A Frequency-Control Approach by Photovoltaic Generator in a PV–Diesel Hybrid Power System

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Abstract—A photovoltaic (PV) system’s output power fluctuates according to the weather conditions. Fluctuating PV power causes frequency deviations in the power utilities when the penetration is large. Usually, an energy storage system (ESS) is used to smooth the PV output power fluctuations and then the smoothed power is supplied to the utility. In this paper, a simple fuzzy-based frequency-control method is proposed for the PV generator in a PV–diesel hybrid system without the smoothing of PV output power fluctuations. By means of the proposed method, output power control of a PV generator considering the conditions of power utilities and the maximizing of energy capture are achieved. Here, fuzzy control is used to generate the PV output power command. This fuzzy control has average insolation, change of insolation, and frequency deviation as inputs. The proposed method is compared with a maximum power point tracking control-based method and with an ESS-based conventional control method. The numerical simulation results show that the proposed method is effective in providing frequency control and also delivers power near the maximum PV power level.

Index Terms—Energy storage system (ESS), frequency control, frequency deviation, fuzzy logic, maximum power point tracking (MPPT).

I. INTRODUCTION

OKINAWA Prefecture is one of Japan’s southern prefectures with subtropical climate, and consists of hundreds of the Ryukyu Islands in a chain over 1000 km long, which extends southwest from Kyushu (the south westernmost of Japan’s main four islands) to Taiwan [1]. Some of those Ryukyu islands are very small, are far from the mainland of Okinawa, and mostly depend on diesel generators for electric power supply. The generation cost of electric power by using diesel generators for electric power supply mostly depend on diesel generators for electric power supply. In isolated islands is expensive compared to a conventional generation. Besides, as the mitigation of global warming and the reduction of CO₂ emissions are of great interest worldwide, the consumption of fossil fuels in these isolated islands must be reduced and clean renewable energy sources must be introduced.

One of the most promising applications of renewable energy technology is the installation of hybrid energy systems in remote areas, where the cost of grid extension is prohibitive and the price for fuel drastically increases with the remoteness of the location. Renewable energy sources, such as photovoltaic (PV), wind energy, or small-scale hydro, provide a realistic alternative to engine-driven generators for electricity generation in remote areas [2]–[4]. It has been demonstrated that hybrid energy systems can significantly reduce the total life cycle cost of stand-alone power supplies in many situations, while at the same time providing a more reliable supply of electricity through the combination of energy sources [5], [6].

This paper concentrates on the control and application of PV–diesel hybrid energy systems, which account for the majority of systems installed today. One of the inherent advantages of PV electricity generation is the absence of any mechanical parts (unless tracking of the sun is included). Professionally installed PV arrays are characterized by a long service lifetime, exceeding 20 years, high reliability, and low maintenance requirements, which are highly desirable for remote area power supplies. In sunny locations, PV generators compare favorably with wind generators, despite the higher investment cost for PV modules per peak Watt [7]. Wind generators require regular maintenance and are susceptible to damage in strong winds.

The penetration of PV systems in Japan is rising. Two factors have been boosting this: improved generation efficiency of PV modules and governmental subsidies for the initial cost of residential PV generation systems [8]. However, PV power fluctuates depending on the weather conditions, season, and geographic location, and may cause problems like voltage fluctuation and large frequency deviation in electric power system operation [9]–[11]. To date, it has not been necessary for small PV generators to provide frequency-regulation services to the isolated utility. In the future, with an increasing penetration of PV generation, their impact upon the overall control of the power system will become significant [12]. This will lead a situation, where the PV generators will be required to share some of the duties, such as frequency control. Therefore, for the large penetration of PV system’s output power in the isolated utility, suitable measures must be applied to the PV system’s side.

Several studies have been carried out to minimize the harmful effects of connecting PV generators to the isolated utility. The most common practice is to use energy storage systems (ESSs) as smoothing devices for a PV system’s output [13]–[24].
However, the capital and maintenance costs of large capacity ESS is a barrier to the large-scale installation of PV systems. Besides, these methods cannot control PV output power considering the power utility condition like load variation. Therefore, they are not into providing any frequency control. All of these methods tried to smooth the fluctuating PV power. However, none of them gave emphasis on controlling the PV power according to the load variation and frequency deviations. Therefore, these methods had no sharing of the duties like frequency regulation.

Some approaches considering frequency control have been reported in [25]–[30]. A state of the art survey of load-frequency-control strategies could be found in [25]. Frequency regulation in an island power system by using a large battery energy storage is discussed in [26]. Here, the sole purpose of frequency control is dependent on the battery and no renewable source is connected with the island power system. In [27], two different methods for generation control in a small isolated power network are presented. The grid-voltage-control method has better performance with respect to the time needed for the system recovery after the load disturbance. The frequency-control method needs more time to bring the voltage back to its nominal values after a load disturbance. Then, it is suggested that battery storage is the possible solution to control load/generation balance. This study is almost same as the method described in [26] except the use of renewable sources. Frequency control in microgrid by using electrolyzer-fuel-cell system is proposed in [28]. Here, the electricity of the electrolyzer system is supplied mainly by the wind and PV powers, and the hydrogen produced by the electrolyzer system is stored in the hydrogen tank to be converted back to electricity in the fuel cells. Therefore, the output variation of renewable plants are not given to the power utility and fuel cells as storage devices are used for frequency control. This method is just a diversion to avoid the interaction of fluctuating renewable power with the utility. In [29], a control approach for a single-phase PV–diesel autonomous power system is proposed. It is claimed that the main advantages of this method are that the automatic voltage regulator (AVR) of the diesel-generator set is eliminated, the power loss of the diesel-generator set’s field circuit is minimized, and faster voltage control response is obtained. However, frequency control by PV generator considering load variation and insolation change is not considered and the feasibility of this method for three-phase system is not discussed. The study of load frequency control for a microgrid is presented in [30]. A load-power estimation method is used and based on the estimated load power, a load frequency control is developed by using an ESS. However, this method does not provide frequency control by the PV generator and uses the ESS to smooth the PV power fluctuation by borrowing power from the diesel generator.

In this paper, to introduce the frequency control by the PV generator, a new control method based on simple fuzzy logic is proposed for the PV–diesel hybrid system. This method uses fuzzy control to produce the output power command. Three inputs are considered for fuzzy control: frequency deviation of the isolated utility; average insolation; and change of insolation. The output power command of the system is decreased to response to a low frequency and is increased to response to a high frequency. First, the proposed method is compared with the conventional maximum power point (MPP) control considering two cases: with and without an ESS. Then, the proposed method is compared with the control method described in [30]. From the numerical results, it is found that the proposed method is effective in achieving the following key features: frequency regulation by the PV generator as it controls the PV power according to the frequency deviation; supplying the possible maximum amount of PV power to the isolated utility without reducing the reliability of the utility; and reduction of the capacity of the ESS.

This paper is organized as follows. Section II provides the system description and methodology. However, specialized topics, such as the optimal energy management and performance of an ESS or modern inverter technology is not discussed in detail in this section as the main focus of this paper is to provide frequency control by the PV generator. Section III describes the results and discussions. Conclusion is drawn in Section IV.

II. SYSTEM DESCRIPTION AND METHODOLOGY

The isolated power utility used in this paper is shown in Fig. 1. This is actually a parallel PV–diesel hybrid power system consisted of a diesel-generator set, a PV generator equipped with a MPP tracking (MPPT) control [31], an ESS, a bidirectional inverter, and ac load. In addition, it is assumed that the isolated power utility is not connected to any large power utility and it is always independently operated as a stand-alone system. The diesel generator supplies the load demand when no PV power/few PV power is available. An intelligent hybrid energy management system is developed combining the supervisory control described in [32] and the frequency control proposed in this paper.

The isolated power system model used for simulation is shown in Fig. 2, where $S_i$ is the insolation, $V_{gc}$ is the open-circuit voltage of the PV array, $I_{gc}$ is the short-circuit current of the PV array, $P_{max}^* \text{max}$ is the MPPT command power, $P_{max}$ is the MPPT output power, $P_{inv}$ is the command power of the bidirectional inverter, $P_{inv}$ is the output power of the bidirectional inverter, $P_{ESS}^*$ is the ESS command power, $P_{ESS}$ is the ESS output power, $P_{f}$ is the generated power by diesel-generator set, $R$ is the droop and $K_i$ is the integral control gain of speed governor, $T_{in}$ is the time constant of the valve actuator servomechanism, $T_d$ is the time constant of diesel engine, $M$ is the inertia constant and $D$ is the damping constant of the diesel-generator set, $\Delta f_r$ is the frequency deviation, $P_L$ is the ac load, and $P_{sys}$ is the PV–diesel hybrid system’s output power.

A. PV System Characteristic and Model

As the design of the power converter and control system is significantly influenced by the PV module characteristics, these will be briefly reviewed here. The PV module is a nonlinear device and can be represented as a current source model, as shown in Fig. 3. The traditional $I - V$ characteristics of a PV module, neglecting the internal series resistance, is given by the
Following [33]:

\[ I_o = N_p I_g - N_p I_{sat} \left( \exp \left( \frac{qV_o}{AKT_{mod}} \right) - 1 \right) - I_{rsh} \]  

where \( I_o \) and \( V_o \) are the output current and output voltage of the PV module, respectively, \( I_g \) is the generated current under a given insolation, \( I_{sat} \) is the reverse saturation current, \( q \) is the charge of an electron, \( K \) is the Boltzmann’s constant, \( A \) is the ideality factor, \( T_{mod} \) is the temperature (K) of the PV module, \( N_p \) is the number of cells in parallel, and \( I_{rsh} \) is the current due to intrinsic shunt resistance of the PV module.

The saturation current \( (I_{sat}) \) of the PV module varies with temperature according to the following [33]:

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

\[ I_g = I_{sc} \frac{S_i}{1000} + I_t (T_{mod} - T_r) \]  

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

The current due to the shunt resistance is given by

\[ I_{rsh} = \frac{V_o}{N_s R_{sh}} \]  

where \( N_s \) is the number of cells in series, and \( R_{sh} \) is the internal shunt resistance of the PV module.

For the PV module, (1)–(4) are used in the development of MATLAB/SIMULINK-based computer simulations. Fig. 4(a) and (b) shows the simulated ampere-volt and power-volt curves for the PV module. Here, the discrete data points shown are taken from the manufacturer’s data sheet [34] for validating the model.
Fig. 4. PV module characteristic curves. (a) Current–voltage curves. (b) Power–voltage curves. The discrete data points shown are taken from the manufacturer’s curves [34], and show excellent correspondence with the model.

From these curves, it is observed that the output characteristics of the PV array are nonlinear and are vitally affected by the variation of insolation.

B. Diesel Generator Model

In Fig. 5, the standard model of the diesel generator and speed governor is illustrated in block diagram form. This model is widely used and describes well the dynamic behavior of small diesel-generator sets, as it has been shown in [35]. The diesel engine and the valve actuator servomechanism are represented by first-order lags, with time constants $T_d$ and $T_{int}$, respectively. Parameters of the speed governor are the droop $R$ and the integral control gain $K_i$. The objective of the integral control is to eliminate the steady-state frequency error and in many cases (particularly in small and older units) may be absent. The actuator position limiter is ignored in the frequency domain analysis, where linearized models are used. Input to the model is the load demand $P_L$, i.e., the output power of the electrical generator. Output is the generator speed $\omega_d$, which is equal (in per unit) to the electrical frequency of the system $\omega$. The derivation of the model equations is a straightforward and rather trivial procedure, and for this reason it is omitted.

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C. ESS Model

ESS is an important component in the hybrid system. However, it also adds major cost to the system. In the hybrid system, batteries are used as an energy buffer. This buffer is necessary because PV output is not consistently available due to a variety of factors, such as, the weather and the time of the day. Most hybrid systems use the batteries for meeting the mismatch in power between the renewable sources and the loads. However, this research does not use a battery for meeting the power mismatch.

The designing of a battery bank model involves modeling of associated parameters such as capacity, voltage, and state of charge (SOC). Based on these parameters, associated variable such as battery gassing current loss is also modeled. The battery model developed in [36] is used in this research. The basic block diagram of the battery bank model is given in Fig. 6, where $I_{BB}$ is the external battery current (A), $I_{GA}$ is the battery gassing current (A), $C_B$ is the actual battery capacity (Ah), and $V_{BB}$ is the voltage of battery bank (V).

The battery is simulated as a voltage source in series with internal resistance. The actual battery capacity is used to calculate SOC. In addition, the battery model also takes into account the losses incurred due to gasification at high voltages and temperatures, and its effects on the capacity through battery gassing current loss model.

Battery model has been divided into the following components [36]:

1) gassing current model;
2) capacity model;
3) voltage model;
4) SOC model.

The details of these models could be found in [36]. The level of discharge of battery determines the life of the battery. Therefore, it is important to monitor the SOC and control charging/
discharging cycle of the battery. The intelligent control in Fig. 1, includes this important factor.

With maximum battery voltage never exceeding the dc bus voltage, a bidirectional half-bridge dc/dc converter is used, which operated in boost mode when discharging and buck mode when charging the battery. The buck–boost converter control topology is adopted from [37] and shown in Fig. 7.

### D. Bidirectional Inverter Model

The inverter is bidirectional, i.e., it not only can supply ac power to the load, but also can charge the battery by rectifying the surplus power when the total supply power exceeds the load power. The bidirectional inverter is modeled by calculating the power conversion losses in dependence of the inverter ac power, where the inverter dc power is expressed as follows:

$$P_{\text{INV,DC}} = P_{\text{INV,AC}} + P_{\text{INV,LOSS}}. \tag{5}$$

For operation of the bidirectional inverter in rectifier mode, both the inverter dc and ac powers are negative, indicating a change of the directional power flow. The inverter loss consists of dynamic power conversion loss $P_{\text{LOSS, dyn}}$ and fixed losses. The dynamic $I^2R$ losses of the inverter can be presented by internal ac resistance, which considers the switching and interconnection losses within the power-conversion device.

### E. Fuzzy Logic Controller Design

Fuzzy logic has been used for decades in the fields of renewable energy [28], [38]–[45]. The main purpose of this research is to develop a frequency-control strategy by using the PV generator. Therefore, no new fuzzy logic development is presented here, rather a simple active power control according to the load and isolation variations is presented by using the fuzzy logic.

In order to control the output power of PV system considering the power utility and isolation conditions, output power command $P_{\text{inv}}$ is generated by the output power command generation system shown in Fig. 8. This command system consists mainly of two fuzzy reasonings. Fuzzy reasoning is described by a set of “if-then”-based fuzzy rules. Fuzzy reasoning is effective when mathematical expressions are difficult by inherent complexity, nonlinearity, or unclarity. Therefore, no deterministic model is required.

First, fuzzy reasoning I is explained. There are two inputs of fuzzy reasoning I. One is frequency deviation $\Delta f$, and the other is average insolation $\bar{S}_i$. Average insolation $\bar{S}_i$ is defined by

$$\bar{S}_i = \frac{1}{T} \int_{t-T}^{t} S_i \, dt \tag{6}$$

where $t$ is the present time, $T$ is the integral interval, and $S_i$ is the instantaneous insolation of PV system. Fuzzy rules and membership functions of fuzzy reasoning I are shown in Table I and Fig. 9, respectively. Here, the power control of the PV system according to the power system condition is accomplished by using frequency deviation $\Delta f$ as the input of the fuzzy reasoning. Fuzzy rules and membership functions that yield an output to reduce the frequency deviation are defined by trial and error. The $i$th fuzzy rule is expressed as follows:

$$\text{Rule } i: \text{ if } \Delta f_x \text{ is } L_x \text{ and } \bar{S}_i \text{ is } M_y \text{ then, } \gamma_i \text{ is } Z_l \tag{7}$$

with $x = 1, 2, \ldots, 7$, $y = 1, 2, \ldots, 7$, and $l = 1, 2, \ldots, 7$. 

![Fig. 7. Buck–boost converter control topology for battery.](image)

![Fig. 8. Output power command generation system.](image)

![Fig. 9. Membership functions of fuzzy reasoning I.](image)
Fig. 10. Membership functions of fuzzy reasoning II.

where \( L_x \), \( M_y \) denote the antecedents and \( Z_i \) are the consequent parts. Fuzzy reasoning \( \gamma_1 \) is calculated by

\[
\gamma_1 = \frac{\sum_{i=1}^{49} w_i Z_i}{\sum_{i=1}^{49} w_i} \tag{8}
\]

where \( w_i \) denotes the grade for the antecedent and is obtained by

\[
w_i = w_{\Delta f_i} w_{S_{i}} \tag{9}
\]

where \( w_{\Delta f_i} \) and \( w_{S_{i}} \) are the grade of antecedents for each rule.

Second, fuzzy reasoning II is explained. Frequency deviation \( \Delta f \) and the change of insolation \( \Delta S_i \) are used as inputs of fuzzy reasoning II, where \( \Delta S_i \) is expressed as follows:

\[
\Delta S_i = S_i(t-1) - S_i(t) \tag{10}
\]

Power command that depends on the power system condition rather than the insolation condition is decided by using the frequency deviation \( \Delta f \) as input for both of the fuzzy reasonings. In addition, the change of insolation \( \Delta S_i \) is used as one of the inputs since the objective is to decrease the frequency deviation. Fuzzy rules and membership functions of fuzzy reasoning II are shown in Table II and Fig. 10, respectively. Setup of fuzzy rules and parameters of membership functions are determined to prevent the increase of frequency deviation. The \( o \)th fuzzy rule is expressed as follows:

\[
\text{Rule } \text{o: if } \Delta f_c \text{ is } H_c \text{ and } \Delta S_i \text{ is } L_z
\]

\[
\text{then, } \gamma_{II} \text{ is } Q_h \tag{11}
\]

\( c = 1, 2, \ldots, 7, z = 1, 2, \ldots, 7, \ h = 1, 2, \ldots, 7 \)

where \( H_c, I_z \) denote the antecedents and \( Q_h \) is the consequent parts. Fuzzy reasoning \( \gamma_{II} \) is defined by

\[
\gamma_{II} = \frac{\sum_{o=1}^{49} w_o Q_h}{\sum_{o=1}^{49} w_o} \tag{12}
\]

where \( w_o \) denotes the grade for the antecedent and is obtained by

\[
w_o = w_{\Delta f_o} w_{\Delta S_{o}} \tag{13}
\]

where \( w_{\Delta f_o} \) and \( w_{\Delta S_{o}} \) are the grade of antecedents for each rule.

The fuzzy rules and membership functions presented in fuzzy reasonings I and II are defined by trial and error. However, it is possible to tune the parameters of the controllers and membership functions of the fuzzy reasonings to achieve the maximum PV power and frequency control. A variety of methods have been proposed for tuning the fuzzy controller such as self-tuning algorithm based on an experimental planning method [46], in which the scaling factors of optimal parameters can be determined efficiently according to the desired performance indexes, Taguchi tuning method [47], and tuning the membership functions [48], [49]. Most of these methods need performance index. Two performance indexes can be formulated based on the frequency deviation (tends to zero) and the maximum PV power (tends to maximum). It will be easy to define performance indexes if the insolation and temperature are predicted one hour ahead.

The sum of the outputs of fuzzy control I \( \gamma_f \) and fuzzy control II \( \gamma_{II} \) become the central power command by using the following:

\[
P_{\text{inv}}^* = P_{\text{rated}} \left\{ \gamma(k) + \frac{\gamma(k+1) - \gamma(k)}{T_s} f(t) \right\} \tag{14}
\]

where \( P_{\text{rated}} \) is the rated power of the PV system, \( T_s \) is the sampling time, and \( f(t) \) is a periodic function such as \( f(t) = t \) (\( 0 < t < T_s \)).

F. ESS Control Strategy

The ESS power command, \( P_{\text{ESS}}^* \) for charging, discharging, and neutral modes can be expressed as follows:

(Charging mode, if \( P_{\text{max}} > P_{\text{inv}}^* \))

\[
P_{\text{ESS}}^* = P_{\text{max}} - P_{\text{inv}}^* \tag{15}
\]

(Discharging mode, if \( P_{\text{max}} < P_{\text{inv}}^* \))

\[
P_{\text{ESS}}^* = P_{\text{inv}}^* - P_{\text{max}} \tag{16}
\]

(Neutral mode, if \( P_{\text{max}} = P_{\text{inv}}^* \))

\[
P_{\text{ESS}}^* = 0. \tag{17}
\]

III. RESULTS AND DISCUSSIONS

In this paper, effectiveness of the proposed method to provide frequency regulation is examined by simulation with the system model and parameters mentioned in [50]–[55]. In order to use the parameters of practical large PV system given in [53] and [54], the rated output power of the PV array is 225 kW. Simulation parameters of the power utility, the PV array, the
TABLE III
SIMULATION PARAMETERS

power conversion system, and the diesel generator are shown in Table III. Here, the integral time $T$ is 100 s, and the sampling time $T_s$ to obtain discrete value of output power command is 10 s. The total simulation time is 30 min. Actual insolation and load data of a summer day of Miyako island [53]–[55], Okinawa, Japan, are used for simulation. Insolation data are collected from The Japan Weather Association (JWA) [56] and load data are collected from The Okinawa Electric Power Company, Incorporated (OEPC) [57]. Insolation and load data of Miyako island of a summer day are shown in Fig. 11. A 30-min sample data of the daily insolation, load, and change of insolation are shown in Fig. 12.

A. Frequency Control Performance Without an ESS

As an ESS is used with the proposed method, a question can arise whether the PV generator alone can provide frequency control or not. To justify frequency control by the PV generator (without an ESS), Figs. 2 and 8 are modified to Figs. 13 and 14, respectively.

Fig. 11. Insolation and load data of a summer day of Miyako island. (a) Daily insolation. (b) Daily load.

Fig. 12. Thirty-minute sample of insolation, load, and change of insolation. (a) Insolation and average insolation. (b) Load. (c) Change of insolation.

The comparative simulation results of the MPPT control [58] and the proposed method (without an ESS) are shown in Fig. 15. Here, the results obtained by the proposed control (without an ESS) are shown by the solid line, and the results obtained by the MPPT control are shown by the dotted line. Fig. 15(a) shows the PV power produced by the MPPT control and the proposed method (without an ESS). From Fig. 15(a), it is observed that the proposed method produces PV power near the MPPT-controlled PV power level and the power produced by the proposed method is controlled according to the load variation to minimize the
frequency deviations. Fig. 15(b) shows the amount of diesel power needed for the system with the proposed control (without an ESS) and the MPPT control. From Fig. 15(b), it is seen that the diesel power needed with the proposed method fluctuates less than the diesel power needed with the MPPT control. Fig. 15(c) shows the frequency deviations, where frequency deviations produced by the MPPT control are ±0.3 Hz at maximum time. On the other hand, frequency deviations produced by the proposed method (without an ESS) are almost zero. Therefore, it can be said that the proposed method can provide frequency control without the help of an ESS.

B. Frequency Control Performance With an ESS

The comparative simulation results of the MPPT control [58] and the proposed method are shown in Fig. 16. Here, the results obtained by the proposed control are shown by the solid line and the results obtained by the MPPT control are shown by the dotted line. Fig. 16(a) shows the PV power produced by the MPPT control and the proposed control. From Fig. 16(a), it is observed that the power produced by the proposed control is more fluctuating than the MPPT power and sometimes is bigger than the MPPT power. Fig. 16(b) shows diesel power needed for the system with the proposed control and the MPPT control. From Fig. 16(b), it is seen that the diesel power produced with the proposed method fluctuates less. As the diesel generator’s response is slow, less fluctuating diesel power is good for practical system operation. Fig. 16(c) shows the frequency deviations, where frequency deviations produced by the MPPT control are ±0.3 Hz at maximum time. On the other hand, frequency deviations produced by the proposed method are almost zero. Therefore, it can be said that the proposed method is effective in reducing frequency deviations of the isolated power system. Fig. 16(d) shows the charging and discharging powers of the ESS. Here, positive power means charging and negative power means discharging.

The outputs of fuzzy reasoning are shown in Fig. 17. From Fig. 17, it is seen that the outputs of the fuzzy reasonings I and II are controlled according to their inputs shown in Fig. 12.

The comparative simulation results using 8-h sample data of daily insolation and load are shown in Fig. 18 for the method described in [30] and for the proposed method, respectively. From Fig. 18(e), it is seen that frequency-control performance of the proposed method is superior to the method described in [30]. From Fig. 18(f), it is observed that the charging/discharging power required for the proposed method is smaller than the method described in [30]. Therefore, the inverter/converter required for the proposed method will be of small size as the charging/discharging power required at an instant is smaller than that of the method given in [30]. Therefore, by using the proposed method, the system cost can be reduced. From Fig. 18(c), it is seen that the PV power supplied by the proposed method is not smooth and it is fluctuating to provide frequency control like a generator in power system. From Fig. 18(d), it is seen that diesel-generated power with the proposed method is smoother than the method described in [30].

C. Feasibility Analysis

During the nighttime, PV power will not be available; therefore, the diesel generator must regulate the power quality of
the isolated power utility system. However, during the daytime, when the diesel generator in conjunction with the PV generator supplies the load, diesel generator alone cannot regulate the frequency deviations because PV output power has fluctuating nature as the insolation varies quickly with time. Moreover, PV power is not controlled according to the load variation. The frequency deviations produced, when only the diesel generator supplies the load and the frequency deviation produced when the diesel generator and the MPPT-controlled PV generator supply the load, are compared in Fig. 19. It has been seen that when only the diesel generator supplies the load, the frequency deviations are within the permissible limit of ±0.2 Hz. On the other hand, when the diesel generator and the MPPT-controlled PV generator supply the load, the frequency deviations are not within the permissible limit of ±0.2 Hz. Therefore, the proposed method is practical considering this problem of frequency deviations.

CO₂ emission. Fig. 20 shows the average and the instantaneous power losses caused by the proposed method (without an ESS) comparing with the MPPT control. In order to control the PV output power according to the load variation by the proposed method (without an ESS), about 8% of the average PV power reduction is noticed. This must be stopped. The proposed method tries to increase or decrease the supplied PV power, \( P_{pv} \), according to load variation. However, loading of PV generator is limited by its MPPT-controlled power. Therefore, if an ESS is used with the proposed method, the loading limit of the PV generator can be increased. When the PV generator is deloading, the power difference between the MPPT-controlled PV power and the command PV power can be used to charge the ESS. This ESS power later can be used to increase the loading limit of PV generator by adding it with the MPPT-controlled PV power. Therefore, the MPPT-controlled PV power is supplied to the dc bus (as shown in Fig. 2), and according to the loading or deloading command of the bidirectional PV inverter, the ESS is discharged or charged. Thereby, full MPPT-controlled PV power is used by the help of an ESS to increase the loading limit of PV generator, which in turn will decrease the use of diesel power and CO₂ emission.

Usually, PV generators connected to an isolated power system or microgrids are equipped with an ESS and an MPPT device [59]–[62]. The ESS is charged by the maximum PV power, and the stored energy is supplied to the load at night [54]. Therefore, the power loss caused by the proposed method (without an ESS) is avoided by using a small capacity ESS, for example: lead-acid battery [63], as the charging/discharging power required for the
The frequency delivered to the consumer must not vary from the declared value by more than ±1% [64] in accordance with the Electricity supply regulation. The system frequency of Okinawa Electric Power Network, Okinawa, Japan, is maintained within the range of 59.8–60.2 Hz under normal condition in order to meet the statutory requirements specified by the grid code. In order to provide frequency response (FR), PV generators must be able to increase or decrease their output with system frequency changes [65].

When the PV generator is working without an ESS, to respond to a low frequency, PV generators must be deloaded to leave a margin for power increase. To respond to a high frequency, PV generators must be loaded. If the operating point of the PV generators can be changed so as to operate it off the MPP, then deloading and loading can be achieved. Deloading and loading of PV generator with MPPT are sometimes challenging. Two-stage MPPT searches the MPP in \( I - P \) curve by following a concept of an equivalent resistance \( R_{pm} \) proportional to the ratio of the open-circuit voltage \( V_{oc} \) to the short-circuit current \( I_{sc} \) (\( R_{pm} = K \times V_{oc} / I_{sc} \), \( K \) constant). This makes the deloading or loading of the PV generator as a fraction of the maximum power a difficult task.

To overcome this problem, the controller of the PV generator is designed to have two separate control modes: the MPPT and FR modes. The PV generator will alternate between the two modes to be able to track changes in operating condition. In MPPT mode, the PV generator searches for the MPP using the two-stage MPPT algorithm. The operating point of the PV system will move to the vicinity of the real peak power point on the load line \( R_{pm} \) at this mode. Once the peak power point is known, it is then possible for the PV generator to be deloaded from loaded condition or to be loaded from deloaded condition in the FR mode, according to the load variation. However, since no ESS is used with the system, loading is limited to the peak
PV power, and power loss is occurred during de-loading as peak PV power is not supplied during de-loading. Therefore, an ESS is used with the proposed method. Available MPPT-controlled PV power is always supplied to the dc bus (shown in Fig. 2), and according to the loading or de-loading command of bidirectional PV inverter, the ESS is discharged or charged, which in turn helps to prevent PV power loss and increases the loading limit of PV inverter.

**D. Cost Analysis**

Cost analysis [66]-[70] is performed for two cases using the Miyako Island model [53]-[55] and 24-h time period. The two cases studied include: 1) PV generator (MPPT control) with diesel-battery system [30]; and 2) PV generator (proposed control) with diesel-battery system. Table IV shows the costs of the different components installed at Miyako Island for the two cases. The cost of the different components are obtained from the various manufacturers. The engineering cost, commissioning, installation, freight, etc., are obtained from the Okinawa Electric Power Company [57].

Knowing the efficiency and the load on the electric generator, the power input to the generator can be calculated as follow:

\[ P_{\text{input}} = \frac{P_l}{\eta} \]  

(18)

where \( P_l \) is the load on the diesel generator. It is assumed that the diesel generator is always operating at 95% of their kW rating while operating in conjunction with the battery bank and the PV generator.

The fuel consumed by the engine depends on the load, and the electrical efficiency is dependent on the displacement power factor of the load. The plot for the fuel consumption obtained from the manufacturer’s data sheet can be mathematically interpreted as follows:

\[ F_C(\text{Lbs}) = 0.5 \ast P_{\text{input}} + 0.5 \]  

(19)

\[ F_C(\text{gallons}) = \frac{\text{Fuel consumed (Lbs)}}{7.1} \]  

(20)

where \( P_{\text{input}} \) is the input to the diesel generator given in kW; 7.1 is the factor that converts pounds to gallons depending on the type of fuel that is used.

The parameters such as the total kWh/gallon supplied by the generator and the total cost of fuel (US$) are given as follows:

\[ \text{kWh/gallon} = \frac{\text{kWh}_{\text{Gen}}}{F_C} \]  

(21)

\[ \text{Total cost (US$)} = F_C \ast \text{cost/gallon} \]  

(22)

where \( \text{kWh}_{\text{Gen}} \) is the total kWh supplied by the diesel generator and \( F_C \) is the total fuel consumed (gallons).

Table V shows the results for the two cases. From Table IV, it has been seen that the system cost of PV–diesel-battery system (proposed method) is less than the system cost of PV–diesel-battery system (MPPT control) [30]. Also, from Table V, it is seen that the PV–diesel-battery system (MPPT control) [30] needs more fuel, i.e., it will increase CO\(_2\) emission compared to the proposed method. From Table V and Fig. 18(f), it can be said that as the charging/discharging power and kWh capacity required for the ESS used with the proposed method are smaller than that of the PV–diesel-battery system (MPPT control) [30], the proposed method incurs less system cost.

**IV. CONCLUSION**

This paper presents a fuzzy-based frequency-control method for the isolated utility-connected large PV–diesel hybrid system considering power system condition and insolation condition. Here, output power command is defined by fuzzy reasoning that has three inputs of frequency deviation, average insolation, and change of insolation. Setup of fuzzy rules and parameters of membership functions are determined by prioritizing to prevent increase of frequency deviation. From the numerical simulation results, it has been found that the proposed method is effective in reducing the frequency deviations significantly in comparison with the MPPT control. Besides, it has better performance than the conventional ESS-based method considering the frequency control and system cost, and it produces power near the
maximum PV power level. The current practice to reduce frequency deviations is the smoothing of PV output power fluctuations. However, proposed method shows a new and simple frequency-control method without smoothing of PV power fluctuations. Therefore, it can be said that the proposed method can be used to share the duties like frequency control if the PV–diesel hybrid system is connected as a distributed source with the power grid.

ACKNOWLEDGMENT

The authors would like to thank the reviewers for their valuable comments.

REFERENCES


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