Electric Power Systems Research 154 (2018) 13–22

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables

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ARTICLE INFO

Article history:
Received 25 January 2017
Received in revised form 8 July 2017
Accepted 8 August 2017

Keywords:
Frequency stability
Low inertia microgrids
Many-objective optimization
Renewable energy resources
Virtual inertia

ABSTRACT

Preserving the frequency stability of low inertia microgrids (MGs) with high penetration of renewables is a serious challenge. To rise to this challenge, the inertia constant of MGs would be virtually increased using energy storages. However, it is important to determine the suitable value of inertia constant for these systems such that the frequency stability is preserved with a lower cost. Frequency droop coefficient of distributed energy resources (DERs) and load frequency controllers' parameters would also affect the frequency response of MGs. Hence, in this paper, inertia constant is tuned together with frequency droop coefficient of DERs and load frequency controllers' parameters. Determining these parameters is modeled as a multi-objective optimization problem and, because the number of objectives is higher than three, the problem is solved by a many-objective optimization algorithm. Comparative simulation studies have been done on an MG with different types of DERs to prove that using the proposed strategy for tuning the MG parameters not only the frequency deviation is highly decreased but also the amount of load shedding is considerably diminished. This would increase the customers' satisfaction. Moreover, considering the inertia constant as a minimization objective, frequency stability would be preserved with a lower cost.

1. Introduction

Due to the environmental concerns, there is an increasing interest in using renewable energy sources (RESs) for power generation. MGs would provide a suitable infrastructure for integrating RESs to the grid at distribution level. MGs can operate in grid-connected or islanded mode. However, in islanded mode, they would encounter challenges in frequency and voltage control. These problems would be exacerbated in MGs with a high share of power-electronically interfaced DERs; due to the low inertia of the grid. In fact, in low inertia MGs, power imbalances result in rapid changes in frequency that might endanger the stability of the system [1].

To address these stability concerns, some methods have been proposed to increase the inertia of MGs. In Refs. [2,3], using synchronous condensers have been proposed for this purpose. In addition to contributing to the inertia of the gird, synchronous condensers would participate in reactive power control. Inverter-based DERs would also emulate the inertial response of synchronous generators by injecting a power proportional to frequency derivative to the grid. In Ref. [4], a control method has been proposed for converters to emulate the behavior of synchronous generators. Virtual inertia has been implemented in Ref. [5] to increase the contribution of distributed generators to oscillation damping. To emulate the inertial behavior of synchronous generators, inverter-based DERs require a temporary source of energy similar to the kinetic energy of the rotor of synchronous generators. In Ref. [6], the energy stored in the rotor of doubly fed induction generator (DFIG) based wind turbines and also the ultracapacitor (UC) installed at the dc-link of converters are used as energy sources for inertia emulation. In Ref. [7], HVDC transmission line is controlled to contribute to the inertia of the grid. HVDC links would transfer the inertial power generated by wind farms to the main grid, transfer inertial power from one area of power system to another area or use the energy stored in the DC link to emulate the inertial response. UC is proposed in Ref. [8] to emulate the inertial response of synchronous generators in an isolated power system. Although some studies have been carried out on contribution of inverter-based DERs to the inertia of MGs, to the best of authors' knowledge, a systematic method for determining the proper value for inertia constant in islanded MGs has not yet been proposed.

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http://dx.doi.org/10.1016/j.epsr.2017.08.007

Nomenclature

R	Frequency droop coefficient of energy resources
H	Inertia constant of the grid
H_{vir}	Virtual inertia
H_{eq}	The equivalent inertia constant of synchronous generators
$P_{ref-old}$	Reference power of energy resources without inertia emulation
$P_{ref-new}$	Reference power of energy resources with inertia emulation
f	Operation frequency of the grid
E	The energy required by UC for inertia emulation
$P_{inertia}$	Inertial power
f_{init}	Frequency before the disturbance
f_{crit}	Critical frequency
t_{crit}	The time it takes the frequency to reach the critical frequency
E_{avail}	The energy available from UC
C	Capacitance of UC
V_{init}	Initial voltage of UC
V_{min}	Minimum permissible voltage of UC
P_{base}	Base power of the grid
V_n	Nominal voltage of UC
P_n	Nominal power of UC
f_{nadir}	Frequency undershoot
f_{max}	Frequency overshoot
t_{st}	Settling time of frequency
Obj_i	The ith objective function
t	Time
Q_{L0}	Initial reactive power of load
Q_L	Current values of the load's reactive power
b	Coefficient of load reactive power dependency on voltage
f_n	Nominal frequency
t_{sim}	Simulation time
$\Delta f(t)$	Deviation of the frequency from the nominal value
f_{min}	Minimum desirable frequency
x	Vector of decision variables
n	The number of DERs that participate in frequency control
x^{up}	The upper limit vector for the decision variables
x^{low}	The lower limit vector for the decision variables
Obj_{li}	The ith objective of the lth Pareto optimal solution
m	The number of objectives
$Ideal\_Obj$	Ideal objective vector
$Ideal\_Obj_i$	The ith element of the ideal objective vector
d^l	Sum of the normalized objectives of the lth Pareto solution
T_g	Governor time constant
T_t	Turbine time constant
T_{BESS}	BESS time constant
T_{UC}	UC time constant
$\dot{P}_{BESS}$	BESS ramp rate
$\dot{P}_{DEG}$	DEG ramp rate
P_{L0}	Initial active power of load
V_0	Initial voltage of load
V	Voltage of the load bus
P_L	Current values of the load active power
a	Coefficient of load active power dependency on voltage
K_{pf}	Coefficient of load active power dependency on frequency
K_{qf}	Coefficient of load reactive power dependency on frequency

In addition to inertia constant, load frequency controllers and frequency droop coefficient of power sources would affect the frequency response of the grid. Fine-tuning the load frequency controllers would reduce the maximum frequency deviation and also bring back the frequency to the nominal value faster. Different methods have been proposed for load frequency control (LFC) in power systems. In Ref. [9] the performance of model predictive controller for LFC in Nordic power system was investigated. Many researchers have focused on tuning the traditional proportional integral (PI)/proportional integral derivative (PID) controllers using evolutionary algorithms. In Ref. [10] bacterial foraging optimization algorithm has been implemented to tune the load frequency controllers of an MG with generation rate constraint (GRC). In Ref. [11] a hierarchical approach based on fuzzy logic has been proposed to improve the quality of frequency control. Electrical vehicles have been implemented in Ref. [12] for frequency control. In Ref. [13], fractional order PID controllers have been proposed for LFC in a multi-area power system. An adaptive set-point modulation technique has been implemented in Ref. [14] to enhance the performance of PI load frequency controllers. To improve the performance of frequency controllers in a three-area thermal power system, in Ref. [15] governors' frequency droop coefficient (R) have been optimized together with the load frequency controllers' parameters.

Since the grid inertia constant (H), frequency droop coefficient of DERs and parameters of load frequency controllers all affect the frequency response of MGs, in this paper, tuning these parameters has been suggested to improve the frequency stability of MGs. Based on different criteria that should be met to have a proper frequency response in MGs, a systematic method is proposed for tuning all the parameters, including R, H and the controllers parameters, simultaneously. The main goal of tuning these parameters is to improve the frequency stability of MG. However, this goal should be achieved with the minimum cost. Hence, tuning these parameters has been modeled as a multi-objective optimization problem which considers both stability and economic aspects. Considering the fact that usual multi-objective optimization algorithms, like non-dominated sorting genetic algorithm II (NSGA-II), would not show a good performance in solving optimization problems with more than three objectives [16], a recently developed many-objective knee point driven evolutionary algorithm (KnEA) is implemented for solving this problem. Finally, to select one of the Pareto optimal solutions obtained by KnEA as the final solution, a strategy based on the minimum sum of the normalized objectives is suggested. Also, a method for determining the characteristics of the ultracapacitor required for emulating the determined inertia is proposed.

The rest of this paper is organized as follows: in Section 2, the required equipment for increasing the inertia constant of the MG is studied. In Section 3, the process of tuning the parameters of MG for improving its frequency response is explained. The studied MG is introduced in Section 4. Then, in Section 5, by simulation studies carried out in Matlab/Simulink, the effectiveness of the proposed method is investigated. Finally, the conclusions of this research are presented in Section 6.

2. Increasing the inertia constant of MG

In this paper, the proper value of inertia constant together with frequency droop coefficient of DERs and load frequency controllers parameters are tuned to improve the frequency stability. To contribute to the inertial response, the power reference of inverter-based DERs should be altered as follows [17]:

$$P_{ref-new} = P_{ref-old} - 2H_{vir} \cdot \frac{df}{dt} \quad (1)$$

where $P_{ref\text{-}old}$, $P_{ref\text{-}new}$, H_{vir} and f are the reference power without inertia emulation (in pu), the reference power with inertia emula-