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Intelligent photovoltaic farms for robust frequency stabilization in multi-area interconnected power system based on PSO-based optimal Sugeno fuzzy logic control

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A B S T R A C T

Currently, the grid-connected large PV farms are extensively installed in power systems. Nevertheless, in addition to the load change, the intermittent power output of PV farms may lead to the serious problem of the system frequency fluctuation. To handle this problem, this paper proposes a new design of Sugeno fuzzy logic controller based on particle swarm optimization (PSO-SFLC) of intelligent PV farms for the frequency stabilization in a multi-area interconnected power system. To handle various scenarios, the frequency deviations and solar insolations are used as input signals of the PSO-SFLC. The output signal of the PSO-SFLC is a command signal for adjusting PV output power. The output power of PV is controlled by the PSO-SFLC to meet the load demand so that the system frequency fluctuation can be suppressed. Without the difficulty of trial and error, the optimal input and output membership functions, and control rules of PSO-SFLC are automatically achieved by PSO. Simulation study in a three-area loop interconnected power system with large PV farms elucidates that the frequency stabilizing performance and robustness of the PV equipped with the PSO-SFLC is much superior to that of the PV with the SFLC and the PV with the maximum power point tracking control in scenarios with various solar insolations and loading conditions.

1. Introduction

Nowadays, the grid-connected photovoltaic (PV) systems are widely placed in power systems around the world. As given in Ref. [1], there are many grid-connected PV farms that are larger than 50 MW in the current net capacity such as Topaz Solar Farm with 300 MW in USA, Huanghe Solar Park with 200 MW in China, and Neuhardenberg Solar Park with 145 MW in Germany etc. In the future, it is anticipated that large PV farms should not only supply the electrical power, but also contribute some ancillary services to power systems such as frequency control support and voltage control [2] etc.

On the other hand, the frequency fluctuation problem due to large load changes affects the quality and stability of power systems [3]. Besides, the intermittent power generation from large PV farms makes the frequency control problem more complicated. Under these scenarios, since the response of the conventional load-frequency control (LFC) by turbine and governor is slow, it may no longer be able to handle this problem.

To deal with the frequency control problem in power systems with PV generators, there are some research works which try to control the power generation of the PV to meet the load power so that the frequency fluctuation is minimized. In Ref. [4], a frequency control by the PV generator in a PV-diesel hybrid power system is proposed. The PV inverter is controlled by two simple fuzzy controllers so that the active power output of the PV can be adjusted to minimize the frequency fluctuation. In Refs. [5–8], the simple fuzzy-based frequency control strategy by the megawatt class distributed PV systems is proposed to reduce frequency deviation and tie-line power deviation in the three-area interconnected power systems. Nevertheless, the difficult problem of the fuzzy control proposed in these works is the setting of membership functions and control rules which depends on the designer's experience and trial and error method. This becomes a difficult obstacle in the fuzzy control design. In addition, the complicated structure of the fuzzy controller is another barrier which causes the difficulty in the control design. The simple structure of the fuzzy controller is highly expected. Moreover, the robustness of the PV with the fuzzy control has not been evaluated in scenario with various load changes and

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solar insolations. This cannot guarantee the control effect of the PV with the fuzzy control in previous works.

This paper proposes a new intelligent control of PV farms using the particle swarm optimization-based Sugeno fuzzy logic controller (PSO-SFLC) for the robust frequency stabilization in a multi-area interconnected power system. The solar insolation and frequency deviation are use as the input signals of the PSO-SFLC so that the PSO-SFLC is able to handle various load changes and solar insolations. The command signal from the PSO-SFLC is employed to adjust the PV output power to meet the load demand so that the system frequency deviation can be eliminated. The PSO is used to automatically tune the membership function and control rules of the SFLC. Simulation study is conducted in a three-area interconnected power system by MATLAB/Simulink. The stabilizing effect and robustness of PV with PSO-SFLC is compared with PV equipped with non-optimal SFLC and PV with maximum power point tracking (MPPT) under several load changes and solar insolations.

The organization of this paper is explained as follows. First, the study system and modeling is presented in Section 2. Next, Section 3 describes the proposed design of the PSO-SFLC. Subsequently, Section 4 demonstrates simulation results. Finally, a conclusion is given in Section 5.

2. Study system and modeling

2.1. Three-area interconnected power system

Fig. 1 depicts the three-area interconnected power system which is used in this study [7]. Each area mainly consists of generator G_i, $i = 1,2,3$, PV farm PV_i, $i = 1,2,3$ and $load_i$, $i = 1,2,3$. As mentioned in Ref. [7], the power rating of generator in each area is obtained from the aggregation of all power rating of generators in each area. As a result, the generator power rating in areas 1, 2, and 3 are 1,000, 1,100, and 850 MW, respectively. Based on the generator power rating in each area, the total power rating is 2950 MW. The size and rating of each PV module and array, and generator in each area are provided in Table 1, where V_{oc} is an open circuit voltage of the PV module, I_{sc} is a.short circuit current of the PV module and N_s is a number of cells in series.

Fig. 2 delineates the linearized model for the frequency control study of the system in Fig. 1. The PV is equipped with the SFLC. Note that, P_{ti}, $i = 1,2,3$ is an output power of turbine generator in the ith area, P_{Li} is a load change in the ith area, P_{ei} is a total electrical power

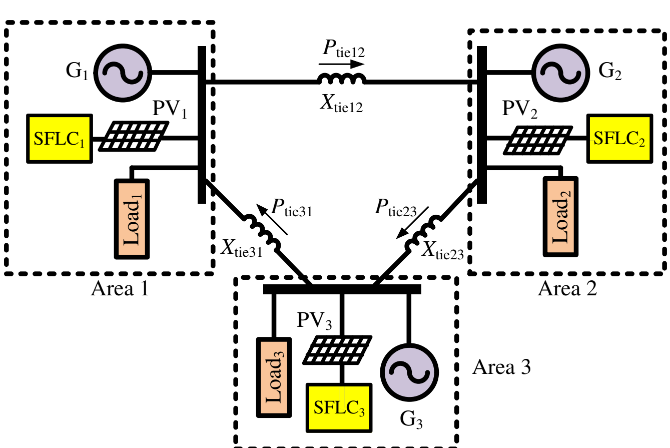

Fig. 1. Three-area interconnected power system.

Table 1
Rated power of generator and PV (1000 MW system base).

Generator		PV module				PV array	
Area	Rated power	Rated power	V_{oc}	I_{sc}	N_s	Area	Rated power
1	1000 MW	85 W	22.2 V	5.45 A	60	1	400 MW
2	1100 MW					2	220 MW
3	850 MW					3	371 MW

in the ith area, Δf_i is a frequency deviation in the ith area, T_{gi} is a time constant of the governor in the ith area, T_{ti} is a time constant of the turbine in the ith area, M_i is an inertia constant in the ith area, D_i is a damping coefficient in the ith area, K_i is an integral control gain in the ith area, R_i is a droop in the ith area, β_i is a frequency bias in the ith area, ΔP_{tie12}, ΔP_{tie23}, ΔP_{tie31} are tie-line power deviations between areas 1 and 2, 2 and 3, 3 and 1, and T_{12}, T_{23}, T_{31} are synchronizing torque coefficients between two areas. System parameters are given in Table 2.

2.2. PV model

Fig. 3 delineates the PV block diagram which consists of PV array, DC/DC converter, MPPT control, DC/AC converter, battery and SFLC. Note that ISO is a solar insolation, P_{PV} is a PV output power, P_{conv} is DC/DC converter output power, P_{inv} is DC/AC converter output power, I_{ref} is a reference current signal from the MPPT control, P_b is a battery power and M_a is a command signal of the SFLC.

A current source is used to model the PV module as depicted in Fig. 4 [7]. The $P-V$ and $I-V$ characteristic curves of the PV module are illustrated in Fig. 5a and b, respectively. The equation of current in this circuit can be expressed by

$$I_o = I_g - I_{sat}\left\{\exp\left[\frac{q}{AKT}(V_o + I_oR_s)\right] - 1\right\} \tag{1}$$

where, I_o and V_o are an output current and an output voltage of the PV module, respectively, I_g is a generated current under the given insolation, I_{sat} is a reverse saturation current, q is a charge of an electron, K is the Boltzmann's constant, A is an ideality factor for the $p-n$ junction, T is a temperature (K), and R_s is an intrinsic series resistance of the PV module.

The saturation current (I_{sat}) of the PV module which varies with the temperature, is given by.

$$I_{sat} = I_{or}\left[\frac{T_{mod}}{T_r}\right]^3 \exp\left[\frac{qE_g}{KT_{mod}}\left(\frac{1}{T_r} - \frac{1}{T_{mod}}\right)\right] \tag{2}$$

and

$$I_g = I_{sc}\frac{ISO}{1000} + I_t(T_{mod} - T_r) \tag{3}$$

where T_r is a reference temperature (K), I_{or} is a saturation current at T_r, T_{mod} is a temperature of the PV module (K), E_g is a band-gap energy and I_t is a short circuit current temperature coefficient.

The current flow in the shunt resistance is provided by

$$I_{rsh} = \frac{V_o}{N_sR_{sh}} \tag{4}$$

where R_{sh} is an internal shunt resistance of the PV module and N_s is a number of cells in series.