ac}$).

2) Modes 4, 5, 6, 7, 8 and 9

In these modes, there is power exchange between the AC and DC microgrids. So in modes 4, 5 and 6 the power will exchange from DC bus to AC bus ($P_{DC2AC} = P_{PV}^{Max} - P_L^{DC}$). Because the power generated from PV (P_{PV}^{Max}) is higher than DC load demand P_L^{dc} so there will be unbalance in power between DC and AC so the supervisor control will send reference signal to BIC to transfer the power to AC bus.
In this case, the power supplied to AC bus is from BIC and from wind generator so if the AC load power demand (P_L^{AC}) is higher than this power, the grid will supply the residual power to load ($P_{grid} = P_L^{AC} - P_{WG}^{Max} - P_{DC2AC}$), but if the AC power is higher than AC load power demand (P_L^{AC}), the grid will absorb the excess of power ($P_{grid} = P_{WG}^{Max} - P_L^{AC} + P_{DC2AC}$).

On the other hand, in modes 7, 8 and 9 the power will exchange from AC bus to DC bus ($P_{AC2DC} = P_{PV}^{Max} - P_L^{DC}$). Where the power generated from PV (P_{PV}^{Max}) is lower than P_L^{dc} so power transfer to DC bus. If the wind power (P_{WG}^{Max}) is larger than P_L^{AC} then the grid will absorb the excess of power ($P_{grid} = P_{WG}^{Max} - P_L^{AC} - P_{AC2DC}$) .But if P_{WG}^{Max} is smaller than P_L^{AC} then the grid will supply the reduction of power ($P_{grid} = P_L^{AC} - P_{WG}^{Max} + P_{AC2DC}$). So the supervisor control can determine the reference power to the bidirectional converter (BIC) with respect to the generated power and the demanded power then BIC controls the power transfer from AC bus to DC bus or from DC bus to AC bus.

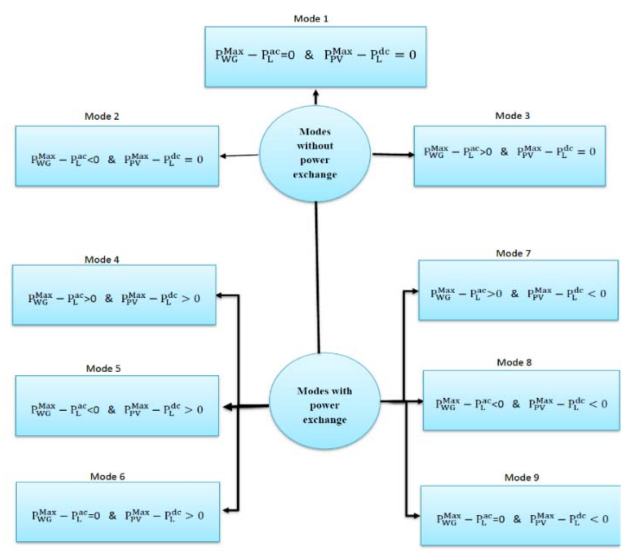


Figure 4. Different operating modes of the hybrid AC/DC micro-grid.

IV. Coordination Control of the Converters

There are four types of converters in the proposed hybrid grid. Those converters have to be coordinately controlled with the utility grid to supply an uninterrupted, high efficiency, and high-quality power to variable DC and AC loads under variable solar irradiation, temperature and wind speed when the hybrid grid operates grid tied modes. The control techniques for those converters are presented in this section.

A. PV Control

When the hybrid microgrid operates in the grid-connected mode, the control objective of the boost converter is to track the MPPT of the PV array by regulating its terminal voltage. The task of MPPT algorithm is to determine $V_{ref}(V_{mp})$ only. Then, there is another control loop (PWM) that PI controller regulates the input voltage of the converter. Its task is to minimize error between V_{ref} and the measured voltage by adjusting the duty cycle [18].

B. *Wind Generation Control*

As shown in Fig. 2, in variable speed wind turbines, PMSG is connected to the utility grid via a back-to-back set of converters. The back-to-back converter consisted of two parts: the generator side converter and grid side converter. The DC terminals of the two converters are collected together with shunt DC capacitor.

1) *Control of the generator side converter*

The generator side converter control is mainly used to control the wind turbine shaft speed in order to maximize the output power. In a variable speed wind energy conversion system, the maximum power at different wind speeds depends on the power coefficient, Cp. The parameters affecting the coefficient Cp are the tip speed ratio λ and the pitch angle β as [15]. To obtain the maximum power production (Pmax) from the wind turbine, the turbine should operate at Cp_max and hence, it is necessary to keep the generator rotor speed ω_m to meet the optimum value of the tip speed ratio (λ_{opt}). The generator speed control is typically accomplished through the generator side converter. Hence, the control of the generator-side converter allows the generator to tune the rotational speed depending on the incident wind variation. the generator rotational speed is governed by the electromagnetic torque, and hence speed control is obtained by generator torque control[15].

2) *Control of the grid side converter*

The main objective of the grid-side converter control is to regulate the DC bus voltage while controlling the active power and reactive power injected into the grid [19].The control strategy of the grid side converter (given in Fig. 2) contains two cascaded loops. The inner loops control the grid currents and the outer loops control the DC-link voltage and the reactive power[20].

C. *Bidirectional Converter Control*

The operation of BIC is to control the power transfer from DC to AC bus or from AC to DC bus with respect to the power demand and the generated power. Power control strategies are normally used for output power control, using prespecified reference values for real power and reactive power compensation.

So the control scheme of BIC depends on the set points for real and reactive power controls. *P(*ref*)* and *Q(*ref*)* are the power set-points, and P_{out} and Q_{out} are the real and reactive power outputs calculated from the measured output voltages and currents of the unit. The *P(*ref*)* value can be set by a supervisory power management system to optimize real power export from the units as discussed before.

V. SIMULATION RESULTS

The operations of the hybrid grid under various source and load conditions are simulated to verify the proposed supervisor control algorithms. It should be remarked that all the simulations are performed using MATLAB/Simulink package.

The demanded power and maximum available power of the proposed microgrid are operated at Irradiance 1000w/m^2, temperature 50^{o}c and wind speed 12m/s.

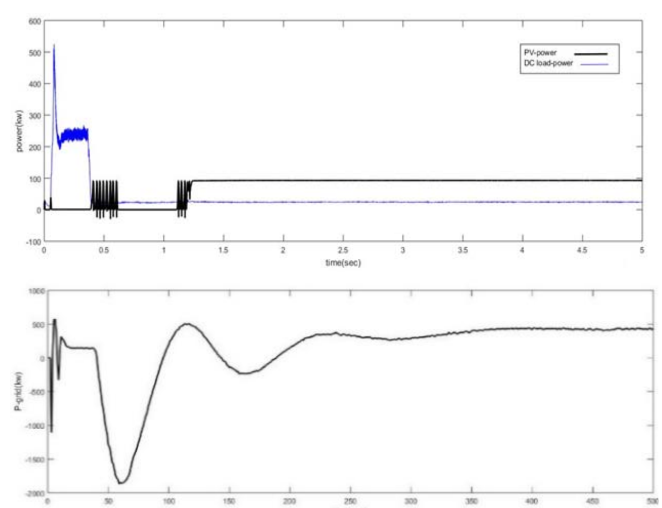
Case A: In this mode the generated DC power (P_{PV}^{Max}) is higherthan the DC load power (P_L^{DC}) so the power will transfer from DC bus to AC bus as shown in Fig. 5.(The results are shown in Table I).The residual power from DC bus is transmitted to AC bus through the inverter by the reference power signal from the output of supervisor control. On the other hand the difference between P_{WG}^{Max} and P_L^{AC} equal 360.04kw. So the all residual power that will supplied to the grid equal 428.74kw.

TABLE I. THE RESULTS OF CASE A

P_{PV}^{Max}	92.8
P_L^{DC}	24.1
P_{WG}^{Max}	1312.98
P_L^{AC}	952.94
P_{dc2ac}	68.7
P_{ac2dc}	0
P_{ref}	68.77
P_{grid}	428.74

a) Case B: If the AC load power (P_L^{AC}) is increased to be larger than the wind power (P_{WG}^{Max}) in this case, the grid supplies the required remaining power as shown in Table I. So the grid power will be a negative sign.

On the other hand, if the DC load (P_L^{DC}) increased suddenly after 3 sec to be larger than the PV power (P_{PV}^{Max}), in this case the power will transfer from AC bus to DC bus as shown in Fig. 6.



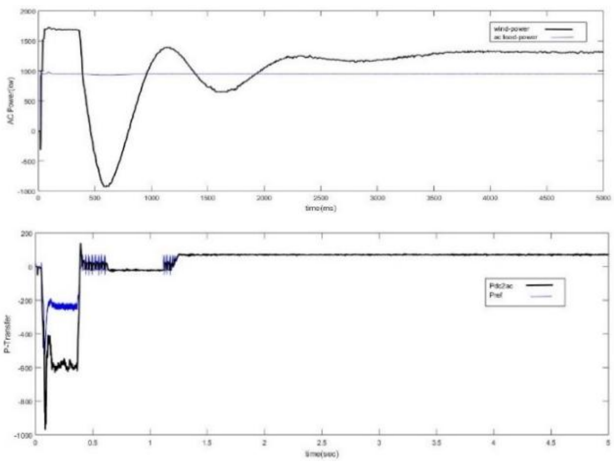
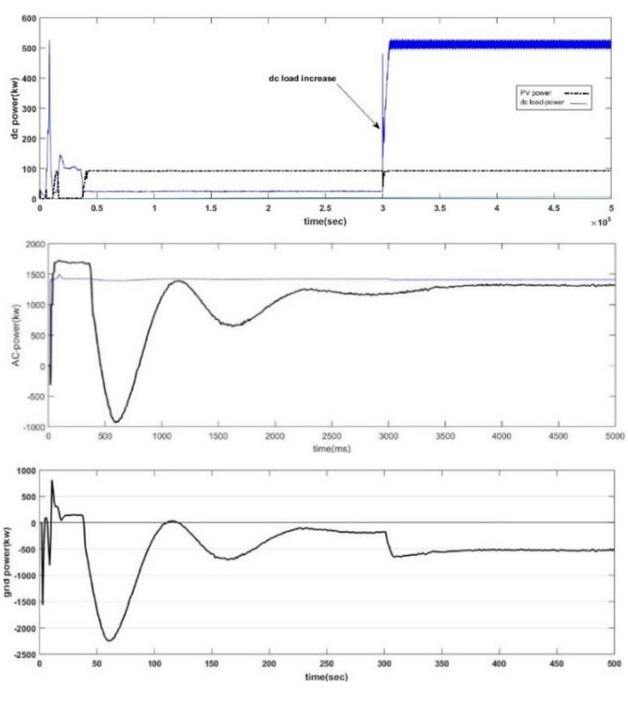


Figure 5. Case A: DC bus power, AC bus power, grid power and PDC2AC with P_{ref}.

TABLE II. THE RESULTS OF CASE B

Time (sec)	0-3	3-5
P_{PV}^{Max} (kw)	92.8	92.8
P_L^{DC} (kw)	24.1	515.5
P_{WG}^{Max} (kw)	1319.5	1319.5
P_L^{AC} (kw)	1410	1410
P_{dc2ac} (kw)	68.7	0
P_{ac2dc} (kw)	0	422.67
P_{ref} (kw)	68.77	422.67
P_{grid} (kw)	-180	-520.88
V_{dc} bus (v)	492.5	497.86



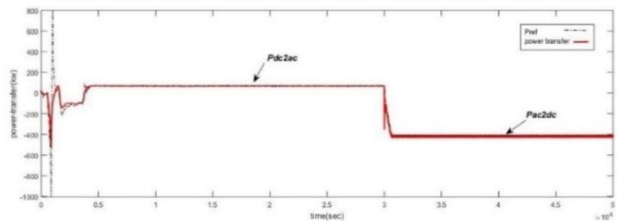


Figure 6. Case B: DC bus power, AC bus power, t grid power, Pac2dc and Pdc2dc with sudden change in dc load.

VI. CONCLUSION

In this paper, Supervisor control for a grid connected hybrid AC/DC microgrid is proposed to control power transfer from the AC to DC bus and from DC to AC bus. Connecting the DC loads to DC bus and AC loads to AC bus to reduce the number of converters in the microgrid and so reduce losses and harmonics in the proposed system and this is the main idea of AC /DC microgrid. Insist the PV and wind generation system to supply the maximum available power to satisfy the maximum efficiency. Adjusting the control scheme for all converters in the proposed system with making it adaptable to the weather conditions. The supervisor controller is tested with different operation modes.

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