Voltage Control of a Hybrid AC/DC Microgrid in Stand-Alone Operation Mode

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Abstract— **The stability of dc and ac bus voltage is of the most important issues in all microgrids including ac, dc or ac/dc hybrid microgrids. In this paper, a hybrid ac/dc microgrid is proposed to reduce processes of multiple reverse conversions in an ac or dc microgrid and to facilitate the connection of various renewable ac and dc sources and loads to power system. Also, all control schemes used among all converters will be developed in order to improve the voltage stability of hybrid microgrid. To give robustness to improve the dynamic voltage stability of the microgrid, a voltage stabilizer is proposed and applied to the doubly fed induction generator (DFIG) installed in ac part. Results are achieved considering the uncertainty of the generators and loads existed in microgrid verifying the robustness of the controllers to restore and stabilize quickly the voltage of both ac and dc grids.**

Keywords-hybrid ac/dc microgrid; stand-alone mode; voltage control

I. Introduction

Nowadays, it is preferred to integrate renewable energies in the microgrid in order to reduce the CO_2 emission and the fossil fuel consumption. The benefits of distributed energy resources are seen to be higher reliability of service, better quality of power supply, and greater efficiency of energy use by utilizing the available waste heat from power generation systems. In addition, the ability to use renewable energy with little or no pollution is becoming increasingly attractive for environmental protection considerations and attracts increasingly important interests. Furthermore, distributed generation can benefit the electric utility by reducing congestion on the grid, reducing the need for new generation and transmission capacity, and offering ancillary services [1].

The ac microgrids [2]–[6] have been proposed to facilitate the connection of renewable energy sources to conventional ac systems. However, dc power from some distributed generators, such as photovoltaic (PV) panels or fuel cells, has to be converted into ac using dc/dc boosters and dc/ac inverters in order to connect to an ac grid. In an ac grid, embedded ac/dc and dc/dc converters are required for various home and office facilities to supply different dc voltages [7].

Recently, dc microgrids are resurging due to the development and deployment of renewable dc power sources and their inherent advantage for dc loads in commercial, industrial and residential applications [8]–[11]. However, ac sources have to be converted into dc before connected to a dc grid and dc/ac inverters are required for conventional ac loads.

Multiple reverse conversions required in individual ac or dc grids may add additional loss to the system operation and will make the current home and office appliances more complicated [7].

The smart grid concept is currently prevailing in the electric power industry. The objective of constructing a smart grid is to provide reliable, high quality electric power to digital societies in an environmentally, friendly and sustainable way. One of most important futures of a smart grid is the advanced structure which can facilitate the connections of various ac and dc generation systems, energy storage options, and various ac and dc loads with the optimal asset utilization and operation efficiency [7]. To achieve those goals, power electronics technology and control schemes play the most important roles to interface different sources and loads to a smart grid.

In [7], [12]-[14] hybrid ac/dc microgrids are proposed to reduce processes of multiple reverse conversions in an individual ac or dc microgrid and to facilitate the connection of various renewable ac and dc sources and loads to power system. So in this paper, a hybrid ac/dc microgrid is proposed and studied.

Since in all the microgrids, the stability of dc and ac bus voltage is of the most important issues, so in this study, voltage stability control of a hybrid microgrid is studied. Also, a voltage stabilizer is proposed to improve the dynamic voltage stability of proposed hybrid microgrid. It was applied to a doubly fed induction generator (DFIG) installed in ac part.

In this study, the uncertainty effect of the generators and loads including the small and large deviations on voltage control of the microgrid is studied. The results verify the efficiency and robustness of the controllers to restore and stabilize quickly the voltage of both ac and dc grids.

II. System Configuration and Resources Modeling

A. *Proposed Hybrid Microgrid Configuration*

A hybrid microgrid as shown in Fig. 1 is proposed and modeled in MATLAB/Simulink.

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PV array is connected to dc bus through a dc/dc boost converter to simulate dc sources. A capacitor C_{pv} is used to suppress high frequency ripples of the PV output voltage [7].

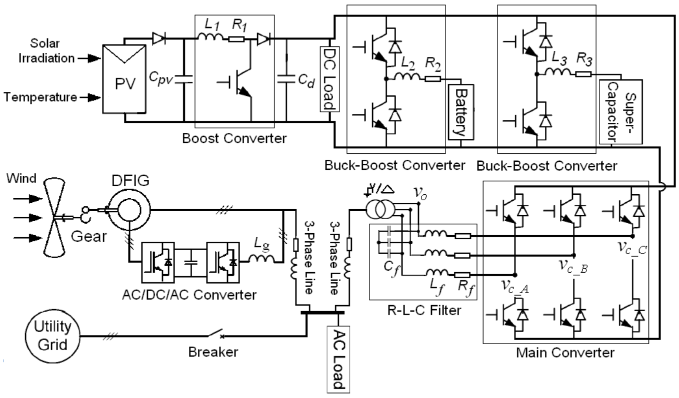

Figure 1. A compact representation of the proposed hybrid microgrid

Also, a wind turbine (WT) with DFIG is connected to an ac bus to simulate ac sources. In addition, a battery and a super-capacitor as the energy storages are separately connected to dc bus through bidirectional (buck-boost) dc/dc converters. dc and ac loads are also connected to dc and ac buses, respectively. The dc load was considered as a pure resistive load, but the connected ac load was included constant-impedance (resistance-inductance), constant-capacitance, and constant-power (induction motor) loads. The rated voltages for dc and ac parts are 400 V and 400 V rms, respectively. A 3-phase bidirectional dc/ac main converter with R-L-C filter connects the dc part to the ac part through an isolation transformer. Furthermore, Two similar ac lines are considered with impedance 0.0024+j*0.000212 Ω.

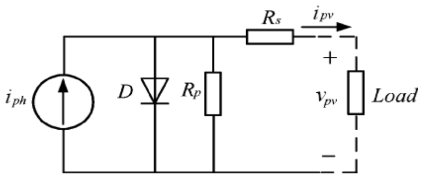

Figure 2. Equivalent circuit of a solar panel

B. Modeling of Energy Resources

1) PV Array

Fig. 2 shows an equivalent circuit of a PV panel modeled by a controlled current source. i_{pv} and v_{pv} are terminal current and voltage of the PV panel, respectively. The current output of the PV panel was modeled by formula shown in [7]. Also, 40 kW PV panel parameters, used in study, were extracted from [7].

2) Battery and Super-Capacitor Storages

Although renewable resources are attractive, they are not always dependable in the absence of energy storage devices. The utilization of energy storage units in power systems can be classified into two categories. One is in response to fast transients and the other is related to steady-state energy exchanging. Super-capacitors are good candidates for the former application and batteries are suitable for the latter one. Currently, the mixed use of fast and slow energy storage units is gaining popularity for interconnection of renewable generation [15].

In this study, a 65 Ah, 200 V nickel-metal-hydride (NiMH) battery was used together with a super-capacitor storage. The battery was modeled using a controlled nonlinear voltage source in series with a constant resistance as shown in [16].

One of the important parameters to represent state of a battery is state-of-charge (SOC) defined as [16]:

$$SOC\,\% = 100\left(1 - \frac{it}{Q}\right) \tag{1}$$

where *it* is the extracted capacity and *Q* is the maximum capacity of battery storage. The battery SOC is between 0%, for an empty battery, and 100%, for a fully charged battery.

Also, in modeling of the present 500 F super-capacitor storage, it was assumed that it is an ideal capacitance, i.e. its resistance was exactly considered to zero.

3) Wind Turbine Generator

In this study, DFIG was considered as a wound rotor induction machine, which needs to excite at both the stator and rotor terminals. Modeling of DFIG is well shown in SimPowerSystem Library of MatLab software. The 50 kW DFIG parameters, used in this study, were extracted from [7].

III. CONTROLLERS

In a hybrid microgrid, when the microgrid works in islanded operation, dc bus voltage must be regulated by microsources and storages located in dc part. And the magnitude and frequency of ac bus are controlled by parallel inverters. The controllers designed for microgrid study are described in the following sub-sections.

1) Boost Converter Controller

In the islanded mode, the boost converter of the PV panel can be designed to support the dc bus voltage as shown in Fig. 3.

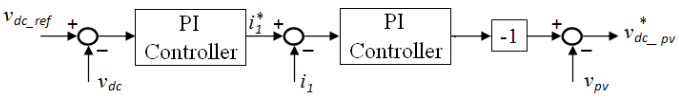

Figure 3. Block diagram of the boost converter controller [7]

2) Coordinated Control of Battery, Super-Capacitor

Battery has high energy density whereas it has relatively slow charging and discharging speed. On the other hand, super-capacitor has high power density and fast response. The mixed use of these energy storage units can make them complimentary to each other. Based on the above characteristics of battery and super-capacitor, a hybrid control scheme was designed as shown in Fig. 4.

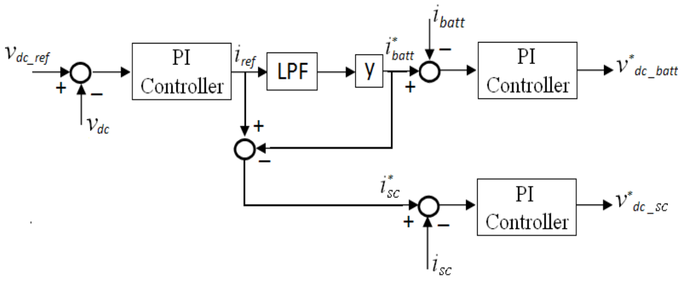

Fig. 4. Coordinated control scheme of the battery and super-capacitor storages

In this scheme, the dc part voltage is coordinately controlled by battery and super-capacitor storages. First, the measured dc part voltage v_{dc} is compared with its reference $v_{dc\text{-}ref}$ and the difference is sent to a proportional-integration (PI) controller to get the current reference i_{ref}. Then i_{ref} is split into two parts. One is the battery current reference i^*_{batt} which is obtained by applying a low-pass filter (LPF) with a cut-off frequency 25 Hz and a coefficient y (equal to 0.8 in this study) to i_{ref}. The other one i^*_{sc} is the difference between i_{ref} and i^*_{batt}. By this means, the high frequency part of the dc part disturbance and somehow low frequency part will be mitigated by super-capacitor and the remained low frequency part of the disturbance is smoothed by battery. The current references i^*_{sc} and i^*_{batt} will be used in the constant current control of the buck-boost converters shown in Fig. 1.

1) Main Converter Controller

Multi-loop voltage control for a dc/ac inverter is described in [17], where the control objective is to provide a high quality ac voltage with good dynamic response at different load conditions. This control scheme was also applied for main converter to provide high quality ac voltage in islanded mode.

2) DFIG Controller

DFIG has several controllers as rotor-side converter controller, grid-side converter controller, and pitch and torque controllers. The objectives of the rotor-side converter are to manage the stator-side active and reactive powers. The DTC scheme proposed in [7] is selected as the control method for the rotor-side converter in this paper.

The grid-side converter is used to regulate the voltage of its own dc bus capacitor. In addition, this model allows using grid-side converter to generate or absorb reactive power. This control system is illustrated in Fig. 5. The voltage of the dc link is controlled by i_{dg}, while the reactive power is controlled by i_{qg}.

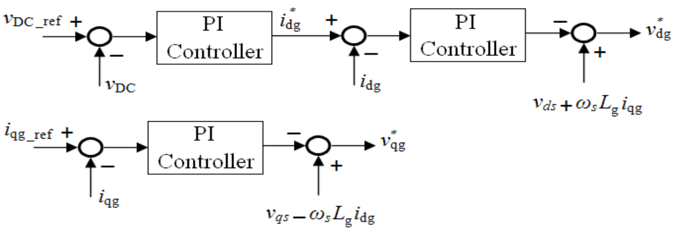

Figure 5. Grid-side converter control block diagram

In islanded mode, the turbine control was designed to deliver power over a range of wind conditions, taking advantage of the variable speed capability of the machine. Above about 75% rated power, the controller works in two distinct regions. When the available wind power is above the equipment rating, the blades are pitched to reduce P_{mech} delivered to the shaft down to the mechanical power 1.0 pu, thereby returning the machine equipment rating to the reference speed for full power operation, 120% of synchronous speed. When the available wind power is less than rated, the blades are fixed to maximize the mechanical power.

However, the reference speed is reduced for power levels below 0.75 pu. This behavior was included in the model by using the following equation for speed reference when the power is below 0.75 pu:

$$\omega_{ref} = -0.67P^2 + 1.42P + 0.51 \qquad (2)$$

To achieve these objectives, the pitch and torque control schemes proposed in [18] were used.

Also in this study, a voltage stabilizer applied in DFIG was proposed and designed to improve the voltage of ac grid as shown in Fig. 7. High frequency part of positive sequence voltage of ac grid is compensated by q-axis current of grid-side converter and its low frequency part is compensated by d-axis and q-axis currents of rotor-side converter. The cut-off frequency of LPF and high-pass filter (HPF) was selected to 10 kHz.

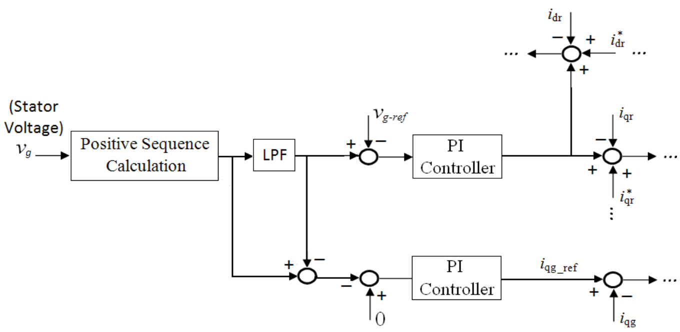

Figure6. Control schematic of the proposed voltage stabilizer applied in DFIG

IV. Dynamic Simulations

In this section, simulations performed in MatLab/Simulink are shown to verify the used controllers. The voltage response of both ac and dc grisd under the different disturbances is shown in Figs. 7-8, respectively. In time 2 s, dc load is increased from 16 kW to 32 kW. Then in time 4 s, the irradiation surface of PV panel is decreased to 200 W/m2. In time 6 s, this surface is increased to the former condition. In addition, in time 8 s, ac load is decreased from 50 kW to 35 kW, and in time 10 s it is again increased to 50 kW. Also, irradiation surface and wind speed were assumed randomly during the simulation as shown in Figs. 9-10, respectively. It can be seen that the designed controllers are well robustness to give a stable voltage of the ac and dc grids and to restore the voltage quickly.

Also, the generated power of PV panel and DFIG, and the current waveform of battery and super-capacitor storages are shown in Figs. 11-14, respectively.

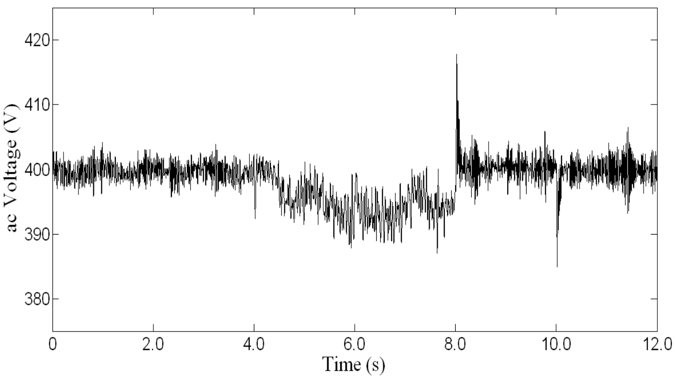

Figure 7. The voltage waveform of the ac grid

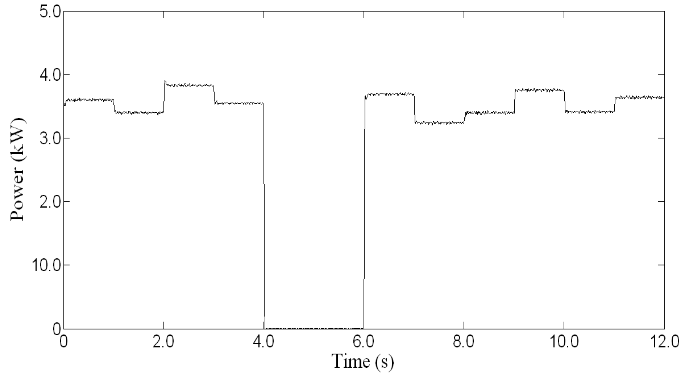

Figure 11. The generated power of the PV panel

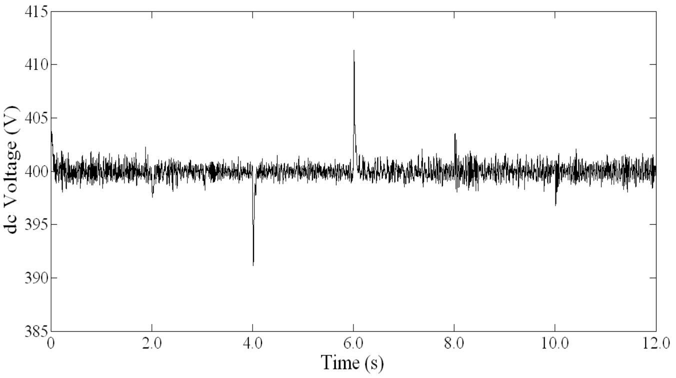

Figure 8. The voltage waveform of the dc grid

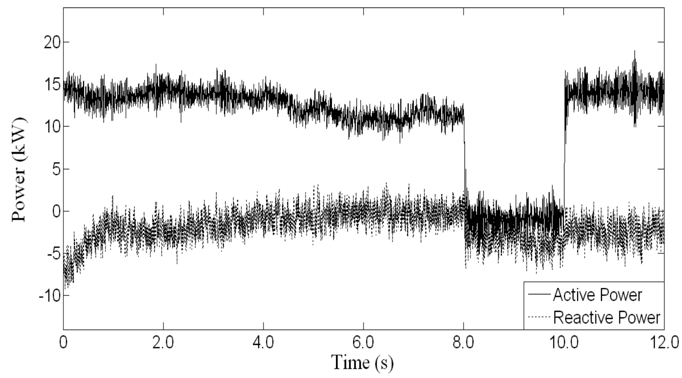

Figure 12. The generated power of the wind farm

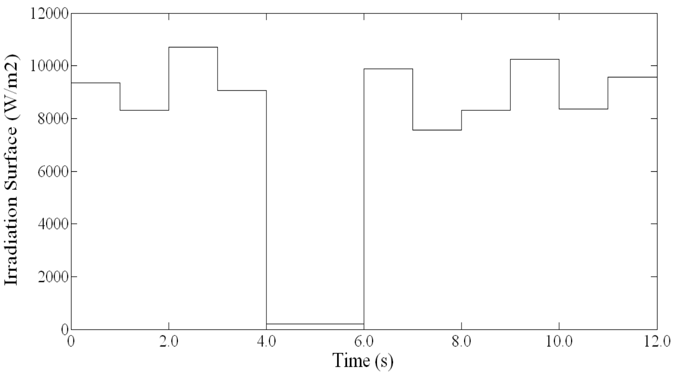

Figure 9. The simulated irradiation surface

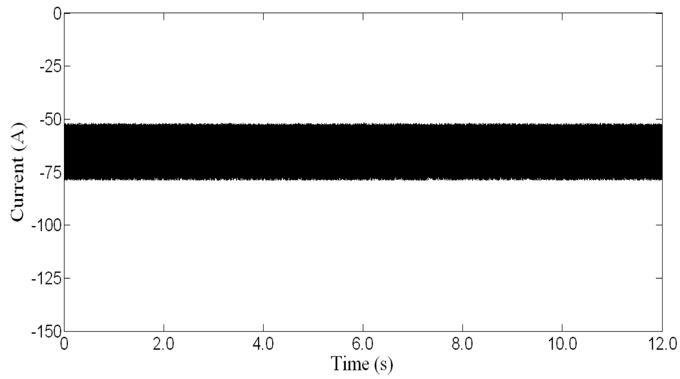

Figure 13. The current waveform of the battery storage

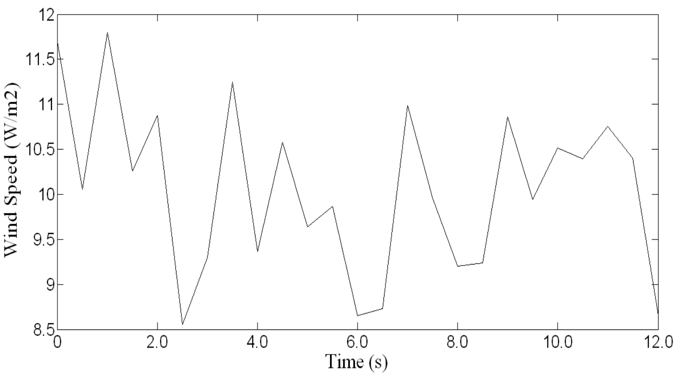

Figure 10. The simulated wind speed

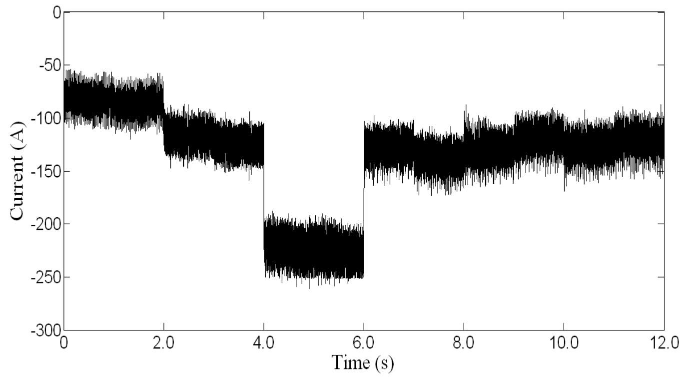

Figure 14. The current waveform of the super-capacitor storage

V. CONCLUSION

In this paper, the controllers among the all converters are designed to improve the dynamic voltage stability of both ac and dc parts of the hybrid microgrid operating in stand-alone mode. dc voltage control is studied under the small and large uncertainty of generators and loads. The achieved results verify the controllers robustness and efficiency to restore and stabilize quickly the voltage of the hybrid microgrid.

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