Cost Assessment of Deloaded Photovoltaic Systems

Pankaj Verma¹, Tarlochan Kaur² and Raminder Kaur³

¹, ², ³ Electrical Engineering Department, Punjab Engineering College (Deemed to be University), Sector 12, Chandigarh, 160012

¹ bluepankaj123@gmail.com, ² tarlochan.kaur@gmail.com, ³ raminder84@gmail.com

Abstract. The maximum power point operation of the photovoltaics (PV) restricts them to participate in the frequency regulation of the connected system. Therefore, it is a common practice to deload the PV systems for generating an active power reserve. However, the deloading causes underrating of these systems, hence additional PV panels are installed to overcome the reserved power. Since the frequency regulations can be achieved by using batteries, hence in this paper, the generation cost of a six bus system is minimized by operating PV generator and batteries in coordination with the synchronous generators. The cost curves obtained by operating PV generator with synchronous generators, and batteries with synchronous generators are compared to justify the deloaded operation of PVs. The cost function minimizations are conducted by using the CVX toolbox in the MATLAB software.

1. Introduction
If we look back around twenty to twenty-five years from the present date, most of the electrical power generation was from thermal power plants, hydropower plants, and nuclear power plants. These generating stations use the synchronous machines as alternators, which inherits the inertial capabilities because of their rotating structures. The area frequency control (AFC) systems installed in these power plants follows a sequence [1] to neutralize the change in the system frequency, where the machine inertia is the first respondent followed by primary control and the secondary control. Whereas, in both the primary and secondary controls, steam pressure/water discharge is adjusted to increase or decrease the alternator speed. However, the Photovoltaic units are static and lack the inertial capability. Moreover, their maximum power point (MPP) operation inhibits them to perform frequency regulation. Today, the global solar PV installed capacity has exceeded the 580 GW mark [2], with 114.9 GW installed in the year 2019. This high penetration of PV units in the power system may cause unwanted characteristics [3-7] in the power system like prolonged system oscillation, reduced system damping, speed fluctuations, lower system inertia, etc.

To enable the frequency regulation capability in PV systems, it is mandatory to operate these systems with some power reserve. To generate the power reserve, PVs are operated at a point away from the MPP, resulting in a deloading of the system. The deloading can be achieved by using certain modified or newly proposed deloading algorithms [8-10], or by using PI-based controllers [11-13], or by using artificial intelligence techniques [14-16]. Although, the deloaded operation of PVs succeed in generating a contingency reserve in the system, but on the other hand this operation reduces the output power of the PV system. As a result, the additional PV units are installed to achieve the rated power. Thus, there is a need to run a cost assessment of deloaded PV systems

As the battery integrated PV systems can perform the frequency regulation of a system [17-18], hence a comparison of generation cost of PVs and batteries operating in coordination with synchronous generators is carried out in this paper. Optimizations are used to minimize the total generation cost of a six bus system for three cases. Whereas, in the first case, only synchronous generators are used to meet the time-varying load demand. In the second case, the generators are operated in coordination with energy storage devices (batteries). And in the third case, the generators
are operated in coordination with the PVs. The optimization studies are carried out using CVX in the MATLAB software.

The structure of the paper is as follows. The six bus system is described in section 2. The generation cost-minimization analysis is conducted in section 3. Conclusions are presented in section 4.

2. System description

The optimization studies are conducted on a six bus system as shown in Figure 1. Three synchronous generators (G₁, G₂, and G₃) are connected on buses 1, 2, and 6. The generator's cost coefficients and power constraints are given in Table 1. The twenty-hour load data is given in Table 2 [19], the total load is assumed to be equally distributed at buses 4 and 5. Whereas, bus 3 is reserved for either connecting PV generator or battery storage. The maximum power of the PV generator is considered as 7.5 MW, and the capacity of the batteries is considered as 30 MWh. For the sake of simplification, the power flow limits are ignored in this study, and transmission losses are assumed to be 10% of the total load.

![Figure 1. Six bus system.](image)

| Unit   | Cost coefficients  | P<sub>max</sub> (MW) | P<sub>min</sub> (MW) | Ramp up/down cost ($/MW) |
|--------|---------------------|-----------------------|-----------------------|--------------------------|
| G₁     | a ($): 177          | b ($/MW): 13.5        | c ($/MW<sup>2</sup>): 0.00045 | 220                     | 100   | 10 |
| G₂     | a ($): 130          | b ($/MW): 40          | c ($/MW<sup>2</sup>): 0.001   | 100                     | 10    | 8  |
| G₃     | a ($): 137          | b ($/MW): 17.7        | c ($/MW<sup>2</sup>): 0.005   | 40                      | 10    | 13 |

| Hour  | Load (MW) | Load (MW) |
|-------|-----------|-----------|
| 1     | 165.4     | 10        |
| 2     | 156       | 11        |
| 3     | 150.8     | 12        |
| 4     | 145.6     | 13        |
| 5     | 145.6     | 14        |
| 6     | 150.8     | 15        |
| 7     | 166.4     | 16        |
| 8     | 197.6     | 17        |
| 9     | 226.2     | 18        |

3. Cost Minimization
The generation cost minimization for the six bus system (Fig. 1) is conducted for three different cases. In the first case, bus 3 is kept as idle and the load is supplied by the generators only. In the second case, battery storage is connected at bus 3. Finally, for the last case, the PV generator is connected at bus 3. A comparison of the generation cost for the three cases is presented at the last of this section. In this study, the PV generator and batteries are used only for providing the ancillary services (frequency regulation), hence, these are operated only during the peak load hours (from hour number 11 to 14).

3.1 Operation with only synchronous generators

In this operation, the generation cost of the synchronous generators is minimized for twenty hours. The cost minimization function is defined by equation (1).

\[
\sum_{t=1}^{T} \sum_{i=1}^{G_n} \left( a_i P_{gi}^t \right)^2 + b_i P_{gi}^t + c_i \right) + R_t \left| P_{gi}^t - P_{gi}^{t-1} \right|
\]

In this equation, \(a, b,\) and \(c\) are the quadratic, linear and constant cost coefficients respectively, \(G_n\) is the number of synchronous generators, \(T\) is the total load hours, \(P_{gi}\) is the generator power, and \(R_t\) is the ramp-up/down cost of the generator. The minimization function is subjected to generation limit (equation (2)) and power balance constrains (equation (3)). Whereas, the initial generator powers are assumed as zero (equation (4)).

\[
P_{g,i}^{min} \leq P_{g,i}^t \leq P_{g,i}^{max}
\]

\[
\left( \sum_{i=1}^{G_n} P_{g,i}^t \right) = P_{d}^t + P_{L}^t
\]

\[
P_{g,i}^0 = 0
\]

In equation (2), \(P_{g,i}^{min}\) and \(P_{g,i}^{max}\) are the generator minimum and maximum generation limits respectively. In equation (3), \(P_{d}\) is the total load power and \(P_{L}\) is the power lost in the transmission losses. For a particular load hour, the transmission losses are assumed to be 10% of the total load. For the first load hour (Table 2), the total load demand is 166.4 MW, thus, the power losses are assumed as 16.64 MW. The optimization results are shown in Figure 2 which shows the power generated by the three generators for different load hours.

![Figure 2. Optimized results of power generated by synchronous generators.](image)

3.2 Operation with synchronous generators and batteries
In this operation, the batteries are operated in coordination with the synchronous generators during the peak load hours (11–14). However, the batteries need charging, hence these are charged during the off-peak hours (2–5). The minimization function for this operation is given as

$$\sum_{t=1}^{T} \left( \sum_{i=1}^{G_{i}^{n}} \left( a_{i} P_{gi}^{t,2} + b_{i} P_{gi}^{t} + c_{i} \right) + R_{i} \left| P_{gi}^{t} - P_{gi}^{t-1} \right| \right) + C_{batt} P_{batt}^{t}$$

(5)

Whereas, $C_{batt}$ is the cost coefficient of batteries and $P_{batt}$ is the power supplied by the batteries. Although the batteries have high installation and operating costs, but these are assessed for a long period (usually years). Therefore, for the twenty-hour operation, the battery’s cost coefficient is kept as 1. A comparison of the installation cost of batteries and PV panels is reported in [11]. However, in this paper, the focus is to reduce the generation cost of a six bus system by using batteries or PVs. The generation limit constraint for the function is same as mentioned in section 3.1, whereas the power balance constraint changes as follows

$$\left( \sum_{i=1}^{G_{i}^{n}} P_{gi}^{t} \right) + P_{batt}^{t} = P_{d}^{t} + P_{L}^{t}$$

(6)

The batteries are operated with a power of 7.5 MW from 11th hour to 14th hour (Energy to power ratio of 4). The optimized power generated by the generators and the batteries is shown in Figure 3. For charging the batteries, the power is extracted from the generators, as a result the load on the system increases during the charging period. A comparison of system load profile with normal operation and operation with batteries is shown in Figure 3. For the operation with batteries, the load increases slightly during the off-peak hours.

![Figure 3. Optimized results of power generated by synchronous generators and batteries.](image)

### 3.3 Operation with synchronous generators and PV generators

The PV generators are operated in coordination with the synchronous generators in this operation. The PV generators are operated only during the peak load hours (11–14). Equation (7) represents the cost minimization function for this operation.

$$\sum_{t=1}^{T} \left( \sum_{i=1}^{G_{i}^{n}} \left( a_{i} P_{gi}^{t,2} + b_{i} P_{gi}^{t} + c_{i} \right) + R_{i} \left| P_{gi}^{t} - P_{gi}^{t-1} \right| \right) + C_{pv} P_{pv}^{t}$$

(7)

$C_{pv}$ is the cost coefficient of PV generator ($C_{pv} = 1$) and $P_{pv}$ is the PV power. The power balance constraint for the above function is given as

$$\left( \sum_{i=1}^{G_{i}^{n}} P_{gi}^{t} \right) + P_{pv}^{t} = P_{d}^{t} + P_{L}^{t}$$

(8)
Unlike batteries, the power generated by the PV generator depends upon the weather conditions. Thus, the power generated by the PVs may fall below the rated power value. For operation under standard conditions, the PV generator injects 7.5 MW for four hours (Fig. 4). However, this power may go down to 6 MW, 5 MW, or even 2 MW depending upon the weather conditions. The optimized result of power produced by the synchronous generators for different values of PV power is presented in Figure 4.

![Figure 4](image_url)

**Figure 4.** (a) Combined power generated by synchronous generators, and (b) Power generated by PV generator.

3.4 Cost Comparison

A comparison of the generation cost of the six bus system for twenty hours when operated with only synchronous generators, synchronous generators and batteries, and synchronous generators and PV generator is shown in Figure 5. For the operation of synchronous generators with PV generator (section 3.3), the generation cost varies with the power generated by the PV generator. As compared to batteries operation, a comparison of the net profit generated by PV generator operation is presented in Table 3. The net profit is highest when PVs operate at its rated power, however, it decreases with the decrease in power generated by PV generator. Overall, the operation with PV generator is beneficial until the power generated by PVs is above 5.9 MW (21.33 % decrease).
Figure 5. Comparison of generation cost for operation with synchronous generators, synchronous generators and batteries, and synchronous generators and PV generator.

Table 3. Cost comparison for different operations

| Operation          | Gen. Power (MW) | PV. Power (MW) | Battery Power (MW) | Cost ($)     | Net Profit compared to battery ($) |
|--------------------|-----------------|----------------|--------------------|--------------|-----------------------------------|
| Synchronous generator | 4696.6          | 0              | 0                  | 7.431e+07    | ___                               |
| Generator + Batteries | 4699.6          | 0              | 30                 | 7.3147e+07   | ___                               |
| Gen. + PV           | Power=7.5 MW    | 4666.6         | 30                 | 7.2844e+07   | 303000                            |
|                     | Power=6.5 MW    | 4670.6         | 26                 | 7.3035e+07   | 112000                            |
|                     | Power=6 MW      | 4672.6         | 24                 | 7.3131e+07   | 16000                             |
|                     | Power=5.9 MW    | 4673.0         | 23.6               | 7.3150e+07   | -3000                             |

4. Conclusions
The generation cost of a six bus system is minimized by operating PV generators and batteries in coordination with the synchronous generators during the peak load hours. The cost minimizations are carried for twenty-hour load profile. The highest generation cost is obtained when synchronous generators are operated without any support. A reduced generation cost is obtained when synchronous generators are operated with batteries. However, the lowest generation cost is obtained when synchronous generators are operated with PV generator (PV at Standard test conditions). As compared to operation with batteries, providing load support using the PV generator is beneficial until the power generated by the PV generator is above 21.33 % of its rated power value.

References
[1] Dreidy M, Mokhlis H and Mekhilef S 2017 Inertia response and frequency control techniques for renewable energy sources: A review Renew. Sustain. Energy Rev. 69 144-55.
[2] Global market outlook for solar power 2019-23 solar power Europe <http://www.solarpowereurope.org>.
[3] Eftekharnejad S, Vittal V, Heydt G.T, Keel B and Loehr J 2013 Impact of increased penetration of photovoltaic generation on power systems *IEEE Trans. on Power Syst.* **28** 893-01.

[4] Pethe A.S, Vittal V and Heydt G.T 2014 Evaluation and Mitigation of Power System Oscillations Arising from High Solar Penetration with Low Conventional Generation *Proc. of North American Power Symposium (NAPS)* Pullman WA USA 1-6.

[5] Hoballah A 2015 Power system dynamic behavior with large scale solar energy integration *Proc. of 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)* Sharjah UAE 1-6.

[6] Bueno P.G, Hernandez J.C and Rodriguez J.R 2016 Stability assessment for transmission systems with large utility-scale photovoltaic units *Renewable Power Generation* **10** 584-97.

[7] Remon D, Cantarellass A.M, Mauricio J.M and Rodriguez P 2017 Power system stability analysis under increasing penetration of photovoltaic power plants with synchronous power controllers *IET Renewable Power Generation* **11** 733-41.

[8] Watson L.D and Kimball J.W 2011 Frequency Regulation of a Microgrid Using Solar Power *Proc. of Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)* Fort Worth TX USA 321-26.

[9] Liu Y, Ying K, Lu Z, Xin H and Gan D 2012 A Newton quadratic interpolation based control strategy for photovoltaic system *Proc. of Int. Conf. Sustainable Power Gener. Supply* Hangzhou China 1-6.

[10] Sangwongwanich A, Yang Y and Blaabjerg F 2016 High Performance Constant Power Generation in Grid-Connected PV Systems *IEEE Trans on Power elect.* **31** 1822-25.

[11] Zarina P.P, Mishra S and Sekhar P.C 2014 Exploring frequency control capability of a PV system in a hybrid PV-rotating machine-without storage system *Int. Jour. Elect. Power Energy Sys.* **60** 258-67.

[12] Hosseinipour A and Hojabri H 2018 Virtual inertia control of PV systems for dynamic performance and damping enhancement of DC microgrids with constant power loads *IET Renew. Power Gener.* **12** 430-38.

[13] Nanou S.I, Papakonstantinou A.G and Papathanassiou S.A 2015 A generic model of two stage grid connected PV system with primary frequency response and inertia emulation *Electric Power Systems Research* **127** 186-96.

[14] Sekhar P.C and Mishra S 2016 Storage Free Smart Energy Management for Frequency Control in a Diesel-PV-Fuel Cell-Based Hybrid AC Microgrid *IEEE Trans. on Neural Networks and Learning Sys.* **27** 1657-71.

[15] Rajan R and Fernandez F.M 2019 Power control strategy of photovoltaic plants for frequency regulation in a hybrid power system *Elect. Power and Energy Sys.* **110** 171-83.

[16] Datta M, Senjyu T, Yona A, Funabashi T and Kim C.H 2011 A Frequency-Control Approach by Photovoltaic Generator in a PV–Diesel Hybrid Power System *IEEE Trans. on Energy conv.* **26** 559-71.

[17] Yi Z, Dong W and Etemadi A.H 2018 A Unified Control and Power Management Scheme for PV-Battery-Based Hybrid Microgrids for both Grid-Connected and Islanded Modes *IEEE trans. on Smart Grid* **9** 5975-85.

[18] Belila A, Benbouzid M, Berkouk E and Amirat Y 2018 On Energy Management Control of a PV-Diesel-ESS Based Microgrid in a Stand-Alone Context *Energies* **11** 2164.

[19] P.P. Zarina and Mishra S 2016 Cost benefit of Using Deloaded PV Instead of Battery *Proc. of IEEE Inter. Conf. on Power Electronics, Drives and Energy Systems (PEDES)* Trivandrum India 1-4.