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Solar Panel and Battery Sizing in Connected and Island Mode Distribution Systems

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Keywords

Battery sizing,
Photo Voltaic,
Distribution system,
Renewable integration,
Optimization.

Abstract

In this study, a distribution system with very high penetration of Photo Voltaic (PV) generation installed is considered. A method is proposed for battery and PV capacity selection in two different scenarios. The first scenario considers an isolated distribution system. The second scenario assumes a 30% injection from the power system. The optimization problem of battery sizing is solved considering the power flow of the system (including the system losses) and the battery constraints. The effect of battery capacity and its initial State of Charge (SoC) on Loss of Load (LoL) is studied. We also consider the change in LOL as result of different contribution levels from the power system and find the minimum power injection needed from the system to avoid LOL.

1. Introduction

The conventional power system is shifting towards renewable and distributed generation more and more in recent years especially Photo Voltaic (PV) technology. The highest levels of PV are integrated into the power system in China, Japan, Germany, and USA. The United States had 40 gigawatts of PV capacity installed as of 2016 and around 40% of new generation installed came from solar energy [1].

The use of renewable energy offers many benefits to the system such as reducing generation prices and decreasing CO_2 emissions released to the atmosphere. But the addition of unreliable and unpredictable renewable generation can also introduce new challenges to the power system operation and planning. Maintaining power system stability, operating the power system at a safe level, voltage and frequency control are some of the new challenges introduced with high penetration of renewable energy [2, 3].

There have been many efforts to tackle the uncertainties associated with PV generation by forecasting the solar power generation [4]. For example, in [5], a solution is introduced to reduce the dynamical order of the power grid and hence, get a faster and more reliable result during disturbance and occurrence of faults in the grid.

Many different methods have been applied to solar power forecasting including statistics and machine learning methods which depend on patterns in data and rely on data mining techniques [6-9]. Also, optimal placement and sizing of the PV units can minimize the distance between generation and load and reduce the losses in the system [10-13]. Another possible solution is scheduling the loads to optimally use the renewable generation [14, 15].

Despite all the efforts for generating accurate and reliable forecasts for solar generation and optimization in their operation, there are still issues remaining due to a certain level of uncertainty associated with these solutions. Therefore, the issues arising from the high penetration of PV generation need to be addressed. Several studies have investigated voltage and frequency control models that counter the voltage fluctuations resulting from sudden changes in PV output while maintaining the system frequency [16–21].

One of the most common and effective methods for optimal operation in distribution systems is integrating an energy storage unit which can help shift the generation to meet the load by storing the surplus generation and discharging when the generation cannot meet the load [22].

In a distribution system depending on the level of the load and the shape of load profiles the PV and the battery unit sizes need to be selected optimally to maintain the system load. The system power flow as well as the battery constraints need to be considered for this purpose. Furthermore, the operation mode of the system and the contribution from the transmission system should be considered.

This paper proposes an optimization method for sizing the PV and battery unit to manage the distribution system while considering all the system, battery, and PV constraints. The proposed method has been applied to a test system in two operation modes. The first case considers the system as an island and manages to meet the only using solar

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generation. The second case assumes a certain level of system contribution which relaxes the constraints on the battery and PV.

The remainder of the paper is organized as follows: An overview of the proposed model is presented in section 2. The test system and the generation and load data are described in section 3. The simulation results are discussed in section 4. Section 5 provides concluding remarks.

2. Problem Formulation

This paper proposes an optimization method for selecting the minimum size of PV and battery units in a distribution system. The power flow constraints of the system alongside the constraints for the PV and the battery units are considered for sizing the Solar panels and storage unit.

2.1. Battery and System Constraints

The battery State of Charge (SoC) is a measure of the charge level of the battery which can provide the system operator with an estimation of the time that the battery can be discharged before it would need to be charged again given a certain discharge rate. Since the battery in this study is connected to the power system for balancing the solar power generation instead of SoC we use State of Energy (SoE) as shown in Eq. (1).

$$SOE_t = SOE_{t-1} + \eta^E \int_{t-1}^{t} (P_{Ch}(\tau) - P_{Dis}(\tau))\, d\tau \qquad (1)$$

where SOE_t is the state of energy for the battery at time t, ηE is the energy efficiency ratio, and $P_{Ch}(\tau)$ and $P_{Dis}(\tau)$ are the charging and discharging powers at the time increment τ, respectively. The energy efficiency is defined as the ratio of the output energy to the injected energy during a full Battery charge and discharge cycle.

While the objective function in this study is to limit the Loss of Load (LoL) probability we need to consider the below constraints for the battery alongside the system constraints described in Eqs. (2–5).

$$P_{Ch} < P_{Ch}^{Max} \qquad (2)$$

$$P_{Dis} < P_{Dis}^{Max} \qquad (3)$$

$$SOE_t \leq 0.9 \cdot CE \qquad (4)$$

$$SOE_t \geq 0.1 \cdot CE \qquad (5)$$

The first two constraints are ensuring that the charging and discharging powers don’t exceed the maximum charging and discharging power allowed by the battery due to current limitations. And the SoE constraints are maintaining the battery charge between 10% and 90% of the battery energy capacity (CE) to prevent leakage current at high voltage levels and maintain a minimum SOE.

We consider a distribution system with different load and solar generation profiles to solve the power flow. Two scenarios are considered in this study. In the first scenario, we assume that the system is operated in isolation and without any power injection from the transmission system. In the second case the system upstream provides up to 30% of the maximum installed load in the system. The solar generation and battery capacity are both calculated for the system to avoid loss of load. We also look into the effect of the initial SOE and power system contribution level on LOL probability.

2.2. Optimization Method

Integer linear programming (ILP) models are commonly used in different optimization applications. ILP is an optimization problem with at least one variable which is restricted to integer values. Integer programming methods are very common in solving unit commitment problems [23].

The battery and PV sizing optimization problems in this study are solved using the ILP optimization method. The objective function is the minimum size and the battery constraints are discussed in equations (1–5) we also add the power flow constraints from the system and a final constraint that limits the final SoE in each day to a minimum of 50%. The integer variable in the formulation shows the charge or discharge mode of the battery. The details of the ILP are discussed in [24].

3. Test Case

The test system employed in this study is the IEEE 13 bus system. A PV unit and a battery system are added to the substation bus in the system. Figure 1 Represents the system under study.

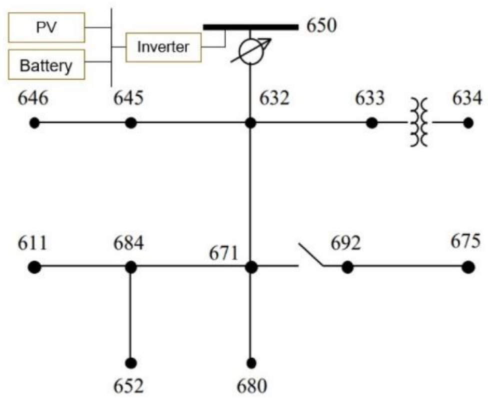

Figure 1. The distribution system under study

The system under study is comprised of two transformers and six loads. A solar panel and a battery unit are connected to the system at the substation level. Several different load profiles are used in this study to replace the loads in the IEEE 13 bus system. The load shapes represent different profiles such as load patterns in a restaurant, hotel, hospital, office and apartment. The different load patterns used in this study are shown in Figure 2.

The solar generation data in this study is from a PV site at the University of Central Florida. The solar power data are recorded in 1s intervals.

The loads in the IEEE 13 bus system are replaced by the load profiles with the same installed capacity. The PV power is scaled based on the PV capacity determined in this study. The data for load and PV generation are from the first week of January 2016.

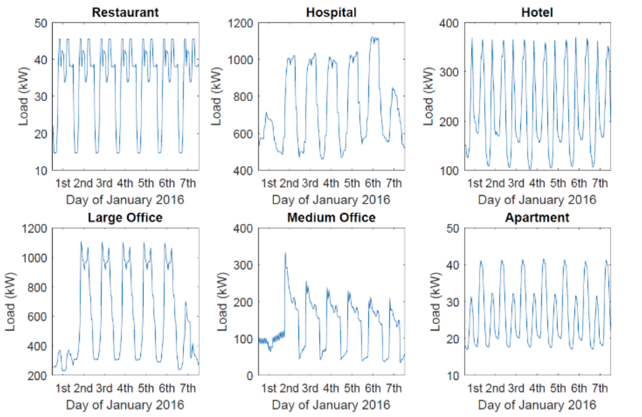

Figure 2. The different load patterns applied to the test system

4. Result Analysis

The power flow in the system is solved at each time step according to the load profiles in the system to determine the amount of generation needed at the substation level including the loss in the system. Then the PV and battery sizing are performed in two scenarios described in section 2 with and without contribution from the power system considering the power flow calculation.

4.1. Island Mode

In the first case study, the distribution system is operated in island mode without any power injection from the power system. The PV capacity is selected based on the amount of solar power generation during daytime considering that we have to maintain the load during the night as well. The minimum PV capacity needed for this system considering the battery efficiency is 4.83 times the maximum installed load which is 673 kW. Figure 3 shows the PV generation for the selected PV capacity and the total system load during the seven-day test period in phase A of the system.

The battery sizing process is an optimization problem with the minimum sufficient battery size as the objective function subject to the constraints discussed in section 2. The battery capacity is the amount of energy we can store in the battery and it also affects the charging and discharging constraints of the battery since the maximum charging current is proportionate to the battery size. If the battery size is not enough or the battery charging limits are reached, even if the excessive solar generation from the PV panels exceeds the sufficient amount to meet the load all through the day, we will experience load loss because the excessive generation cannot be stored. Figure 4 shows the solar generation plus the battery output against the load when the battery capacity is not sufficient.

The Figure 4 shows that until the battery charge is not depleted to its minimum level the system is able to provide the load (The first two days of the simulation). But when the SOE gets to its minimum level because the battery capacity is not enough the demand for the system cannot be met.

Larger battery capacity will increase the amount of energy storage as well as the power ratio for charging and discharging the battery. Our tests show that in most cases the maximum charging and discharging rate of the battery are the limiting factors rather than the capacity of the battery. Therefore, the minimum battery capacity to operate the system in island mode may even exceed 24 times the maximum load in kWh to allow sufficient charging and discharging rates. The LOL percentage for different battery capacities applied to the test system in this study is shown in Figure 5. In this case the initial battery charge is assumed to be at 50%.

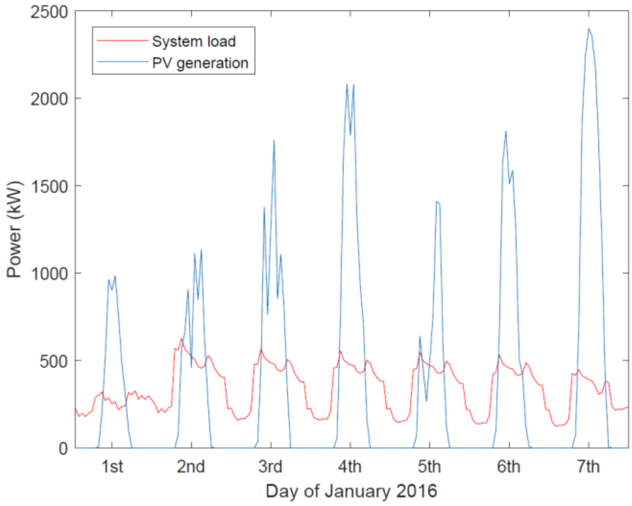

Figure 3. The load and PV generation profiles in the test system

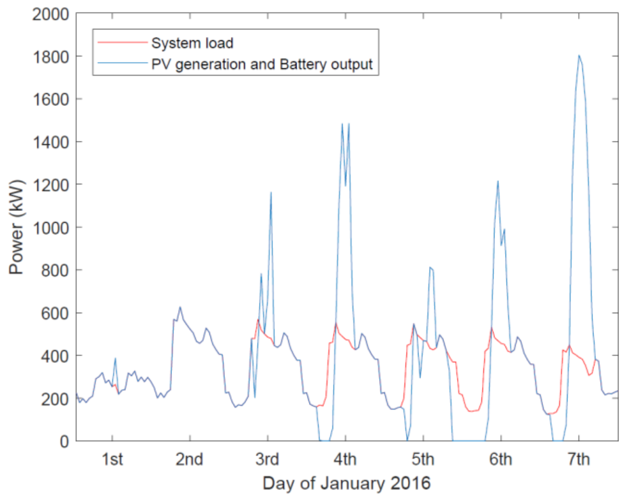

Figure 4. The load against the PV generation and battery output when the battery capacity is not sufficient

Figure 6 Shows the PV and battery generation when the battery size is 40 times the maximum load in kWh and the initial battery charge is at 50%. The PV generation combined with battery output can always support the load in the system. The areas where the combined PV and battery output is over the load are due to the battery reaching its maximum charging current or maximum capacity.

The Initial battery charge has a significant impact on the LOL probability and the results for the battery sizing process. For example, Figure 7 Shows the PV and battery generation when the battery size is 50 times the maximum load in kWh, but the initial battery charge is at the 25% level.

The effect of the initial battery charge on the LOL percentage considering the same battery capacity (40 times the maximum load in kWh) is shown in Figure 8.

Therefore, to consider the effect of the initial charge and limit its effect on the battery sizing process we assume a starting amount of 50% initial charge for the battery and add another constraint which limits the battery SOE to a 50% minimum at the end of each day.

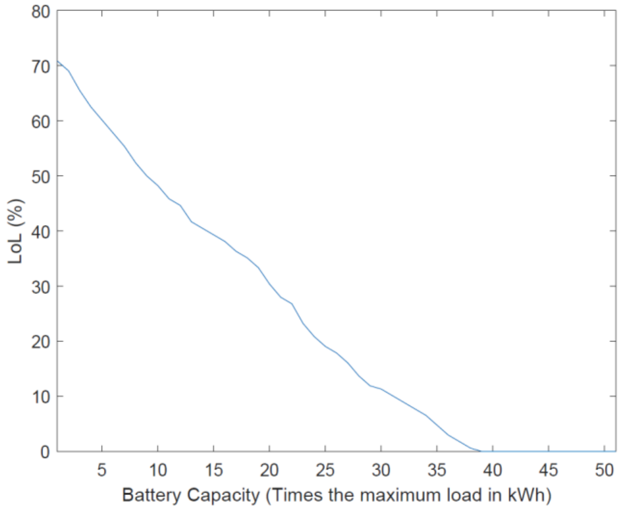

Figure 5. The LOL probability for different battery capacities

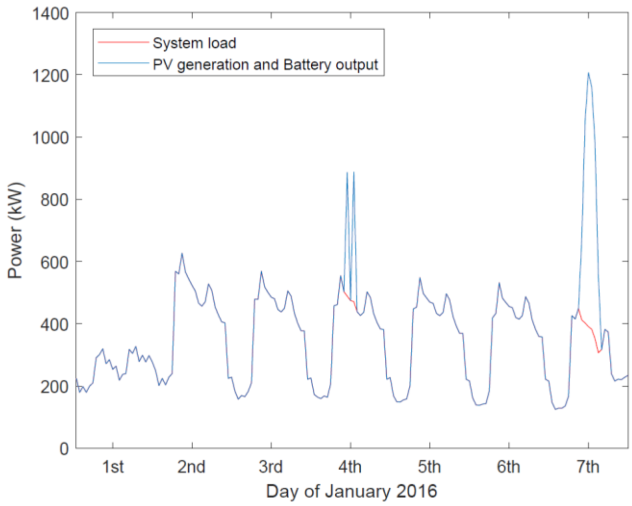

Figure 6. The load against the PV generation and battery output when the battery capacity is sufficient

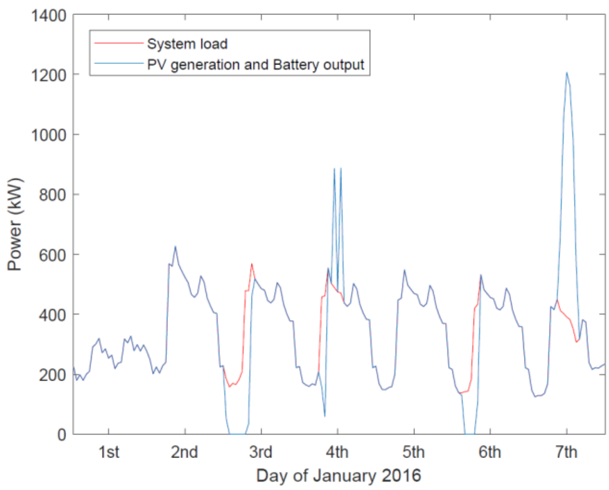

Figure 7. The load against the PV generation and battery output with an initial battery charge of 25%

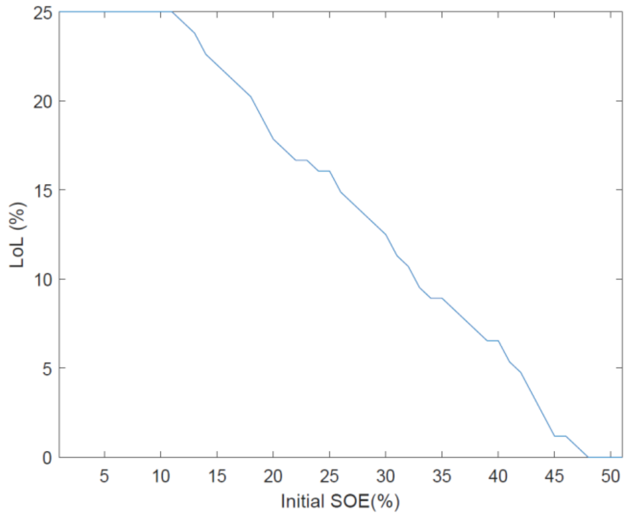

Figure 8. The LOL probability for different amounts of initial SOE

4.2. Connected to the Transmission System

In the second case study the distribution system is connected to the transmission system and a maximum limit (30 % of the maximum load installed) is considered for the power injection from the power system. The PV capacity is selected based on the amount of solar power generation during daytime to maintain the load during the entire test window and maintain at least 50% SOE at the end of each day. The minimum PV capacity needed for this system considering the battery efficiency is 1.9 times the maximum installed load which is 673 kW. Figure 9 shows the PV generation for the selected PV capacity and the total system load during the seven-day test period in phase A of the system as well as the maximum system contribution.

The next step is finding the minimum battery capacity needed to avoid LOL considering the same constraints as the first case except that the power system can contribute a maximum of 30% of the installed load when necessary. The LOL percentage considering the different battery sizes for the second case is shown in Figure 10.

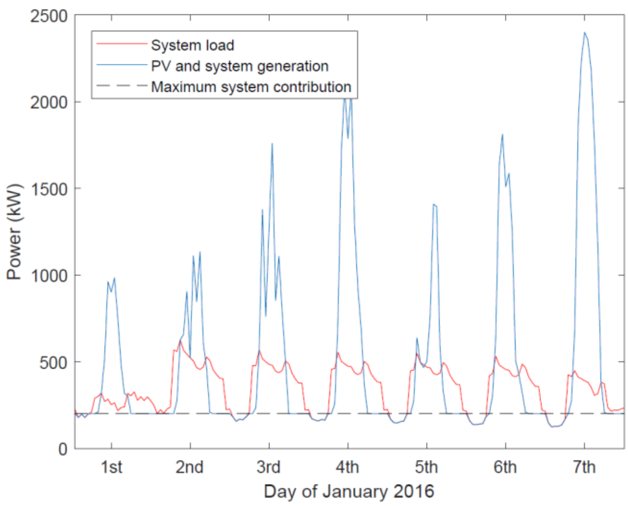

Figure 9. The LOL probability for different amounts of initial SOE

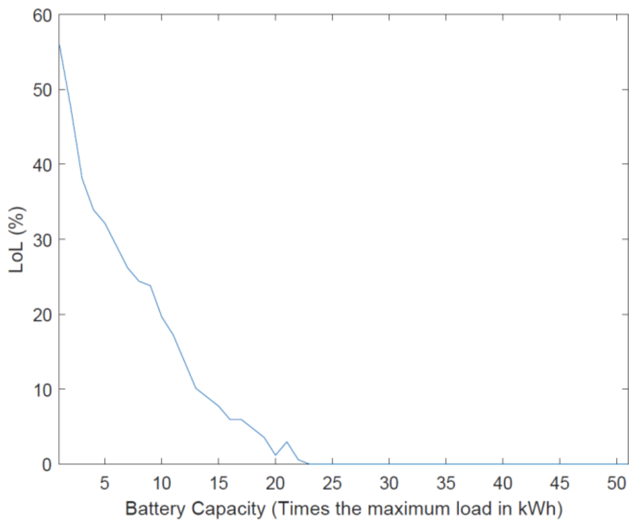

Figure 10. The LOL probability for different battery capacities

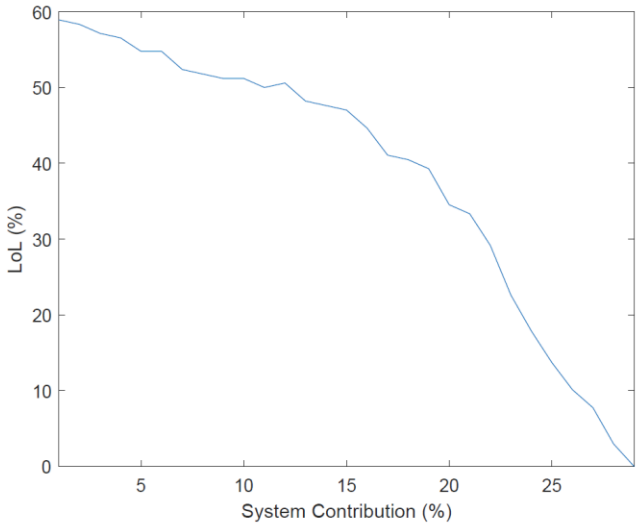

Figure12. The LOL probability for different levels of system contribution

The results in Figure 10 Are achieved assuming the initial battery charge of 50%. The effect of the initial battery charge in the LOL probability (the battery capacity is 25 times the maximum load in kWh) is shown in Figure 11.

Finally, a comparison between the two case studies in this paper shows the significant effect of system contribution in sizing both the PV and battery units. A maximum of 30% contribution from the power system in this study brought the minimum PV capacity from 4.83 to 1.9 times the maximum load. The minimum battery capacity also decreased from 40 times the maximum load in kWh to 25 times. Therefore, the system contribution level in the distribution system will greatly affect the capacity of PV and battery units that are needed to be installed for the system to be able to meet the load at all times. Figure 12 shows the effect of system contribution on the LOL percentage assuming a battery capacity of 25 times the maximum load in kWh with initial charge of 50%.

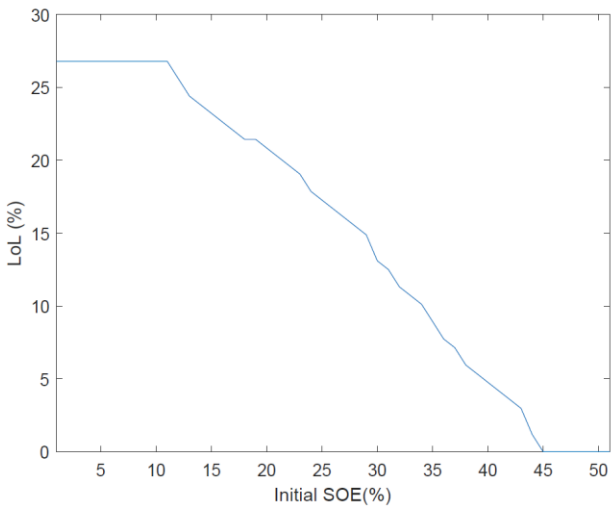

Figure11. The LOL probability for different initial battery charge levels

As a result, we can calculate the system contribution level needed in any distribution system based on the PV and battery capacity installed in the system and the system and battery constraints. Further investigations can be considered for this study such as simulations with different scenario generations similar to the proposed events in [25]. An optimization on the network reconfiguration can also help with the battery and PV sizing [26].

5. Conclusion

This paper proposes a battery and solar panel sizing method in a distribution system with high penetration of solar power. The proposed method finds the minimum installed capacity needed for the solar panel and battery unit based on the operation mode. We consider the power flow constraints from the system as well as the battery constraints such as maximum charging current. The effect of the system contribution and initial charge of the battery on the battery sizing problem is also studied and taken into account.

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