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Optimization of operational cost for a grid-supporting PV system with battery storage

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Coupling an energy storage to a photovoltaic (PV) system not only increases the self-consumption but also solves the over-voltage issues if the cycling of the storage is properly controlled. Whatever the application the storage is used for, the primary concern of the system owner is to maximize the profits. Therefore, this paper addresses an energy management system for a PV system coupled with battery energy storage, which maximizes the daily economic benefits while curtailing the power injection to the grid in such a way that helps to mitigate over-voltage problems caused by reverse power flow. A time dependent grid feed-in limit is proposed achieve this objective. The daily operational cost that includes the energy cost and the battery degradation cost is considered as the objective function. The non-linear constrained optimization problem is solved using dynamic programming. The analyses are made to investigate the economic benefits of charging the battery from the grid. It is found that there is a possibility for these systems for participating in load-levelling if batteries are charged from the PV system. In order for that to be feasible, the peak-hour sell-back price for the energy from storage should be higher than the off-peak utility electricity price.

1. Introduction

Building integrated PV systems have continued to make rapid progress around the world over the past few years. Increasing the PV penetration level in the low voltage (LV) grid creates several technical issues mainly related to the power quality [1–4]. The most critical problem is the voltage rise because of the reverse power flow [5]. A significant percentage of the energy generated from the PV system is injected into the grid because of weak correlation between residential load and the power production from the PV system. This results in reverse power flow. In the early stages, power curtailment was used to deal with this problem [6,7]. Even though this is a feasible solution, this increases the payback time of the PV system because part of the energy generation from the system is wasted. Later, new standards came in to effect such as VDE-AR-N 4105 [8], allowing inverters to operate in voltage regulation mode by absorbing reactive power from the grid when the power injection from the PV system goes above a certain threshold [9]. However, as the number of PV generators connected to the LV grid increases, the total losses in the network will also increase as a result of higher consumption of reactive power by the PV inverters [10–12].

The power penetration into the grid from renewable energy systems especially wind and solar is increasing rapidly. The power output of these systems is highly intermittent and fluctuating in nature. As the total capacity of such sources becomes significant, the complexity of controlling the system increases. Therefore, utilities will need to adopt energy storage solutions to help integrate these renewable sources into the grid [13,14]. The future grid essentially requires energy storage to balance the generation and consumption as well as to maintain the grid stability. The main applications of grid level storage are capacity firming, spinning reserve, load-levelling, improving power quality, and frequency regulation [15,16].

Recently, a growing trend to increase the self-consumption in residential level PV systems has been observed. This is mainly due to customers' desire for independence from the grid electricity, continuous increases in electricity prices, a decrease in feed-in-tariffs, and various kinds of incentives provided in some countries. According to IHS technology, a tenfold increase in the global market demand for residential PV systems coupled with battery energy storage (BES) is expected over the next three years, where

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the current capacity is 90 MW. Currently, lithium-ion batteries dominate this market. The major barrier preventing the market from taking off is the high price of the lithium-ion batteries. However, a reduction in the average price is expected in the coming years, making storage more attractive. In addition to increasing self-consumption, these small systems can have several other applications: improving power quality, peak shaving, and load-levelling. Whatever the application they are being used for, the system owner's primary objective is to increase the economic benefits besides energy independence. Therefore, if these systems are going to be used for utility applications, a profitable business case should be available from the utility side and a proper energy management system that maximizes the economic benefits should be available from the system owner's side.

Several studies have been presented on the literature on the topic of optimal energy management for grid-connected PV systems coupled with energy storage. All of them involve solving optimization problems subject to certain constraints, assuming the day-ahead forecasts of load profile, PV power production profile, and the energy prices are available. The objective function varies depending on the application of the storage, and the choice of the optimization algorithm depends on the complexity of the objective function and the constraints. In Ref. [17], the optimum energy dispatch schedule is found where the storage is utilized for peak shaving. The main purpose is to minimize the demand charge. The net energy exchanged with the grid over the planning horizon has been considered as the objective function, and the dispatch schedule that minimizes the objective function has been found using linear programming. Ref. [18] also describes the optimum dispatch schedule with the same purpose, but there the objective function is the energy cost. The peak shaving is achieved by setting a constraint on the power drawn from the grid. As they have considered different tariffs for energy from the PV and the grid, the objective function becomes non-linear, hence dynamic programming is used to solve the optimization problem. Ref. [19] presents optimal control strategies for battery storage considering different objectives such as maximizing battery life, maximizing self-consumption, and minimizing energy cost. They have also used dynamic programming. Ref. [20] addresses the problem of over-voltages due to reverse power flow. They minimize the net power injection to the grid over the planning horizon using quadratic programming aiming to minimize the impact on the grid from PV systems. In addition, they also maximize the economic benefits by introducing selectable weights in the objective function which are calculated based on greedy-search heuristic algorithm.

In this work, our objective is to maximize the economic benefits for the system owner while optimally contributing to over-voltage mitigation in the grid. Further, we investigate whether residential PV systems coupled with BES can participate in grid load-levelling and identify the requirements for utilizing them for such applications. A scenario where a distribution grid has a high PV penetration, but with limited storage, is considered. As the amount of storage is limited, the objective is to use it optimally, storing as much power as possible, while giving high priority to the period where the over-voltage issues are most likely to occur. Two different configurations of a residential PV system coupled with BES have been considered for the sake of comparison of the performances.

The paper is organized as follows. Section 2 describes the system configuration and Section 3 presents the methodology used. Section 4 details the mathematical formulation of the problem and Section 5 describes the application of dynamic programming for solving the optimization problem. Finally, results of a simulation study are provided in section 6, and we conclude that the proposed algorithm can successfully optimize the operational cost while limiting the power injection into the grid helping it to mitigate possible over-voltage issues caused by high PV penetration.

2. System configuration

Two different configurations of residential PV systems coupled with BES can be found: DC- and AC-coupled systems [21]. In a DC-coupled system, the battery bank is connected to the intermediate DC link directly or through a bi-directional converter. The grid converter could be bi-directional if the batteries are supposed to be charged not only from the PV array but also from the grid. In a AC-coupled system, the battery bank and the PV array are connected to the AC bus via a bi-directional battery converter and an inverter respectively. Fig. 1 illustrates the two different configurations. In this study, both configurations are considered in order to compare the performances. The grid converter in the DC-coupled configuration is considered bi-directional.

3. Methodology

Our objective is to maximize the economic benefits for the system owner while helping the grid to maintain the voltage profile within acceptable level. The cause of the voltage rise problem is the reverse power flow due to high PV power penetration. However, it should be noted that the PV production profile over the day approximately takes the shape of a quadratic function having maximum around solar noon, on a clear sky day. Hence, PV systems affect the grid voltage quality principally around solar noon. Having energy storage units in the network, the active power injection into the grid can be controlled. As stated in the introduction, in this study we consider a case with a significant amount of PV penetration but a limited amount of storage. As not all the PV generators are coupled with BES, the existing storage units should be optimally controlled so that the negative impact on the grid voltage quality is minimized. In this work, we do not consider coordinated control of energy storage units. Instead, we optimize the operation of the individual PV systems with BES independently.

The system has a hierarchical control, in which the optimization or the energy management layer lies on top. Every day before midnight, the energy management system (EMS) optimizes the scheduling of the battery bank for the next 24 h using the forecasted load profile, PV generation profile and the day-ahead electricity pricing information. The EMS calculates the average power transfer to the battery and the energy transfer over the selected time intervals and sends this information to the power management system. Then the power management system calculates instantaneous references (power references, current references and/or voltage references) for the component level controllers.

4. Mathematical formulation of the problem

The notations used to represent the power flow averaged over a specific time interval of Δt measured at points A, C, D, and E are represented in Fig. 1 along with the sign convention. The arrows in the figure indicate the direction of positive power flow. According to this sign convention, battery discharging and power injection into the grid are considered as positive. $\eta_{cj}, j=\{1,2,3,4\}$ represents the efficiencies of the converters adopted in two different configurations. A typical efficiency characteristic of a power electronic converter is shown in Fig. 2. Usually this is available in the product data sheet. It can be represented by a rational function