

An Overview to the Concept of Smart Coupling and Battery Management for Grid Connected Photovoltaic Battery System

Deepranjan Dongol, Elmar Bollin, and Thomas Feldmann

Abstract—The paper gives an overview on the need for smart coupling for battery management in grid integrated renewable energy system (RES). Grid integrated photovoltaic (PV) battery system, as being popular and extensively used has been discussed in the paper. Smart coupling refers to intelligent grid integration such that it can foresee local network conditions and issue battery power flow management strategy accordingly to shave the peak PV and peak load. Therefore, a need for predictive energy management arises for smart integration to the grid and supervision of the power flow in accordance to the grid conditions. This is also a running project at the Institute of Energy Systems (INES), Offenburg University of Applied Science, Germany since January, 2015. The paper should provide insights to the motivation, need and gives an outlook to the features of desired predictive energy management system (PEMS).

Index Terms—Battery management, optimization, predictive energy management, smart coupling

1. Introduction

The use of photovoltaic (PV) systems is increasing day by day along with the promotion of renewable energy. According to report from Wirth^[1], PV generated power covered approximately 6.9% of Germany's total net electricity consumption in 2014. The same report states that "on sunny days, PV power can at times cover 35 percent of the momentary electricity demand and on weekends and holidays up to 50 percent"^[1]. More and more PV systems are being integrated to the low voltage grids due to favorable feed-in tariff policies. On sunny days, PV production by far exceeds the local load demand and despite the provision of feeding the surplus PV energy to

the grid issue over the grid stability rises as low voltage grids are not designed to take in high power generation. As such the section of the grid with high PV penetration experiences rise in the voltage as a result of reverse power flow^[2].

As mentioned in [3], VDE AR-N 4105 (Technical minimum requirements) allows only a maximum 3% increase of the nominal voltage caused by PV penetration. Also the mismatch between peak PV power generation and peak load demand makes grid connected PV system without energy storage less effective as shown in Fig. 1 from a case example. One common and widely used solution to shave off the PV peak-feed is the use of batteries as energy storage system to ease PV integration and relieve stress on the utility grid for effective demand side management. This paves the way for a systematic battery management. As cited in [4], from the studies it has been pointed out that the benefits of storage systems depend on its operation strategy and that even with storage system the challenge of grid stability needs to be considered in order to have a grid serving system. Grid serving systems are those that ensure the reliability and stability of the power Grid^[5].

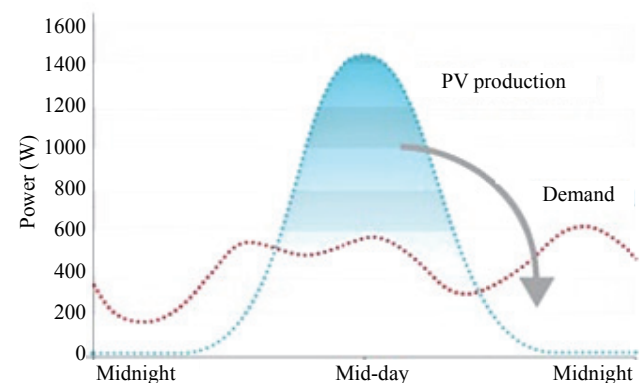


Fig. 1. Peak shaving strategy for demand side management^[6].

The challenges associated with PV systems and the requirement for scheduling comes from fluctuating power generation. On sunny days, the power production is peak and more than sufficient to meet the load demand. While on cloudy days or days without sun and during the night time the PV power production is insufficient or zero. Similarly, the passing clouds can significantly reduce the PV power

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production. For grid connected systems forecasting of load demand and grid electricity price are also equally important factors to be considered in order to manage scheduling of power flow such that the system performance is efficient and economic. The performance of such system should ensure grid stability too. Similarly, the active and reactive power flow management with the utility grid clearly depends on this energy management strategy based on the forecasts and scheduling.

2. Battery Storage

The battery storage considered for this system is lead acid batteries in general because of its wide range of use and popularity in PV systems. Proper charge cycle management of lead acid batteries determines its

performance and the lifetime. The deep discharging of the lead acid battery leads to deposition lead sulfate on the positive plates the process known as sulfation. Similarly, overcharging leads to loss of water and generation of hydrogen gas as a result of heat developed during the electrolysis process and deforms the battery causing it to bulge in appearance^{[7],[8]}. This degrades the battery performance and its life time. There are different charging strategies for the lead acid batteries which are explained in great detail in [9].

Manufacturers such as rolls battery^[10], recommend charging the lead acid battery in three different stages by varying the charging voltage and current at each stage which can be shown in Fig. 2. The charging current is gradually decreased in each stage as the charge builds up in the battery.

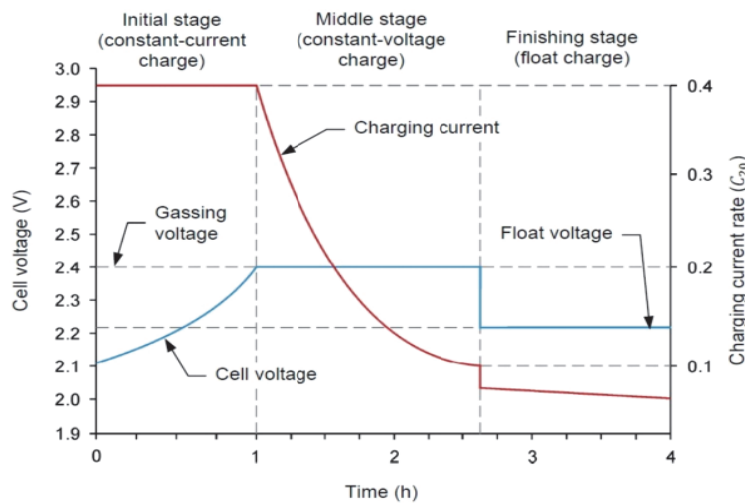


Fig. 2. Modified constant voltage charging method^[9].

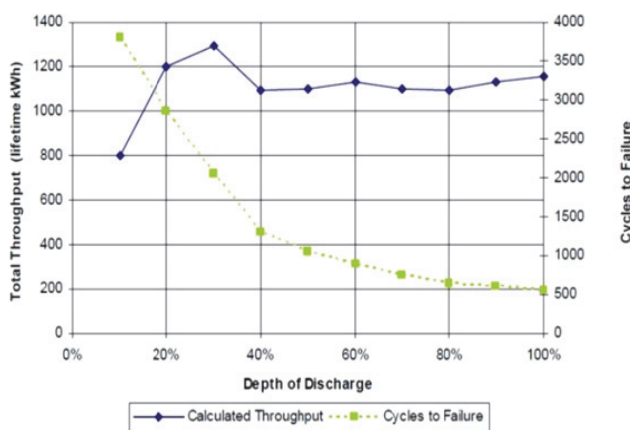


Fig. 3. Cycles to failure and total throughput for a flooded flat plate battery based on data supplied by the manufacturer^[11].

Similarly, the lifetime of the battery also depends on the number of charge cycles before the battery needs to be replaced as shown in Fig. 3. A charge cycle constitutes of a complete charge and discharge cycle of the battery.

A proper battery flow management strategy is therefore

required to manage the charge and discharge cycle of the battery as its charge capacity, charging time, throughput and lifetime is limited. The battery flow management is discussed in Section 3.2.

3. Desired System Features

The grid integration of PV battery system leads us to two important points to be considered for implementing an intelligent energy management control algorithm: A smart coupling with the grid and proper battery power flow management which is discussed as follows.

3.1 Smart Coupling

The integration of renewable energy system to the grid brings challenges to the grid stability as the power not only flows from the distribution transformer to the consumers but also in the reverse direction. In order to maintain the power quality and security smart solutions are equally important. The smart solutions allow self-regulation of the system by monitoring the grid conditions and optimizing

the power flow accordingly. This would also allow flexibility for more grid integration of renewable energy systems with existing infrastructures and policies. This would also encourage the policy makers in making favorable decisions to promote the use of renewable energy systems from household to industrial scale.

Smart coupling is a proposed concept at Institute of Energy Systems (INES) which is an intelligent integration of the local INES grid with the utility grid to monitor the status of the local network and control the power flow exchange such that the grid stability is maintained. The unique feature of smart coupling is that it operates autonomously within the local network without external intervention and has predictive feature for operation and can foresee network conditions. This is achieved by monitoring the voltage and frequency of the grid and responding to the energy flow accordingly. The real part of the voltage rise $d\bar{V}$ over the grid impedance \bar{Z} caused by the PV feed current \underline{I} is expressed as [12]

$$\frac{d\bar{V}}{V_N} = \text{Re} \left\{ \frac{d\bar{V}}{V_N} \right\} = \text{Re} \left\{ \frac{\bar{Z}\underline{I}}{V_N} \right\} \cong \frac{(PR) \pm (QX)}{|V_N|}. \quad (1)$$

Equation (1) indicates that the voltage control can be obtained by controlling active power P and reactive power Q . One commonly proposed strategy for maintaining the voltage within the permissible limit has been to control the load tap changing (LTC) transformer. In [13], the author has formulated a mixed-integer programming and solved it by genetic algorithm to achieve the predictive voltage control for a distributed network with renewable energy sources. Optimization is carried out to control voltage and reactive power flow. Artificial neural network (ANN) approach has been used to conduct the weather forecast. The proposed idea is to minimize the voltage deviation in the bus by controlling the LTC transformer. In [14], the author has presented model predictive control which operates to maintain the voltage within the feasible range of defined voltage in the bus by controlling the LTC transformer.

Similarly, as still the majority of grid power is supplied from conventional rotational power generation station, a balance between energy supply and demand is important in order to avoid frequency shifts and avoid grid instability [15]. Therefore, for grid integrated systems it is important to control the active power flow to maintain stable frequency within permissible the limits. According to VDE interim solution for low voltage networks, droop function must be implemented at 50.2 Hz [16]. Fig. 4 shows the implementation of the droop function. According to the droop function, the active power reduction should be 40 % of generated power per Hertz. At 50.2 Hz $\leq f_{\text{grid}} \leq 51.5$ Hz the active power reduction can be expressed by

$$\Delta P = \frac{20P_M (50.2\text{Hz} - f_{\text{grid}})}{50\text{Hz}} \quad (2)$$

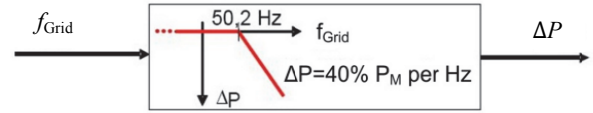


Fig. 4. Frequency control droop function^[16].

where P_M denotes the generated power, ΔP is the power reduction, and f_{grid} is the system frequency.

Beyond the frequency range $47.5 \text{ Hz} \leq f_{\text{grid}} \leq 50.2 \text{ Hz}$, the system should be disconnected from the grid. The droop based active power curtailment strategy has also been discussed in [17].

This direct curtailment of active power is cost ineffective which leads to the need of active and reactive power flow management. In [18], the authors present a convex optimization approach suggesting optimizing the reactive power flow such that maximum active power is delivered for PV inverters. If the reactive power control is not sufficient only then the active power feed could be reduced accordingly until the desired voltage level is reached^[12]. Present solar inverters are well advanced and techniques such as space vector modulation enable the control of both active and reactive power independently^[19]. As mentioned in [20], a power factor of 0.9 in typical low voltage grids is sufficient to keep the voltage in the permissible limits. Despite the flow of reactive power increases power loss in the inverter the advantage of controlling reactive power is that maximum active power can be fed.

3.2 Battery Power Flow Management

The key to battery management is to shave off peak PV feed during sunny days and provide the stored energy during peak load demand. Knowing when to charge and discharge the battery is important for sensible and economic operation of the system. A simple grid connected PV battery system would simply charge and discharge the battery without considering PV generation and load demand profile. This means that the battery bank might not be available to store surplus PV energy during peak PV feed on sunny days and provide with backup power when needed. Similarly, if the stored energy cannot be used during peak load demand, its operation is uneconomic^[21]. There are two provisions for charging the battery bank, either from PV system or the utility grid. Since a single grid electricity price has been considered, the battery bank is charged from the grid only if the grid is unstable or unreliable, in conditions when PV energy is not sufficient such as in cloudy days or night time. The operation of the batteries also needs to obey the constraints defined by its state of charge (SOC) and maximum charging and discharging power of the battery bank.

Several strategies for battery management in grid connected PV battery systems have been developed over

the years. The battery management algorithm as cited in [21] focuses on reducing the electricity bill price and claims to effectively reduce the electricity bill by as much 28% verified by experiment results. The algorithm presented also takes peak PV feed shaving into consideration. The proposed algorithm takes PV module impedance, converter losses, battery rate-capacity effect and storage capacity limit for given solar irradiance, load profile and billing policy into account thus implementing a holistic approach for optimization using dynamic programming. Depending on the ratio between the peak hour and off peak hour electricity price, it is determined whether the PV energy is supplied to the load or to charge the battery during off peak hours. Also, the charging of the battery is done at cheapest grid electricity price whereas the discharging is done when the grid electricity price is most expensive. The charging and discharging process incurs losses and as such a compensation price variable is defined which limits the charging and discharging current magnitude and time for the battery.

The algorithm presented in [22] focused more on economic power flow in the grid connected PV system with batteries. The presented system supplies load demand at best cost and takes into account feed-in tariff, grid electricity price and cost of battery operation in terms of battery replacement cost. The battery replacement cost is calculated in terms of degrading state of health (SOH) health of the battery which is derived from difference in SOC of the battery over time. The optimization is performed using dynamic programming approach and the simulations results shows that the peak shaving is achieved at this minimal cost of operation which helps the PV integration to the grid. Similarly, a fuzzy logic optimization for PV battery system has been proposed in [23].

So it is clear from the study of different battery management strategies that the operation of battery bank considering PV peak shave always leads to economical operation of the system and vice versa.

4. Optimization Requirement

The challenge for the intelligent grid integration related to smart coupling and battery management needs to be addressed with a proper optimization strategy. The optimization needs to be done such that maximum of PV energy is economically utilized with meeting local demand, grid feeding and storage while monitoring and maintaining the grid stability. The system is also constrained with battery characteristics and hence limits batter power flow. The voltage and frequency of the grid also limits the injection of active power. The optimization should also be able to predict the response on the system in future in reaction to the sequence of control inputs assigned beforehand based on forecast data and minimize the error

between real output and predicted output. The control strategy should ensure that the load demand is always met with the best optimal power flow algorithm in the system.

A simulation of system with intermittent source, storage and load with multi-step optimization as presented in [24] claims to have very good performance assuming the power supply from the intermittent sources to be constant over 5 minutes time horizon. Similarly, multi-step optimization has been discussed in [25] to have smooth performance and easy to implement. The optimization strategy has to be based on real time in order to have superior performance of the system^[26]. This provides a scope for implementing model predictive control (MPC) strategy. The advantage with MPC is its ability to provide optimal control signals based on prediction from the system model and at the same time minimize the output error. Since the system is based on forecast model it is prone to disturbance and deviations for which MPC approach could be an ideal solution for real time^[27]. The concept of MPC can be visualized in Fig. 5. It can be seen that the control input u varies to minimize the difference between set output y and the predicted output \hat{y} over the time horizon $[K, K+N-1]$.

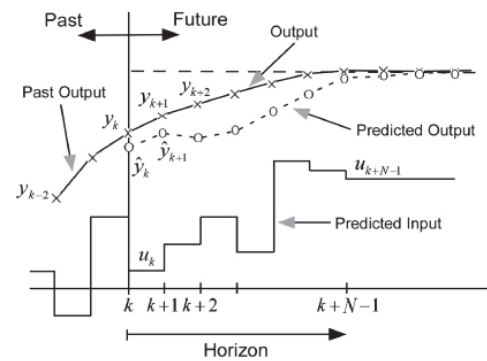


Fig. 5. Model predictive control concept^[28].

5. Conclusions

The study concludes that peak PV shaving and peak load shaving should lead to an economic operation of the PV battery system for which the proper battery power flow management strategy is required. Predictive features allow smart integration of grid integrated systems such that it is able to respond to grid conditions and supervise the power flow accordingly so that the permissible grid standards are not violated. As such energy management system with predictive features is necessary and can be termed as predictive energy management system (PEMS). The uniqueness of this PEMS scheme is its ability to predict sequence of events in future and generate control signals accordingly. For a real time operation, it is important not only to solve the optimization problem on the basis of predicted data but also constantly monitor the current state and vary the control inputs accordingly to minimize the output error.

In order to realize the PEMS, the idea is to implement model predictive control (MPC) concept to achieve the goals of smart coupling and battery management for our work at INES. Although the PV battery system has been focused in this paper, the implementation of PEMS should provide a platform for integration of other renewable energy sources too in future.

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