Control Engineering Practice 59 (2017) 77–99

Contents lists available at ScienceDirect

Control Engineering Practice

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

A two-level control strategy with fuzzy logic for large-scale photovoltaic farms to support grid frequency regulation☆

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ARTICLE INFO

Keywords:
Coordinated control strategy
Fuzzy logic controller
Grid frequency regulation
Large-scale PV farm
Battery state-of-charge control
Multi-area power system

ABSTRACT

This study proposes a two-level coordinated control strategy with fuzzy logic for appropriately adjusting the total active power supplied to a grid by large-scale photovoltaic (PV) farms in order to regulate grid frequency. For a solar farm, the strategy includes a central coordinating controller and many local controllers at PV power assemblies, treated as agents. In detail, the central controller uses a frequency regulation module based on a new automatic-tuning fuzzy-logic controller scheme to compute the appropriate reference values according to the total power needed. Then, the individual reference value for each local controller is determined. Each local controller governs all power-electronic converters installed at the PV agent to inject power into the grid according to the individual reference value received. Additionally, each local controller uses an algorithm to manage the state-of-charge of the battery bank installed at the agent so that it remains in the safe range of 20–80% while operating and close to the desired idle value of 50% at the steady state. Besides, a special control mode is developed and integrated into the overall strategy to aid rapid recovery of the grid frequency under emergency conditions. Numerical simulations demonstrate that the suggested strategy has the good response in terms of injecting an appropriate amount of power into the grid to regulate the frequency deviation into acceptable ranges of ± 0.2 (Hz) in the transient state and ± 0.05 (Hz) at the steady state, even when the weather conditions (solar radiation, air temperature), AC system load, and important control parameters of the grid suddenly change. Furthermore, the effectiveness in improving the grid-frequency stabilization by using the proposed strategy is validated within a four-area power system, where four PV farms are connected and the operating parameters of the grids at the areas are fairly different.

1. Introduction

In recent years, large-scale PV solar farms have been widely used to inject active power into electric grids (Datta, Senjyu, Yona, Funabashi, & Kim, 2009; Ishikawa, Naitoh, & Senjyu, 2012; Datta, Senjyu, Yona, Funabashi, & Kim, 2009, 2011, 2013). Nonetheless, large-scale solar farms, consisting of many local small PV power agents, can cause the grid frequency to deviate beyond the acceptable standard range of ± 0.2 (Hz). Moreover, in the case of multi-area power systems with many connected large-scale PV solar farms, the distortion in grid frequency will worsen sharply without a suitable and efficient coordinated control strategy. As well, energy storage systems (ESSs) have been broadly used in real large-scale PV farms to markedly enhance the robustness of farm performance in the face of unpredicted changes in weather condition. According to Ghiassi-Farrokhfal, Kazhamiaka, Rosenberg, and Keshav (2015), an optimal design for solar farms with ESS is also necessary to maximize overall revenue in cases where grid-connected PV farms are considered as major components in a real energy market. Hence, the problem of regulating grid frequency in a power system that encompasses large-scale PV farms that use battery banks to manage energy needs to be examined and resolved satisfactorily. Toward resolving this issue, some control strategies have been proposed in Datta et al. (2009, 2011, 2012, 2013), Sun, Zhang, Xing, and Guerrero (2011), Kakimoto, Takayama, Satoh, and Nakamura (2009), Xin, Liu, Wang, Gan, and Yang (2013), Delille, François, and Malarange (2012), Bevrani, Habibi, Babahajyani, Watanabe, and Mitani (2012), Bevrani and Shokoohi (2013) and Bai, Abedi, and Lee (2016).

More specifically Datta et al. (2009, 2011, 2012) describe a coordinated control method based on fuzzy logic for PV-diesel hybrid systems without battery banks. This method has been proposed for regulating grid frequency. It employs two 49-rule fuzzy logic controllers (FLCs) to compute the reference value for the active power that should be delivered to the grid. Nonetheless, in some cases, such as when the

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☆ This work is a significant modification and improvement over the study in our brief conference version (Thao & Uchida, 2015b).

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http://dx.doi.org/10.1016/j.conengprac.2016.11.006
Received 22 April 2016; Received in revised form 28 September 2016; Accepted 11 November 2016
0967-0661/

Nomenclature

P	Physical value of active power, in Watts
β	Value expressed in per-unit system of P
δ	Ratio value expressed in percent
j	Index of local agent in a PV farm
k	Present step of sampling time in control

Superscripts

*	Reference value

Meas	Measured actual value
Pre	Predicted value
Min	Minimum value
Max	Maximum value
TrS	Value computed in the transient state
StS	Value computed at the steady state
Diff	Difference value

solar radiation decreases a large amount and the system load increases a large amount, a PV system without battery banks or another ESS may not supply sufficient power to the grid to allow the frequency to be stabilized. As shown in Datta et al. (2013) and Sun et al. (2011), grid-connected PV systems with battery banks for managing energy have been used to control the grid frequency. The fuzzy-based coordinated strategy described in Datta et al. (2013) has been evaluated within the test case of a three-area power system where some PV farms are connected. In most of the studies mentioned above, the state-of-charge (SOC) values of battery banks installed at the PV farms have not yet been managed strictly to stay within the ratio value range of 20–80% recommended to ensure durability of the battery banks.

As presented in Kakimoto et al. (2009), a proportional main controller and a double-layer capacitor for a grid-connected PV system have been applied to stabilize the grid frequency. The control approach not only has a relatively simple structure but also allows fine response. However, impacts of AC system loads in the grid were not examined deeply in Kakimoto et al. (2009). Furthermore, a dynamic frequency-control technique that uses ultracapacitors as the major ESS to ameliorate the inertia of an isolated power grid on a French island, has been proposed in Xin et al. (2013). This technique well stabilized the grid frequency in the studied case, which involves a high penetration of PV solar and wind generators in an isolated grid. In addition to these systems, a frequency control technique based on a power curtailment algorithm using Newton quadratic interpolation (NQI) for grid-connected PV systems without ESS has been introduced and appraised in Delille et al. (2012). The main idea of the method in Delille et al. (2012) is to tune frequently the operating point of the PV arrays so as to achieve the desired power amount. This scheme has not yet been tested within a large-scale PV farm that includes many local grid-connected solar agents.

The researchers in Bevrani et al. (2012) have presented an online tuning approach that uses a combination of fuzzy logic and particle swarm optimization (PSO) to tune the design parameters of a proportional–integral controller. The goal of this intelligent control approach is to regulate the frequency of a typical AC microgrid, where some PV panels, wind turbine generators, ESSs, and fuel cells are connected. In another study, to address the issue of regulating both grid frequency and voltage for the distributed power generation, a model-free method based on the adaptive neuro-fuzzy inference system (ANFIS) has been introduced (Bevrani & Shokoohi, 2013). This method can well control the grid frequency and voltage even when there are unpredicted changes to the system load and the line parameters of the grid. The efficacy of the proposed ANFIS is dependent on the training process used to determine the parameters that determine the structure of the ANFIS, but this process often requires a larger amount of calculation and suitable databases.

In Thao and Uchida (2016), a prior study by the present two authors showed a simple single-level control method suitable for a small PV power agent, but no coordinated control strategy was proposed for a large-scale PV farm. In addition, the tolerable range of grid frequency deviation at the steady state used in Thao and Uchida (2016) was ±0.075 (Hz), which is 50% larger than the often-used range of ±0.05 (Hz). A coordinated strategy for PV farms was presented initially in Thao and Uchida (2015b). However, some other crucial issues have not been considered and evaluated, including: (i) special control for recovering rapidly the grid frequency in emergency conditions, (ii) supervision of the difference between the reference signal and the actual value of total power supplied from a PV farm, and (iii) performance within a multi-area power system with many PV farms connected. As well, the algorithm that determines whether the grid is operating in the transient or steady state is simple and not highly accurate, which has a detrimental effect on the SOC management of battery banks in the PV farm. Lastly, the output scaling factors of the 49-rule FLCs in Thao and Uchida (2015b, 2016) are fixed values that are chosen manually, which may noticeably impair the ability of the control strategies to cope with large uncertainties in weather conditions and grid parameters.

Hence, in this paper, the above three issues (i, ii, iii) are studied carefully to resolve them thoroughly; moreover, the algorithm that determines the operating state of the grid is made significantly more accurate, which can better regulate the SOC of battery banks in the PV farm. Additionally, a modified 49-rule FLC scheme is employed in the central controller. The output scaling factor under this scheme is now adjusted automatically by a new complementary 6-rule FLC proposed here. This means the output scaling factor of the proposed FLC scheme is an online changeable value, instead of being a fixed value as in Thao and Uchida (2015b, 2016). The ultimate objective of using this is to contribute to a substantial enhancement of the performance and adaptability of the suggested coordinated strategy. In addition, the structure of the proposed control strategy is much improved by new and useful features (described by Figs. 4 and 8 in Section 3) that were not present in the brief version shown in Thao and Uchida (2015b). Furthermore, many illustrative diagrams, detailed explanations, test cases and simulation results are newly presented here.

The proposed coordinated strategy with fuzzy logic to support stabilization of the grid frequency for large-scale solar farms that use battery banks has the following key aims.

a) The total active power delivered from a PV farm to the grid should be tuned to ensure that the frequency is within a tolerable range. Two acceptable ranges for frequency deviation are ±0.2 (Hz) for the transient state and ±0.05 (Hz) at the steady state, where the nominal frequency is 60 (Hz).
b) At each local PV agent of the farm, the SOC of the battery bank should be maintained in the safe ratio range of 20–80% during the operating time to enhance the durability of the battery bank. Moreover, the steady-state SOC of the battery bank should be governed to an idle ratio value of 50% so long as the grid frequency deviation is in the small range of ±0.05 (Hz). This function is intended to guarantee that the battery bank will have sufficient capacity for promptly supplying or absorbing energy as needed at the next operation time.
c) A control mode to regulate immediately the grid frequency devia-