PEAK SHAVING CONTROL METHOD FOR ENERGY STORAGE

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Peak Shaving is one of the Energy Storage applications that has large potential to become important in the future's smart grid. The goal of peak shaving is to avoid the installation of capacity to supply the peak load of highly variable loads. In cases where peak load coincide with electricity price peaks, peak shaving can also provide a reduction of energy cost. This paper addresses the challenge of utilizing a finite energy storage reserve for peak shaving in an optimal way. The owner of the Energy Storage System (ESS) would like to bring down the maximum peak load as low as possible but at the same time ensure that the ESS is not discharged too quickly (rendering in an undesired power peak). This paper proposes a method for calculation of an optimal shave level based on recorded historical load data. It uses optimization methods to calculate the shave levels for discrete days, or sub-days and statistical methods to provide an optimal shave level for the coming day(s).

Keywords: Energy storage, peak shaving, optimization, Battery Energy Storage System control

INTRODUCTION

Electricity customers usually have an uneven load profile during the day, resulting in load peaks. The power system has to be dimensioned for that peak load while during other parts of the day it is under-utilized. The extra costs in keeping up with the peak demand are passed to the customers in form of a power fee, i.e. you pay for your maximum peak load [1].

By utilizing an ESS, peak load can be reduced and hence the power fee. The ESS is controlled to charge up during off-peak hours and discharged during peak hours (Fig. 1). Households' peak loads often coincide with the peak load of the overall grid. That means the cost of energy is also high during these times. In such cases the benefit of peak shaving is double; by reducing both the power fee and the cost of energy. Peak shaving can also be used by utilities or plants of renewable energy to increase the capacity of the existing grid infrastructure. T&D upgrades can be deferred into the future providing a more cost efficient upgrade path for the power system.
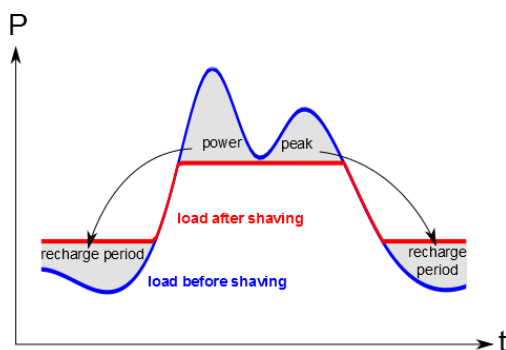

Fig.1 Principle of peak shaving. Area corresponds to power x time, i.e. energy.

As it is mentioned in [1] the challenge with peak shaving is to design a control scheme that detects the peaks on time and fully exploiting the capacity of the ESS. Most of the control schemes found in literature suggest using a predefined shave level depending on the maximum load or how the load looks like. Since load forecasting is quite difficult to achieve, if hard limits are applied there is a good chance to miss the peak or to discharge the battery in smaller peaks leaving the biggest peak intact.

To be more specific [2] focuses mostly on dimensioning the battery for peak shaving. Considering that the power hence the energy to be shaved is known beforehand then the most optimal battery size is searched. However, only focus on the dimensioning of the battery is given and not the control algorithm.

Furthermore, in [3] hard limits regarding charge and discharge of the battery are assigned. This approach would work perfectly if the load was already known, but misfires may occur if the load is different than expected. In [4] peak shaving for an industrial load is described. This approach is time based, where the battery is discharged during pre-defined time slots. [5] proposes an optimal peak shaving strategy that minimizes the power peak by using a shortest path algorithm. By optimal management of the stored energy, the peak power that is demanded from the generator/power supply is minimized. However, this approach was found computationally expensive, puts unnecessary stress to the battery and it is strongly depended on historical data. The latter is the highest risk when designing a control approach. If the actual data deviate from the historical then inaccurate charge/discharge commands will lead to increase the peaks rather than shaving them (Fig.2).
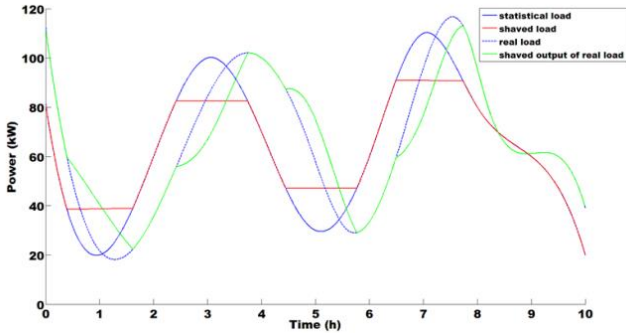
Fig.2 *Example of an inaccurate peak shaving*

PROBLEM STATEMENT AND NOVELTIES

The amount of peak power that can be reduced by an ESS is limited by its energy storage capacity, its maximum charge and discharge powers, and the load characteristics, meaning how much energy the load peaks hold. The proposed method aims to find the optimal shave level by utilizing optimization methods to find the optimal shave level based on recorded historical data. Moreover by applying statistical analysis an optimal shave level with a confidence interval of utilizing the available energy completely can be provided.

The proposed method can be summarized in (Fig.3). Historical load data are recorded and arranged accordingly. The arrangement may involve for instance separation in working days and weekend days. After that the optimal shave levels are calculated for each day and then statistical analysis is provided to choose the optimum shave level based on a confidence interval that is chosen by the ESS operator.
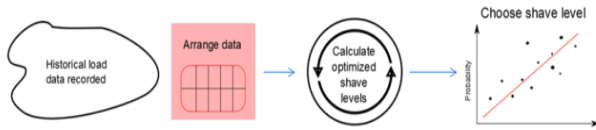

Fig.3 *Overview of the proposed solution*

Besides calculating the optimal shave level, different options for the recharging schemes are possible. The default option is that the battery is recharged as soon as charge power is available; that is when the load is less than the shave level. In case a (not expected) load peak occurs, this recharge scheme provides the best probability that we have energy available to shave the peak. Two other options provide nightly charging, either with a constant charge power, or at a minimal constant load level.

Optimization function

The changing variable in the optimization is the shave level, and the objective function is the energy in the battery. The proposed scheme is general and can be utilized in both charge and discharge operations while it can be applied to any data load set. The optimization aims to utilize just as much of the battery capacity that the user desires (by default 100% of ESS storage capacity). It works by integrating the difference between load and shave level, with the condition that during charge, the battery must not be charged above the specified maximum State-of-Charge level (default 100%). The objective function (which is minimized) is the error between available battery capacity and actual capacity used.

$$\min_{L(t)_{max}<x<L(t)_{min}} f(x) \tag{1}$$

There f(x) is the objective function that should be minimized,

$$f(x) = \left| C_{batt} - \left(\max \int_{t_0}^{t} (L(t) - x)dt - \min \int_{t_0}^{t} (L(t) - x)dt \right) \right| \tag{2}$$

C_{batt} is the battery energy capacity, x is the shave level and L is the load.

A first observation is that the objective function should have a distinct global minimum, as illustrated in Fig.4. For each given load profile and battery combination, only one optimal shave level must exist, and the error in battery utilization must be strictly non-descending when moving away from this optimal level in either direction.
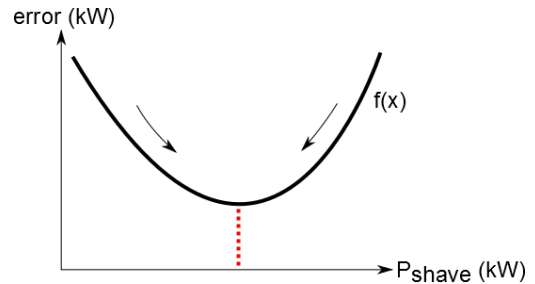

Fig.4 *Distinct global minimum of the objective function*

Optimization algorithm

First a vector covering the whole shave level range for optimization is created. The error (f(x)) for each shave level is calculated. If the error is bigger than the tolerance levels, the smallest error is selected in order to create a new vector of shave levels around the smallest error. The new vector spans between the previous and the next shave level. Fig.6 illustrates the implemented optimization routine. Assume that the original shave level vector ranges from P_1 to P_5. The function will calculate how well the battery is utilized with each level and it will calculate the error for each level. Let us also assume that the smallest error corresponds to power level 3, P_3, and it is above the tolerance limits. Then the new shave level vector will range from P_2 until P_4. The process is repeated until the calculated error is less than an acceptable limit (here it was set to <1kWh), hence until the optimal shave level is found.
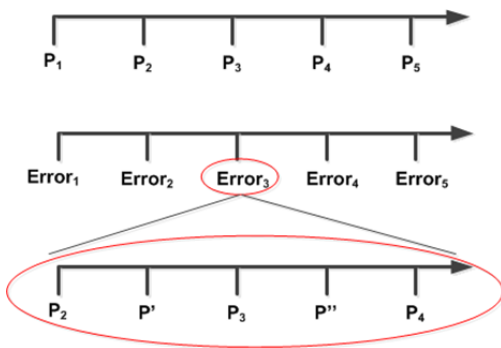
Fig. 6: *Illustration of the optimization routine*

(Fig. 7) summarizes the proposed method in a flow chart. Note that the optimization scheme is applicable for both charging and discharging operations.
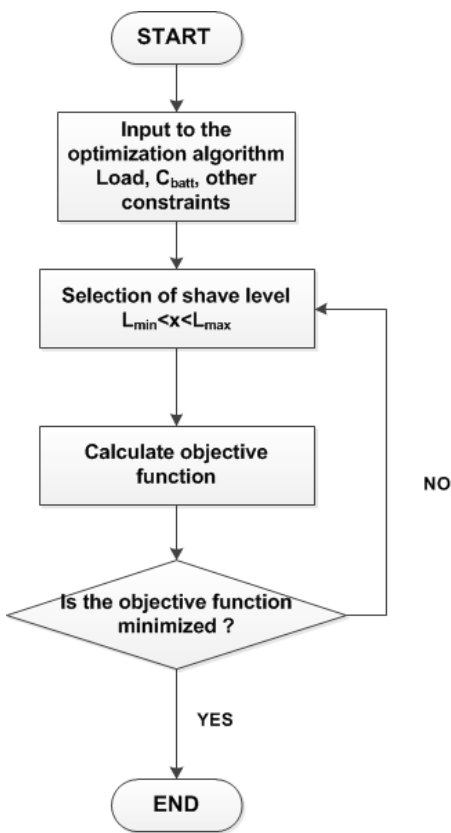

Fig.7 *Flow chart of optimization scheme*

Many methods for finding the minimum of functions exist, and some are probably more computationally efficient than the one presented here. The presented optimization routine was chosen because of easy and straight-forward implementation.

CASE STUDY

A customer case has been used to test the developed solution. A BESS installed at LV substation level in Western Sweden with 75 kW/75 kWh capacity has been used. The energy storage is located in a distribution grid with large penetration of renewables while charge of electric vehicles is planned. So, undesired load peaks are expected. The ABB solution include among else, the installation of 100 kVA PQF Active Power Quality Filter converter with a Battery Energy Storage System for active and reactive power compensation and active filtering of harmonics. (Fig. 8) depicts an overview of the system and (Fig.9) how the load looks like.

Table 1. Simulation parameters

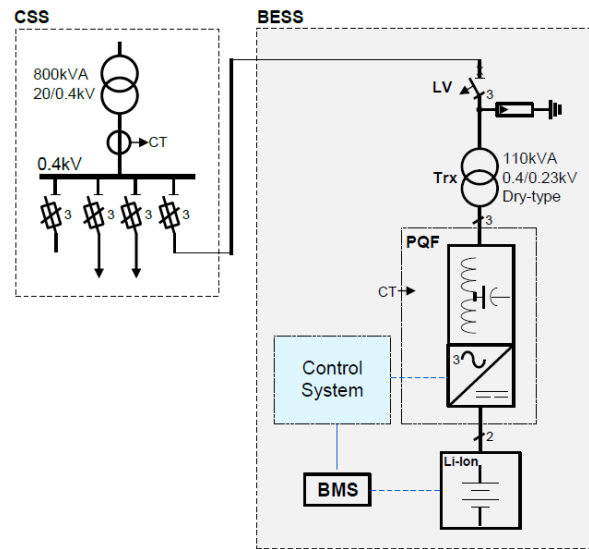| Battery Capacity	75 kWh
Max. Charge/Discharge Power	75 kW
Round trip efficiency	80%
Duration of recorded data	1 year

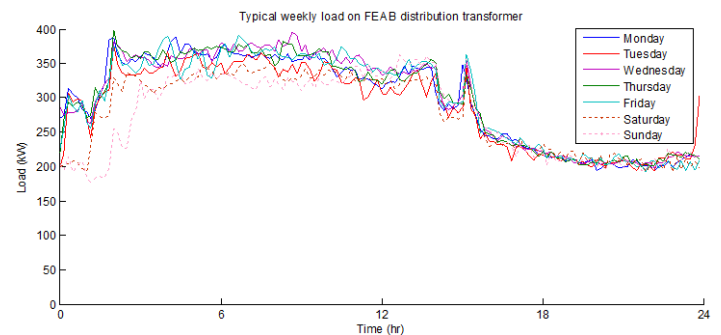Fig.8 *Overview of the installed system*

Fig 9. *Load profile for different days*

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RESULTS

Several scenarios of charging and discharging will be presented. Note that the ESS operator can divide the given load into smaller sub-loads. The following selections are offered.

1. Peak shaving without charging. In this mode the available energy of the battery is used for peak shaving. When the operation has been completed the battery will have used all the available energy.

2. Peak shaving with intermediate charging: Here peak shaving is performed but at the same time, an effort has been made to charge the battery whenever is possible.

3. Standby mode: In this mode, the BESS is inactive and no charging or recharging occurs.

4. Optimal charging mode: The goal here is to fully charge the battery with the lowest power as possible.

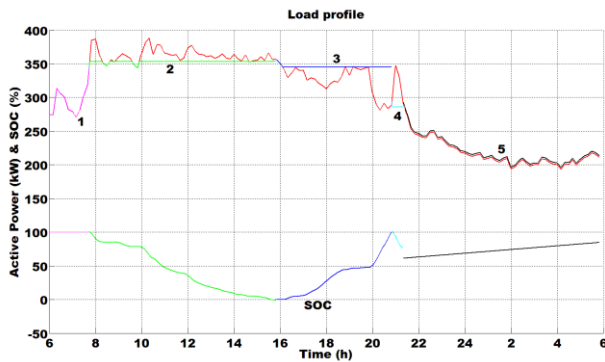5. Charging with constant power: In this operation the battery is charged with constant power.

Fig.10: *Script results for a specific day. Standby mode (1), Peak shaving without charging (2), optimal charging (3), peak shaving without charging (4), charging with constant power (5). The red curve is the original load.*

In Fig.10 the load was divided in 5 segments. As it can be seen with the load division the peaks are efficiently shaved and the battery is charged whenever that is possible without misfires or exceeding the shave level. Of course the efficiency depends on how good statistical data we have on our disposal. During the charging with constant power it is noticed that the SOC level does not reach 100% hence the battery is not fully charged. This occurs because all the optimizations are performed with a tolerance error. In these simulations the tolerance error in the energy optimization was chosen to be less than 1 kWh.

In Fig.11, peak shaving with intermediate charging was chosen. The ESS was fully discharged at the end of period 2 and was recharged during the next period in optimal charging mode.
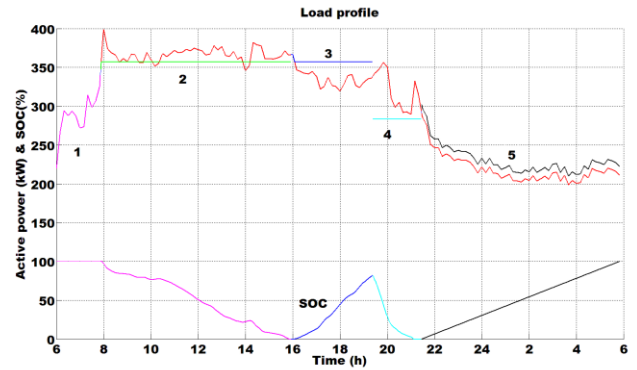

Fig.11: *Script results for another work day. The sequence followed was standby mode (1), peak shaving with charging (2), optimal charging (3), peak shaving without charging (4) and charging with constant power (5).*
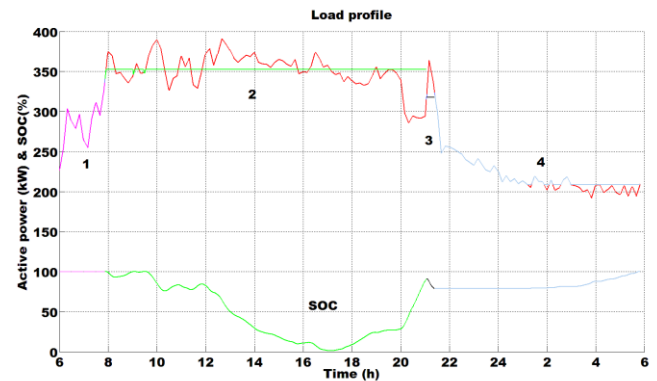

Fig.12: *Sequence followed, Standby mode (1), peak shaving with charging mode (2), peak shaving without charging (3), optimal charging (4).*

In the load profile of (Fig.12), the chosen operation was peak shaving with intermediate charging, at the end of the period the battery was charged because there was an opportunity to charge the battery. The next period peak shaving without charging was chosen and finally optimal charging in the end in order to make sure that the battery would be fully charged for the next day.

STATISTICAL ANALYSIS

Although the ESS operator can perform the optimization for every day individually, it is desirable to calculate the shave levels for a larger set of historical data. So, there are two options; either every day the BESS will be programmed with different shave levels or by using statistical analysis a fixed value can be chosen which can be applied for the given period of time e.g. a week or a month.
The approach[1] that was followed is described below.

1. Calculation of shave levels for charging and discharging, for the whole data set, as described above. This will result in gathering the shave levels for charging or

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[1] The statistical analysis makes sense if we treat the sub-loads in the same way for all the selected days

discharging for all the days.

2. When optimal shave levels have been calculated for a set of discrete days, distribution fitting is applied on the optimal shave levels to identify a Probability Distribution Function (PDF) with good data fitting. In this this example case the normal distribution provided a good fitting, as indicated in Fig.13.
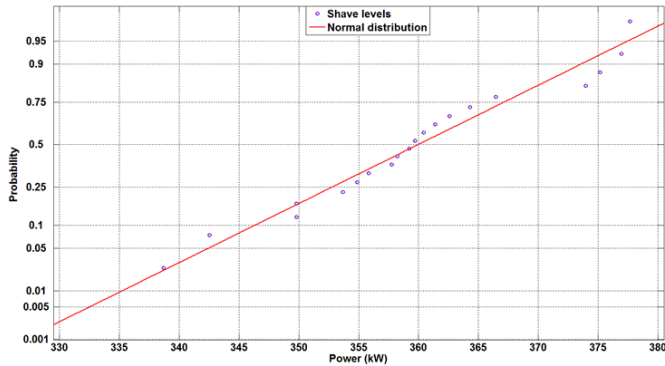

Fig.13 *Normal distribution of the shave levels for peak shaving*

3. When data is fitted to a PDF the corresponding Cumulative Probability Function (CDF) is calculated. With the CDF it is possible to locate a shave level where the probability of having a misfire is sufficiently small, see Fig. 14. This probability will be chosen by the ESS operator.
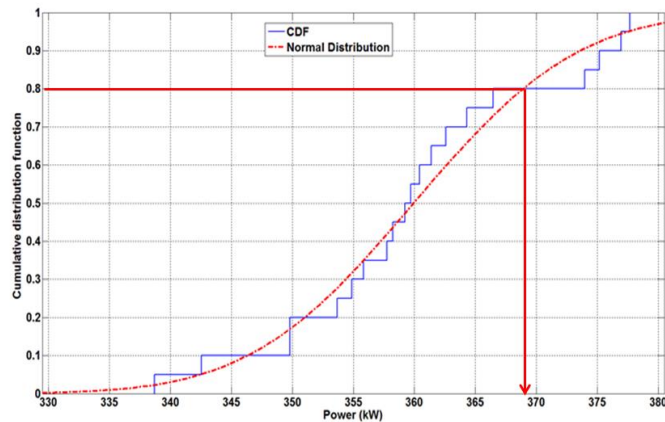

Fig. 14 *Data set 20 days, peak shaving without intermediate charging. 80% probability of success (i.e. not running low on battery energy) yields a shave level of ~369 kW.*

CONCLUSIONS & FUTURE WORK

In this paper an optimization algorithm combined with statistical analysis was developed for the energy storage peak shaving application. Compared with other methods proposed in the literature the computational time is significantly smaller and we do not have to deal with large integration errors. Also the variety of options which are offered to the ESS operator with different charge and discharge modes in combination with the option to divide the load in smaller sub-loads, provides an agile

method where the operator can dynamically change the operation during a given time frame. Furthermore, increased flexibility and a higher battery utilization can be achieved. The statistical analysis helps to operate the battery effectively. The final conclusion is that the presented peak shaving control method can provide improved performance compared to other known methods.

The next step in this exercise would be to include a more detailed battery model for Battery Energy Storage Systems. By incorporating a runtime battery model, modeling V-I characteristics and thermal behavior will provide dynamic calculation of quantities such as charge and discharge power which is dependent on State of Charge (SOC), State of Health (SOH), battery voltage and temperature.

Apart from choosing the shave level that will utilize the available energy and use statistical methods to make sure that this is sufficient, it would be prudent to take into account the cost of energy in terms of losses in the system. For example reserved battery energy could be used for other applications or for shaving bigger peaks. Moreover, since deeper shave levels will be chosen, a relationship between the reduction of the power fee and the battery deterioration should be found.

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