Stabilizing solar farm power output by micro gas turbine integration: Emission performance

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Abstract. Worldwide growth of Photovoltaics (PV) technology has been close to exponential rate in the past decades. However, the increase of power generation by PV imposes new challenges on the existing electrical grid due to the unpredictability of PV power output that depends mainly on solar irradiance. One of the solutions to stabilize solar farm power output fluctuation by hybridizing Micro Gas Turbines (MGTs) that is controlled to meet the total power production target. Thus, the objective of this paper is to investigate the effect of different operation strategies on the environmental performance on MGT integrated solar farm. Different operation strategies for MGT integrated solar farm have been implemented to constantly produce a total power output of 800 kW throughout the year. The three strategies then compared by analysing emission produced by MGTs. A simulation was conducted in Simulink environment using real ambient temperature and global sun irradiance data. It was found that Operation Strategy 3 reduced carbon dioxide (CO₂) by 13.8%, nitrogen oxides (NOx) emission by 3.2%, and carbon monoxide (CO) by 97.9%. This shows that the proposed strategy could stabilize the total power output of the solar farm at minimum emission level.

1. Introduction

Fossil fuels including coal, oil and natural gas are the primary energy sources [1]. Yet the steady increment of energy consumption is always coupled with pollution and climate change that could harm human life and the environment [2]. Fortunately, renewable energy specially PV power generation could provide an alternative [3]. PV power generation noticed significant growth in recent years. However, PV penetration to the grid could causes various impacts to electrical grid systems [4]. Large-scale growth of PV causes concerns in keeping supply-and-demand balance as the power output of PV shows considerable fluctuations due to weather conditions. One of the current issues reported by CAISO is the well-known “Duck Curve,” which represents the net load on the grid (e.g., total demand minus wind and solar generation) [5]. The duck curve illustrates two areas of concern. First is the possibility of excess generation in the middle of the day due to the inability of the thermal fleet to integrate a large amount in the solar generation, resulting in solar
generation being curtailed and over-generation. The second area of concern is the need for resources to ramp up quickly enough to meet the evening peak.

Different solutions have been considered by researchers such as employing various storage technologies, batteries, electric capacitors and fuel cells [6]. The cost of energy storage systems remains the major challenge besides the sizing problems [7, 8]. Furthermore, methods like control strategies based on moving average, low pass filters and ramp rate limitation have also been proposed for mitigating PV power output fluctuation [7, 9–11]. The main drawback with the control strategies-based on low pass filter and the moving average is that they lag PV power output and therefore would not provide the same level of smoothing as the ramp rate limiting methods.

Although several studies have been conducted to study the impact of solar farm power quality delivered to the grid and ways to minimize it, there is a lack of studies on the performance of hybridizing a PV with MGT to keep the total power output of the plant constant. Concerns on using hybrid system using MGT is the lack of studies on hybridizing PV with MGT using new concept operation strategies that could solve the problem of power output fluctuation. The impact on the grid due to the unpredictable changes of weather which in return reduces PV overall efficiency. Besides, MGT performance depends on the load factor. It is well known that when MGT operates at partial loads negatively affects efficiency while emission and fuel consumption increase. Therefore, a new method is proposed and simulated to stabilize PV power output fluctuation. Thus, the objective is to investigate the effect of different operation strategies on the environmental performance of MGT integrated solar farm.

2. Materials and methods

Environmental data has been collected from a workstation at district of Pekan, Malaysia. Sun irradiance $I_G$ and ambient temperature $T_{amb}$ [12]. Data were collected for one year. The simulation of the system is conducted based on the real profile of environmental data. The system components are selected based on the capacity of the plant objective as it must produce constant output of 800 kWh throughout the year. That is achieved by 5 MGT units and 3080 PV modules. The overall system is demonstrated as shown in figure 1.

![Figure 1. Overall system.](image-url)
2.1. PV system modelling

Sizing and modulation of the solar farm is based on methods proposed by [12–14]. The model basically requires two inputs which are the $T_{\text{amb}}$ and $I_{G}$. Based on the hourly inputs, the model calculates the amount of energy generated by the PV module, $E_{PV}$ [kWh] as the output in that hour. Table 1 presents technical data of chosen PV module and matched inverter during sizing process.

Table 1. PV and inverter specifications.

| Inverter Input (DC) | Value                  | PV Parameter        | Value |
|---------------------|------------------------|---------------------|-------|
| Type designation    | PVS800-57-1000kW-C     | Peak power ($P_{\text{max}}$) | 315 W |
| DC voltage range, mpp ($U_{\text{DC, mpp}}$) | 600 to 850 V | Rated voltage ($V_{\text{mpp}}$) | 54.7 V |
| Maximum DC voltage ($U_{\text{max (DC)}}$) | 1100 V | Rated current ($I_{\text{mp}}$) | 5.76 A |
| Maximum DC current ($I_{\text{max (DC)}}$) | 1710 A | Open circuit voltage ($V_{oc}$) | 64.6 V |
| Efficiency          | 98.8%                  | Maximum system voltage ($U_{L}$) | 600   |

2.2. MGT modelling

The mathematical model of MGT units was developed based on the C-200 micro turbine model manufactured by Capstone Turbine Cooperation [15,16]. A 200 kW MGT unit was chosen based on the availability of commercial models and demand need. The performances are reported at ISO conditions, by definition, it is at standard sea level pressure of 101.325 kPa, 15 °C of $T_{\text{amb}}$ and at 60% of relative humidity. As shown in table 2, at the rated power output, $E_{\text{MGT,FL}}$ which is 200 kW, the MGT unit can achieve electrical efficiency, $\eta_{\text{MGT,FL}}$ up to 33%.

Table 2. Capstone Turbine specifications.

| Parameter                          | Value       |
|------------------------------------|-------------|
| Net power output                   | 200(0/-4) kW |
| Net efficiency (LHV)               | 33(0/-2) %  |
| Nominal steady fuel flow (HHV)     | 2400000 kJ/hr |

To mathematically model the MGT unit, the method formulated by [13] was implemented. The modelling method are analogy to the backward facing quasi-static approach in which the actual input of the MGT unit were treated as outputs. As shown, the inputs of the model were $T_{\text{amb}}$ and $LF$ respectively, while, the output of the model were power output, $E_{\text{MGT,FL}}$, fuel energy consumption, $Q_{fuel, MGT}$, exhaust temperature, $T_{Ex}$, and the exhaust mass flow rate, $\dot{m}_{Ex}$. The data on $T_{\text{amb}}$ were used as input parameters to calculate the temperature derating of the output parameters at full load operation.

2.3. Operation strategies

The three operation strategies had the same set up of equipment, and therefore only the method of operation is elaborated. All operation strategies controlled MGT units on desired LF in order to keep the total power output of the plant constant through the year at 800 kW. Figures shown below are example cases when solar farm generates 300 kW. Figure 2 (a)-(c) illustrates MGT unit’s interaction in each operation strategy. Strategy 1 keeps the plant total output at 800 kW by subtracting the power produced by PV plant from the 800 kW to get the amount of power (kW) needed to be generated by MGT units. The needed value then is divided equally into 5 MGT units. Thus, all MGT units will run at the same LF at all cases.

Figure 2(b) shows strategy 2 with all units operate sequentially. MGT 1 will operate in the full load, once the demand is higher than the MGT capacity, the MGT 2 will on the operation. In strategy 3, MGT performance and efficiency were taken into consideration. As high LF ensure that MGT will require less
fuel ration and low emission, the aim of this control strategy is to either keep the MGT units operating at LF larger than 0.6 all the time, or 0 which is off. The strategy operates the units according to PV output by dividing the needed power by the max number of MGT units that can operate it by considering LF larger than 0.6. The strategy is shown in figure 2(c).
2.4. Environmental analysis
To evaluate emission performances of the hybrid system under each of the strategies, the Emission Reduction Index (ERI) analysis was utilized as a benchmark. The ERI is an indicator that reflects the amount of emission reduction that can be achieved by the hybrid system as compared to the conventional system. The type of emissions acknowledge in the ERI analysis were narrowed down to only CO\textsubscript{2}, NO\textsubscript{x} as well as the CO emission. In the case of MGT, the Emission Factor (EF) were calculated based on [15] and [16] method using EF. The calculated EF of the MGT unit were then substituted into equation 1 to obtain the total amount of CO\textsubscript{2}, NO\textsubscript{x} and CO emission produced were $n$ is type of emission

$$E_n = EF_n \times (P_{net})$$ (1)

3. Results and discussion
Figure 3 shows operation of the plant delivering constant power output of 800 kWh to grid on a randomly chosen day. As PV generation increases, MGTs generation will decrease to meet the total power output of 800 kWh throughout the day. MGTs are running according to the solar farm generation with respect to demand.

3.1. Environmental performances
Emission Reduction Index was used to obtain the total amount of CO\textsubscript{2}, NO\textsubscript{x} and CO emission produced by each MGT unit under all strategies. Figure 4 presents CO\textsubscript{2} emitted by MGT. The values are closely equal where that is justified by the equal levels of MGT Emission factor for CO\textsubscript{2} while running at partial loads.

NO\textsubscript{x} emission as show in figure 5 was expected to be at nearly equal ranges for all MGT units using all strategies because the emission factor value was very low. Operating MGT at partial loads do not affect the amount of NO\textsubscript{x} as compared to CO2 that has higher emission factor at lower LF.
Figure 3. Condition of all MGTs with PV output when controlled by any of the three strategies.

Figure 4. CO$_2$ emission by the three operation strategies.

Figure 5. NO$_x$ emission by the three operation strategies.
Figure 6 shows that the highest MGT units in emitting CO was in Strategy 1. This is because the continuous occurrence of LF that lays between LF ranges from 0 to 0.4. The first four units in strategy 2 emitted 1,219.2 kg of CO, were MGT5 alone emitted 1,523.45 kg of CO, and this is because the low LF that MGT5 was operated at, in which the first four MGT were capable of satisfying the demand for 84% of the time, and MGT5 was operated only when the surrounding temperature reduced the performance of MGT 1, MGT 2, MGT 3 and MGT 4. The maximum LF recorded for MGT 5 was 0.32. Strategy 3 was expected to emit the lowest CO emission as the algorithm keeps MGT running at high LF.

4. Conclusion
The hybrid MGT-PV solution succeed in stabilizing power output fluctuation throughout the year at constant power output. It was found that different operation strategies had different emission levels. Operation Strategy 3 was chosen to be the optimum way for operating the plant because it has the lowest levels of CO₂, CO and NOₓ emission. Therefore, operating MGTs at the highest LF possible as in Operation strategy 3 was the key of emitting the least emission percentages in result. Further studies should be conducted to reduce percentage of MGT emission production at higher levels.

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