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Multi-objective voltage and frequency regulation in autonomous microgrids using Pareto-based Big Bang-Big Crunch algorithm

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ABSTRACT

Voltage and frequency regulation is one of the most vital issues in autonomous microgrids to ensure an acceptable electric power quality supply to customers. In this paper, a real-time control structure including power, voltage, and current control loops is proposed for microgrid inverters to restore voltage and frequency of the system after the initiation and load changes. The Proportional-Integral (PI) gains of the voltage controller are optimized in a real-time basis after a perturbation in the microgrid to have a fast and smooth response and a more stable system. The current controller produces Space Vector Pulse Width Modulation command signals to be fed into the three-leg inverter. The multi-objective optimization problem has objective functions of voltage overshoot/undershoot, rise time, settling time, and Integral Time Absolute Error (ITAE). The modified Multi-Objective Hybrid Big Bang-Bing Crunch (MOHBB-BC) algorithm is employed as one of efficient evolutionary algorithms in order to solve the optimization problem. The MOHBB-BC method obtains a set of Pareto optimal solutions; a fuzzy decision maker is used to pick up the most preferred Pareto solution as the final solution of the problem. Results from testing the control strategy on a case study are discussed and compared with previous works; according to them, the proposed method is able to obtain dynamic PI regulator gains to have a more appropriate response.

1. Introduction

The increasing contribution of renewable energy sources in the form of Distributed Generations (DGs) such as photovoltaic systems, wind turbines, microturbines, and fuel cells is undeniable in modern power grids. A microgrid, which is a distribution system consisting of renewable and nonrenewable DG units and different types of loads, is able to operate in both grid-connected and islanded modes. In the grid-connected mode, the voltage and frequency of the system are dictated by the upstream power grid and consequently, DGs have the duty of injecting a constant power to the grid. However, in the islanded mode, the microgrid is disconnected from the upstream grid, and subsequently, DGs have the responsibility of controlling the voltage and frequency of the microgrid. In addition, most renewable DG types generate electrical power from DC sources (such as photovoltaic) or variable frequency AC sources (such as wind power). Thus, the intermittent nature of electric power generation from these DGs make them need AC/AC or DC/AC converters (inverters) for voltage and frequency regulation as a prerequisite to be connected to the main electric network . Consequently, the most convenient way to control DGs in microgrids is to control their converters.

Since microgrids face more challenges in the islanded mode than the grid-connected mode, it is important to present an efficient control strategy in order to preserve the constancy and power quality of load supply. The main objectives in an islanded microgrid is to preserve the voltage and frequency of the microgrid in the permitted range. DGs are allowed to use one of two power control strategies: either the active-reactive power control strategy (PQ mode) in the grid-connected mode or the voltage-frequency control strategy (VF mode) in the islanded mode. In order to control the voltage and frequency of microgrids, several consecutive control loops are suggested in literature with different configurations (Al-Saedi, Lachowicz, Habibi, & Bass, 2013). The first control loop, as suggested in some works like (Al-Saedi, Lachowicz, Habibi, & Bass, 2012), is the power control loop. The second control loop for controlling the voltage and frequency of islanded microgrids is the voltage control loop. The voltage controller sends a reference current signal to the current control loop (as the last control loop) by eliminating the voltage error through Proportional-Integral (PI) regulators. Current controllers are divided into two categories of linear and non-linear types

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(Abouloifa et al., 2014). In the non-linear one which is based on Hysteresis Current Control (HCC), despite compensating the current errors and producing Pulse-Width Modulation (PWM) signals with acceptable dynamic responses, an inadequate total harmonic distortion (THD) is resulted since it does not produce zero voltage vectors (Davoodnezhad, Holmes & McGrath, 2014). In order to overcome this problem, a linear type of current controller is proposed in Fantino, Busada, & Solsona (2015) based on Space Vector PWM (SVPWM). This modulation not only is able to compensate the current error through the PI regulator or predictive control algorithms, but also independently performs error compensation and PWM signal production. As a result, the controller provides an adequate response with a low ripple. Eventually, the transmitted signals from the current control block enter the SVPWM module, which is responsible for generating command signals for the three-leg Voltage Sourced Inverter (VSI). In this way, the microgrid-based inverter can be controlled to achieve desired control objectives.

The appropriate performance of the control structure to control the voltage and frequency of the microgrid depends on proper PI regulator gains (Sakthivel, Vijayakumar, Senthilkumar, Lakshminarasimman, & Paramasivam, 2015). In control structures proposed in literature, regulator gains can be determined statically or dynamically (Seidi Khorramabadi & Bakhshai, 2015). Dynamic gains are continuously updated after a perturbation in the system, whereas static ones are constant for all situations. Since the set point of the system is altering due to inevitable changes happening in microgrid loads and configuration, an acceptable performance using static gains is not guaranteed. On the other hand, dynamic tuning of regulator gains is done using optimization algorithms (Deb, 2009). The optimization problem of real-time tuning of PI regulator parameters can be formulated as a Linear Programming (LP) with linear objective function and constraints. A more sophisticated method is to model the problem as a Nonlinear Programming (NLP). Optimization problems, either LP or NLP, can be solved using mathematical-based tools such as Lagrangian method or evolutionary search techniques such as Dynamic Programming (DP), Genetic Algorithm (GA), or Particle Swarm Optimization (PSO). Evolutionary search techniques, which may offer a better solution than classical mathematical methods in solving an optimization problem, are applied to solve microgrid-related problems in literature.

Authors in Ali Nandar (2013) have used the GA algorithm for each step change in input wind power for dynamically tuning of the PI regulator in order to stabilize the frequency of the microgrid. In Wies, Chukkapalli, and Mueller-Stoffels (2014), adjusting frequency in an islanded microgrid is discussed using an online GA method for tuning of the Proportional-Integral-Derivative (PID) controller. In Al-Saedi et al. (2013), the PSO algorithm is used to dynamically tuning of PI regulator gains used in the power controller in order to control the voltage and frequency of the islanded microgrid. The suggested structure in Xu and Li (2014) includes the voltage regulator block as the outermost control loop and the current regulator block as the innermost control loop which uses an adaptive method for tuning the PI regulator used in the STATCOM for voltage regulation. On the other hand, the faster the convergence rate of the optimization algorithm in real-time applications, the more the possibility of meeting the control objectives. To this end, the Big Bang-Big Crunch (BB-BC) optimization algorithm, with a higher convergence rate compared with previous optimization algorithms, has been used in recent studies of power system applications. For example, in Othman, El-Khattam, Hegazy, and Abdelaziz (2015), this algorithm is used for optimal placement of DG units in unbalanced distribution system. The integration of the BB-BC algorithm with the capabilities of the PSO algorithm results in introducing a new algorithm called Hybrid BB-BC (HBB-BC), which has a higher exploration capability compared with the basic BB-BC algorithm (Kaveh & Talatahari, 2010). Authors in Sedighizadeh, Esmaili, and Esmaeili (2014) have used the HBB-BC algorithm for optimal reconfiguration and DG power allocation in distribution networks.

Multi-objective optimization problems can be solved using two different techniques: Pareto-based methods that obtain Pareto (non-dominated) optimal solutions or combination techniques that combine objective functions to get a single objective function (Deb, 2009). In Pareto-based methods, the optimization algorithm achieves a set of non-dominated Pareto solutions and stores them in a memory. In the second method, all objective functions are combined to form a single objective function to be optimized. In these methods unlike Pareto-based methods, the result is a particular answer that satisfies all objectives in an acceptable level. However, since in most multi-objective optimization problems the objectives' optimal values happen in different directions, the technique of converting objective functions into a single objective one may not obtain an efficient solution. Consequently, Pareto-based methods is more preferred in such problems.

In this paper, an algorithm is proposed for real-time optimal regulation of voltage and frequency in a DG inverter by means of dynamically tuning of PI regulators after occurring a perturbation in autonomous microgrids. The main advantages of the proposed method is to use dynamic controller gains to regulate voltage and frequency of microgrids on a real-time basis. The proposed optimization problem includes four objective functions of minimizing voltage overshoot/undershoot, rise time, settling time, and Integral Time Absolute Error (ITAE). The modified Multi-Objective HBB-BC (MOHBB-BC) evolutionary method is used to solve the optimization problem to get Pareto solutions. An operator called crowding distance (Lei, Gong, Zhang, Li, & Jiao, 2014) is used here in order to preserve the diversity of Pareto solutions for improved exploration capability. The MOHBB-BC obtains a Pareto set of PI proportional and integral gains for the voltage controller; in order to choose the best compromised solution among the optimal Pareto solutions, a fuzzy decision maker is used here. The control structure proposed in this paper includes power, voltage, and current controllers. The nominal frequency and voltage set point of the system are calculated in the power controller based on the conventional droop characteristic. Afterwards, the values obtained from the power controller block enter into the voltage controller block in order to eliminate the voltage error. The voltage controller uses the optimal proportional and integral gains for the PI controller on a real-time basis. Reference current signals, produced in the voltage controller, arrive the current controller block to eliminate the current error. Since the elimination of error in the voltage controller is done through regulators with the capability of real-time tuning of proportional and integral gains, there is no need to use dynamic gains in the current controller, and consequently, static gains are used in the current controller block. Finally, signals resulted from the current controller block are delivered to the SVPWM module in order to generate command signals for the three-leg VSI for the purpose of voltage and frequency regulation in the islanded microgrid.

The rest of this paper is organized as follows. In Section 2, the proposed control structure for voltage and frequency regulation of the islanded microgrid is discussed. The principles and regulations of the proposed algorithm and objective functions for the optimization problem are also described in this section. In Section 3, the solution method of HBB-BC is introduced. In Section 4, results obtained from simulations are explicated to show the efficiency of the proposed control structure. Finally, Section 5 concludes the paper.