CONTROLLER DESIGNING TO IMPROVE THE VOLTAGE AND FREQUENCY STABILITY OF A HYBRID AC/DC MICRO-GRID

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ABSTRACT

In this paper, the voltage and frequency control of a proposed hybrid AC/DC Micro-Grid is studied. The main objective of this study is to develop the PI, self-tuning fuzzy and wavelet controllers and compare their performances through the study of the voltage and frequency control of the Micro-Grid under disturbances. First, only PI controllers based Micro-Grid is analyzed by MatLab/Simulink during the load and generation uncertainties to show their good control performances. Then, self-tuning fuzzy controllers are follow to show a superior robustness and efficiency compared to the PI controllers during the islanding event. Finally, the wavelet controllers are studied to show and verify a much more ability, precision and robustness than the PI and even the fuzzy controllers to quickly restore and stabilize the Micro-Grid during events such as the islanding.

INTRODUCTION

A Micro-Grid is defined as two or more DGs or storage assets configured in a network and capable of operating either in parallel with, or independent from, a larger electric grid, while providing continuous power to one or more end users [1]. Multiple reverse conversions (AC to DC and then DC to AC, and/or vice versa) required in individual AC or DC Micro-Grids may add additional loss to the system operation and will make the current appliance more complicated. Therefore, recently, hybrid AC/DC Micro-Grids, consisting of various AC and DC distributed generators (DGs) and loads, are proposed to reduce processes of multiple reverse conversions in an individual AC or DC Micro-Grid [2].

In this paper, a hybrid AC/DC Micro-Grid is proposed, modeled and studied in MatLab/Simulink. Also, since in all Micro-Grids the voltage and frequency control is one of the most important issues; therefore, control schemes are designed in order to control the voltage and frequency of the Micro-Grid.

PI/PID controllers are well known, widespread and easily applicable and they have robust performance in a wide range of operating conditions [3]. Therefore, PI controllers were used in this study. The firefly optimization algorithm (FOA) was also used to optimize PI controllers. It is a nature-inspired metaheuristic algorithm, inspired by the flashing behaviour of fireflies. However, it is difficult to achieve the ideal effect for the conventional PI controllers due to the influences of the nonlinear and time-variant factors existed in the systems. Fuzzy control is a somewhat intelligent and cost-effective nonlinear control [4]. Chaiyatham *et al.* [5] proposed a self-tuning fuzzy PID (SFPID)-type controller to control the frequency of a Micro-Grid. The SFPID controller is not sensitive to the variations of system structure, parameters and operating points. In addition, it can be easily implemented in practical systems. This paper applies a typical SFPI controller for the proposed Micro-Grid. Simulation results confirm the superior performance and robustness of SFPI controllers in comparison with PI controllers to stabilize the voltage and frequency of the Micro-Grid. Also, wavelet transforms (WTs) have been recently used in the modeling, analysis, and control of distributed energy resources [6]–[7]. The WTs have the ability to decompose wideband signals into time and frequency domains simultaneously in order to focus on short time intervals for high-frequency components and on long time intervals for low frequency components.

In this paper, wavelet-based multi-resolution PI (MRPI) controllers are developed for the robust and precise voltage control of the proposed Micro-Grid under disturbances. The performances of the MRPI controllers-based Micro-Grid are found to be much more robust and quicker than those of the optimized PI or even fuzzy controllers-based Micro-Grid.

PROPOSED HYBRID AC/DC MICRO-GRID CONFIGURATION

A hybrid Micro-Grid as shown in Fig. 1 is proposed. A 35kW PV array is connected to the DC bus through a DC/DC boost converter. Also, a 45kW wind turbine (WT) with a doubly fed induction generator (DFIG) is connected to an AC bus.

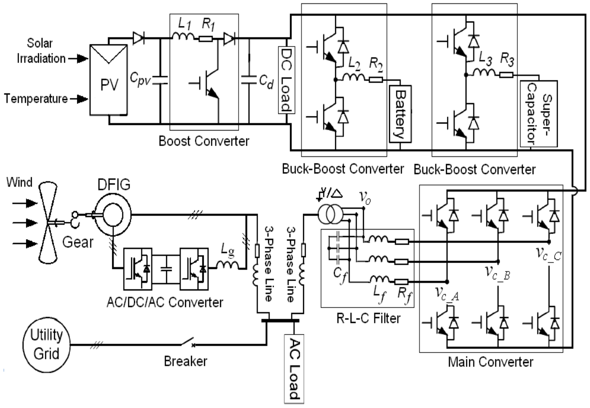

Fig. 1. A representation of the proposed Micro-Grid

In addition, a battery and a super-capacitor (SC) are separately connected to the DC bus through the bidirectional (buck-boost) DC/DC converters. DC and AC loads are also connected to the DC and AC buses, respectively. The rated voltages for the DC and AC parts are 400V and 400Vrms, respectively. A 3-phase inverter with R-L-C filter connects the DC part to the AC part through an isolation transformer.

CONTROLLERS

In this study, when the AC part of Micro-Grid is directly connected to the utility grid, the magnitude of the DC part voltage can be regulated by the parallel inverters and energy resources located in DC part. Also, the magnitude and frequency of the AC part voltage are the same with the utility grid. However, when the Micro-Grid works in the islanded operation mode, the DC part voltage must be regulated by the only micro-sources and storages located in the DC part. Beside, the magnitude and frequency of the AC part are controlled by the inverter. Controllers used for both operating modes are described in the following.

Grid-Connected Mode

Boost converter controller

When the hybrid Micro-Grid operates in the grid-connected mode, the control objective of the boost converter is to track the maximum power point (MPPT) of the PV panel. To achieve this objective, P&O method proposed in [8] was used.

Coordinated control of battery and SC storages

Based on the above characteristics of battery and SC, a hybrid control scheme was designed as shown in Fig. 2.

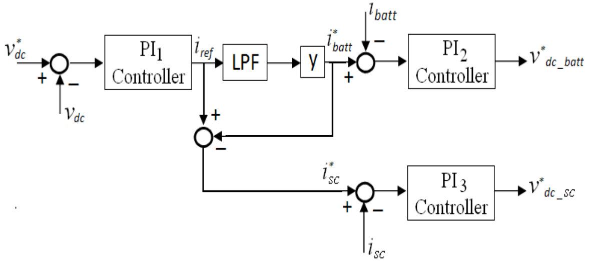

Fig. 2. Control scheme of the battery and SC storages

Inverter controller

The inverter was designed to provide a pre-defined reactive power. The proposed control scheme and detailed schematic of the inverter are shown in Figs. 3 and 4, respectively. i^*_{fd} and i^*_{fq} are showing the active and reactive powers, respectively, transferring between DC and AC parts. In this study, i^*_{fd} was considered to zero.

Islanded Mode

When Micro-Grid operates in the islanded mode, inverter acts as a voltage source to provide a stable voltage and frequency for the AC grid. DC grid voltage will be also controlled by the battery and SC.

Multi-loop voltage control for a DC/AC inverter is described in [9], where the control objective is to provide a high quality AC voltage with a good dynamic response at the different load conditions. This control scheme was also applied for the inverter to provide high quality AC voltage in islanded mode, as shown in Fig. 5.

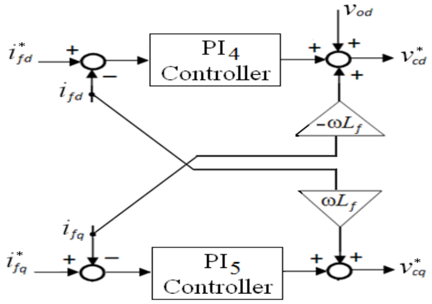

Fig. 3. Inverter control scheme in grid-connected mode

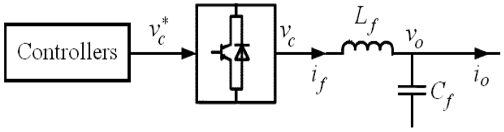

Fig. 4. Detailed schematic of the inverter

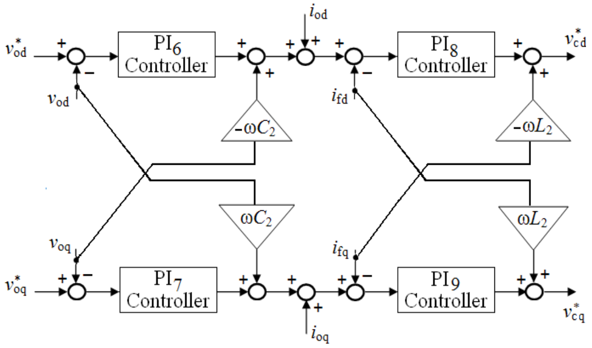

Fig. 5. Inverter control scheme in islanded mode

FIREFLY ALGORITHM

The primary purpose for a firefly's flash is to act as a signal system to attract other fireflies. X.-S. Yang formulated this algorithm by assuming [10]: 1) All fireflies are unisexual, so that one firefly will be attracted to all other fireflies; 2) Attractiveness is proportional to their brightness, and for any two fireflies, the less brighter one will be attracted by (and thus move to) the brighter one; however, the brightness can decrease as their distance increases; 3) If there are no fireflies brighter than a given firefly, it will move randomly.

Since once the islanding is occurred, DC and AC parts voltage and AC part frequency will intensely change, so their improvement was considered in the FOA algorithm.

SELF-TUNING FUZZY PI-TYPE CONTROL

In this paper, SFPI controllers are designed to improve the voltage control performance yielded by PI controllers for the proposed Micro-Grid.It keeps the simple structure of the PI controller and it is not necessary to modify any hardware parts of the original control system for implementation [11]. Three SFPI adaptive controllers were replaced in PI_1, PI_6 and PI_7. Their general configuration is shown in Fig. 6, in which a fuzzy inference module is added to conventional PI controller to adaptively tune the gain parameters (k_p, k_i) according to the error e and change in error Δe.

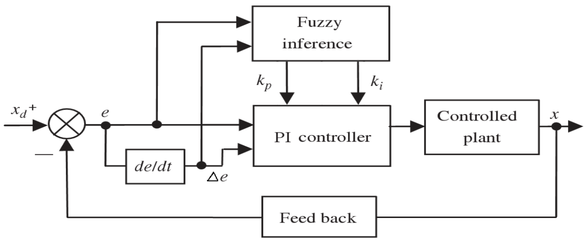

Fig. 6. Structure of self-tuning fuzzy PI controller

MULTIRESOLUTION ANALYSIS

The DWT begins with passing the discrete signal $x[n]$ of length N through a high-pass filter with impulse response $H[n]$ and through a low-pass filter with impulse response $G[n]$. The outputs of the high- and low-pass filters constitute one level of decomposition of the discrete signal. Again, the outputs from the low-pass filter can be downsampled by two and then passed through another pair of high- and low-pass filters (identical with the first pair). This constitutes the second level of decomposition of the discrete signal [12].

In this study, wavelet 'db4' was used and the proportional and integral of the voltage error (e) were implemented by the output of the low-pass and high-pass filters of first decomposition level, respectively. Totally three DWT-based voltage controllers DWT_1, DWT_6 and DWT_7 were replaced in PI_1, PI_6 and PI_7.

DYNAMIC SIMULATIONS

In this section, simulations performed in MatLab/Simulink, are shown to verify the improvement in voltage and frequency stability by the optimized PI controllers. At the first, the fluctuation of the solar irradiation level is considered during the islanding operation. In second 6, the irradiation level is decreased from 800 kW/m2 to 200 kW/m2, and then increased to 800 kW/m2 in second 7. The DC voltage to these disturbances is shown in Fig. 7.

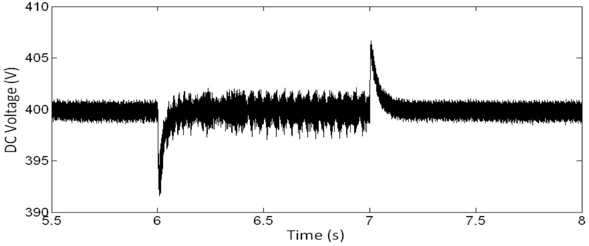

Fig. 7. DC bus voltage during the solar irradiation change

Furthermore, the AC load change is studied during the islanding operation. In second 6, the AC load is increased from 30 kW to 50 kW and then decreased to 30 kW in second 7. The AC voltage and AC frequency response to these disturbances are shown in Figs. 8-9.

Now, simulations are shown to verify the improvement in voltage and frequency stability via SFPI controllers compared to the PI controllers. The response of the Micro-Grid due to islanding occurrence including AC bus frequency and DC bus voltage is respectively shown in Figs. 10-11.

As seen from simulation results, PI controllers are not able to stabilize the Micro-Grid. While, SFPI adaptive controllers will remove the oscillations of the voltage and frequency.

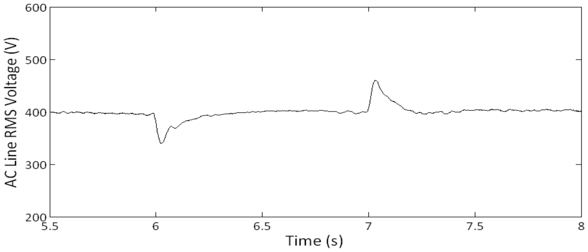

Fig. 8. AC bus voltage during the AC load change

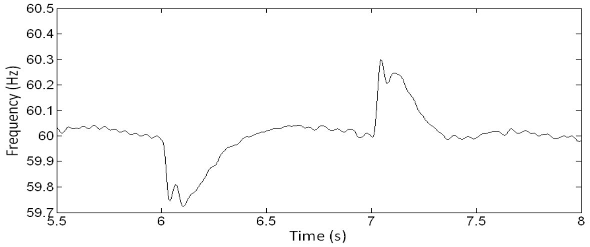

Fig. 9. AC bus frequency during the AC load change

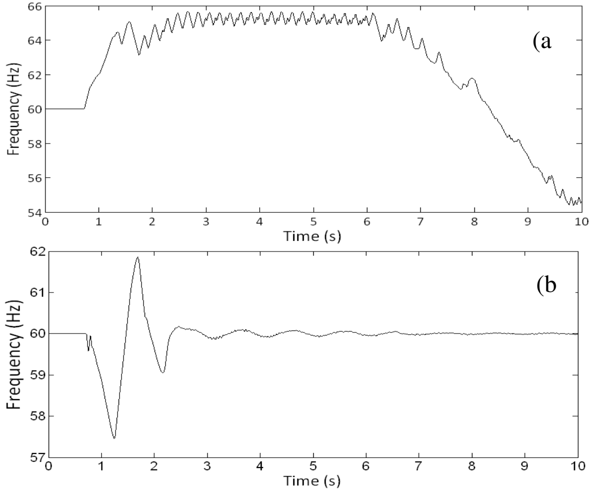

Fig. 10. AC frequency due to islanding: a) PI b)SFPI controllers

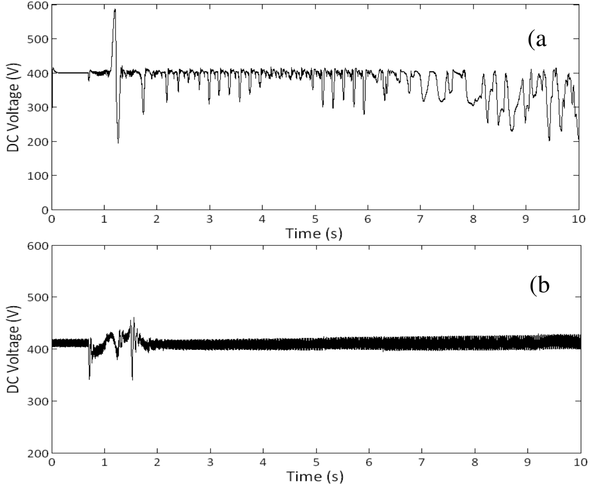

Fig. 11. DC voltage due to islanding: a) PI b) SFPI controllers.

In continue, simulations are shown to verify the improvement in the voltage control through the MRPI voltage controllers compared to the PI-based voltage controllers. The voltage and frequency responses of the Micro-Grid under the islanding event occurred in time 0.7 s are shown and compared for both voltage controller types in Figs. 12-14. It can be seen that the wavelet-based controllers are more robustness to quickly control and stabilize the voltage and frequency of the hybrid Micro-Grid as compared to the PI-based voltage controllers.

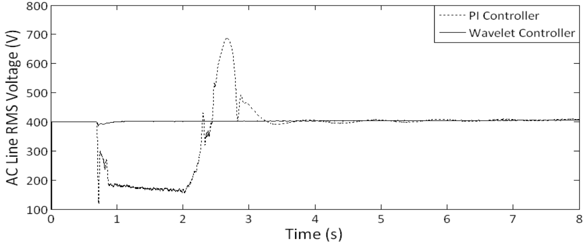

Fig.12. AC bus voltage during the islanding event

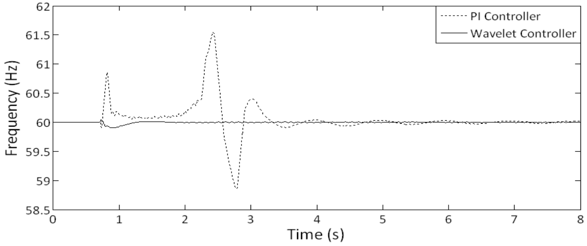

Fig.13. AC bus frequency during the islanding event

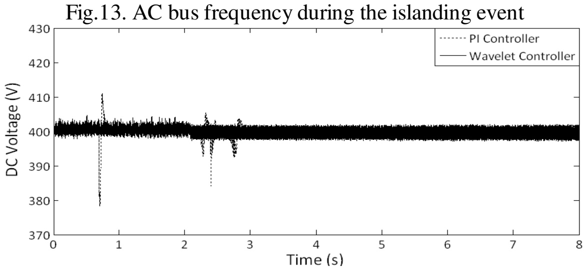

Fig.14. DC bus voltage during the islanding event

CONCLUSION

In this paper, a hybrid AC/DC Micro-Grid was proposed and studied. Then, the controllers of Micro-Grid converters were designed and developed to improve the dynamic voltage and frequency stability of the hybrid Micro-Grid. The PI controllers among the converters were designed and optimized by the firefly algorithm to stabilize and restore the voltage and frequency of the Micro-Grid during uncertainties existed in the load and generation powers. Then, three SFPI-based controllers were designed and implemented in place of the PI controllers located in the control schemes of the inverter and storages. Results are achieved during the disconnection from the utility grid (islanding), and show that the SFPI controllers are more robustness and able to stabilize the voltage and frequency of the Micro-Grid as compared to the optimized PI controllers. In continue, three DWT-based controllers were designed and replaced in the PI controllers of the inverter and storages. Results achieved during the islanding, show much more precise, correct and robust performance for DWT-based controllers to quickly control and stabilize the hybrid Micro-Grid than the optimized PI or even SFPI controllers.

The next work done by the authors introduces a novel wavelet neural network (WNN)-based MRPI controller replacing in a few PI controllers for the voltage and frequency control of the hybrid Micro-Grid. The proposed controller uses a four-layer WNN for online tuning of the MRPI controller. The WNN is comprised of an input layer, a mother wavelet layer, a wavelet layer, and an output layer. The inputs of the WNN are *e* and e(1-z^{-1}), in which z^{-1} is the time delay and *e* is the voltage tracking error between command and actual voltages. The outputs of the WNN are considered as the gains of the MRPI controller. Better tracking control performance and more robustness and precision against the disturbances are achieved using the WNN-MRPI than the MRPI control scheme.

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