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An Evolutionary Optimization Algorithm to Planning the Time of Delivery Schedule and Factor in a Hydroelectric Power Plant with Battery Energy Storage Capability

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Abstract: The modernization of regulation and legislation rules of the power systems in nowadays is partially due the penetration of renewable resources generation and an energy store capability. The generation based on alternative source has an intermittent pattern and its linkage with a hydroelectric generation plant should be considered in the expansion of generation matrix. Some pioneer projects are conducted in Brazil that confirms this relevance. The battery energy storage is another functionally possible today and must be considered in the technical and economic analysis. This paper presents a method based on evolutionary approach that intends to optimize a time of delivery schedule and factor with objective of the decrease the payback time. In front of the optimized time of delivery schedule and factor is proposed an optimal law of control of a battery storage system. Experimental data was employed and the results reached could be used to better operate energy storage systems and deal with regulation aspects.

Keywords: Energy storage; Evolutionary computation; Hydroelectric power generation; Optimal scheduling; Optimization.

1. INTRODUCTION

The electric sector has been undergoing transformations and facing technical, economic and regulatory challenges related to different factors, among which are: insertion of dispersed and intermittent renewable generation sources and their impact on the management of the system; Deployment of energy storage systems; New possibilities and demands brought about by intelligent networks; Frequent regulatory uncertainties that pose serious risks to investors in the sector; Inclusion of the environmental component in public policies and citizen awareness (Yamagata & Hajime, 2013; Zygiaris, 2013; Castro & Brandão, 2010).

The generation of electric energy from sources subject to variations or discontinuities, is conditioned to the feasibility of compensating them. However, an intermittent supply presents operational problems that entail systemic costs, not always computed in the evaluation of its competitiveness against other supply options and in the definition of its price (Castro & Brandão, 2010; Midttun, 2012).

In Brazil has been considered that intermittent supply would normally be offset by increased hydroelectric generation. Yet, such a procedure is not always feasible or economical, since the inflow to the reservoirs that have been depleted to meet that unforeseen generation may be insufficient. Alternatively, the compensation has to be made by thermoelectric generation. Thus, it is evident the need to minimize this intermittence, since its compensation, besides having value, usually has cost, or fuel or use of storage of hydroelectric (ANEEL, 2008; MCTI, 2014). Energy consumption has variation throughout the day, lack of storage requires constant adjustment of generation and can cause price volatility and consequently market fluctuations. Hourly volatility reflects the large disparity in production costs of different resources, which leads to a sharply sloping market supply curve. This curve added to a highly variable and inelastic demand curve explains price volatility (Walawalkar & Apt, 2008; Green, 2010; Xie, 2014)

Thus, this paper intends to contribute in the optimization of the Time of Delivery Schedule and Factor, in the dimensioning of the energy storage system and in the optimal operation of the storage system.

2. OPTIMIZATION ALGORITHM TO PLANNING OF THE TIME OF DELIVERY SCHEDULE AND FACTOR

2.1 Problem definition and its restrictions

Todays the price of energy is uniform over the day and over the year in most of generation segment. This price is stated on ANEEL (Agência Nacional de Energia Elétrica) site, at auction section, which occurs periodically. This particularity tends to be changed according to the international scenario. An example is the one practiced in California, with the companies Pacific Gas and Electric Company (PG&E),

Southern California Edison and SDGE. The Fig. 1 shows a schedule of the time of delivery factor employed by PG&E during 2016. This schedule was planned to improve the capacity deliverability. This aim justifies a factor of more than 2 along the August until October between 4 pm to 10 pm. This schedule and scaling factors procedure must result in a mean cost over the year close to the unit. This is one of the restrictions of the problem that must be treating.

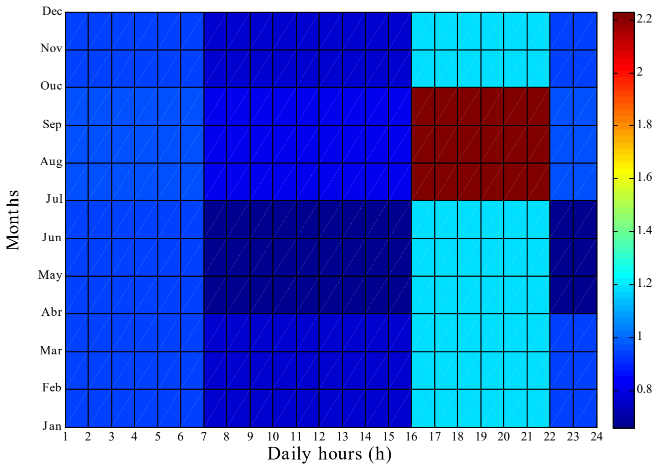

Fig. 1 Time of delivery factors of PG&E during 2016.

Another restriction to be imposed is the number of periods, which a year could be divided, and the minimum duration of each period. E.g.: the maximum number of periods in a year must be 3 and its durations shouldn't be less than 3 months. The same restriction is imposed to a day axis. There must be defined the maximum number of periods and its minimum duration. E.g.: a day can have up to 4 periods with a minimum duration of 4 hours each. In addition, The Time of Delivery factors must be enclosed in some minimum and maximum interval, e.g.: [0.7 1.3].

Based on those restrictions and with the objective of increase the returns of the generation power plant an objective function could be established as:

$$\xi = \sum_{i=1}^{M} \sum_{j=1}^{N} w_{ij} g_{ij} \tag{1}$$

where ξ is the value of the objective function; w_{ij} is factor in the *i*-th month and in the *j*-th time of day; g_{ij} is the generation at *i*-th month and in the *j*-th time of day; *M* is the number of months and *N* is the number times employed in the discretization of a day. Typically, values to *N* are 12 and to *M* are 24. The total number of factors to be estimated by the algorithm is equal to N times M. When typical values are adopted, the number of factors is 288, resulted by the number of months of the year and the number of hours of the day (12 x 24). The optimization algorithm should operate receiving g_{ij} and estimate w_{ij} that maximize ξ with subject to the restrictions presented previously.

2.2 Codifications of the feasible solutions

Each candidate solutions must be capable to represent the time of delivery schedule and factors. This representation must be design in such way that improved the restriction checking and the objective function calculus. If those desired aspects are achieved the computational performance of the optimization algorithm could be improved.

So, each candidate solution is coding in a structure composed by:

- **`strPer:`** A scalar indicating the month of the year where the first period starts;
- **`durPer:`** A vector of duration of each period. The number of elements in this vector is equal to the maximum periods desired. The sum of its elements must be equal to *M* (12 if the discretization of a year is done in months);
- **`str:`** A vector indicating the start hour of each period. The start hour informs the starting of first factor along a day;
- **`cro:`** A matrix *N* x *M* where each element coding the multiply factor;
- **`dur:`** A matrix *N* x *M* where each element coding the duration of each factor. The number of elements in this vector is equal to the maximum different factors in a day. The sum of its elements must be equal to *N* (24 if the discretization of a day is done in hours).

The same pattern of the Time of Delivery schedule and factor may have different representations. This is not resulting in problems. The pattern presented in the Fig. 1 could be represented by:

- **`strPer:4;`**
- **`durPer:[6 3 3];`**
- **`str:[7 7 7];`**
- **`cro:[0.6585 1.1941 0.9299; 0.8067 0.9569; 0.7741 1.1982 0.9399];`**
- **`dur:[9 6 9; 9 6 9; 9 6 9].`**

2.3 Genetic algorithm to planning of the time of delivery schedule and factor

The search and optimization process has several components, as: search space, where all the solution possibilities for a specific problem are considered, and the cost function, that it is the way to evaluate the elements on the search space. There are a number of search methods and evaluation functions. The traditional search and optimization techniques starts the process with only one candidate that, iteratively, is manipulated using some heuristics, normaly statics, associated straight to the problem. Normaly, these process heuristics have very complex computational simulation, in addition to don´t be sufficiently robust. That way the genetic algorithms (GA) are receiving attention, demonstrating robustness on the stochastic search applied to optimization problems. The following aspects are the differential of the GA:

- Uses the codification of a set of parameters, instead of use own parameters;
- Uses a population and not an unique point;
- Uses cost and compensation information, instead of use derivatives or other auxiliary knowledge;
- Uses probability transition rules, instead of not deterministic transition rules.Trabalham com codificação do conjunto de parâmetros e não com os próprios parâmetros.

Based on the characteristic of the problem, an approach based on Genetic Algorithms was adopted. Each generation is constituted by the evolutionary loop. The evolutionary loop is composed by a Crossing, Mutation, Evaluation and Natural Selection operators. The loop is repeated until there is no change in the fittest individual for a number of generations. The crossing operator operates only on the factor vector, since operating over the duration vector of each flag could incur transgression of the daily duration (24 hours). Parents are chosen by means of the roulette wheel algorithm in order to benefit the survival of the fittest individuals. From each crossing two children are generated, and the mutation operator acts on all the parameters that define the individual as describe in the Subsection 2.2.

The individuals and the parameters that will be mutated are chosen at random way. The mutation of the vectors occurs by permutation between the chosen elements, and the mutated individual becomes a new individual. A particularity of the algorithm implemented is to make parents living together with its children and mutated individuals. Thus, prior to the selection process, all individuals are evaluated and the fittest are more likely to survive for the next generation. The size of the population is kept constant from generation to generation.

3. OPTIMAL LAW TO CONTROL OF A BATTERY BASED STORAGE SYSTEM

Since a system has an energy storage capability and there is a possibility of different price factors during the day the charging and delivery times must be planned. This problem could be treating as an optimization one. The restrictions of this problem are the energy capability, E_{max}, and the nominal power, P_{nom}, of storage system. The objective function could be defined as:

$$\xi = \frac{1}{2}\left(\mathbf{g}-\mathbf{g}_s\right)^T \mathbf{W}\left(\mathbf{g}-\mathbf{g}_s\right) \tag{2}$$

where ξ is the objective function, $\mathbf{g}$ is the generation expected during a day, $\mathbf{g}_s$ is the charging/discharging profile to be optimized and $\mathbf{W}$ is the price factor adopted.

The restrictions of power and energy associated of the storage system could be written as:

$$\mathbf{H}\mathbf{g}_s \leq \mathbf{b} \tag{3}$$

$$\mathbf{H} = \begin{pmatrix} \mathbf{I}_{NxN} \\ \mathbf{I}_{NxN} \\ \mathbf{a}_{NxN} \\ \mathbf{a}_{NxN} \end{pmatrix};\mathbf{a} = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 1 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 1 \end{pmatrix};\mathbf{b} = \begin{pmatrix} P_{nom}\mathbf{I}_{NxN} \\ -P_{nom}\mathbf{I}_{NxN} \\ 0 \\ E_{max}\mathbf{I}_{NxN} \end{pmatrix}$$

The objective function could be defined to optimize other indexes in a power system. The definition of the objective function must be conducted take into account the location of the storage system and its associated costs. The optimization problem is configured as a quadratic optimization and could be solved by a Sequential Quadratic Programming (SQP) method.

4. RESULTS

4.1 Optimization of Time of Delivery Schedule and Factors

To present how algorithm performing an optimization of the time of delivery schedule and factor the generation profile will be used Fig. 2. In the Fig. 2, the hot colours indicating more generation need and the cold colours point out the opposite.

The Fig. 3 illustrates the optimization performance over each generation. To setup the algorithm the profile of Fig. 2 was employed; during a day is possible 4 different factors with a minimum duration of 3 hours each; along a year it is possible up to 4 seasons with a minimum duration of 2 months; the factors must be enclosed between 0.7 and 1.3. The optimized Time of Delivery Schedule and Factor achieve an increase around of 4.78% in the price of energy generated. The Fig. 4 shows a schedule of the time of delivery factor as results of optimization algorithm.

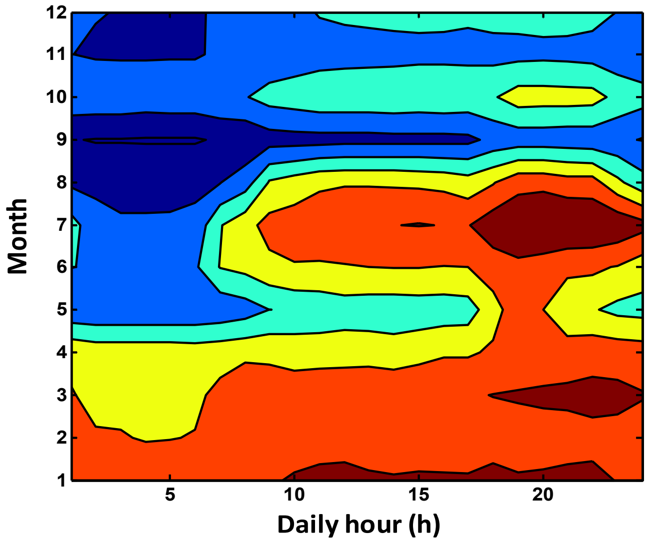

Fig. 2 Generation profile over an entire year.

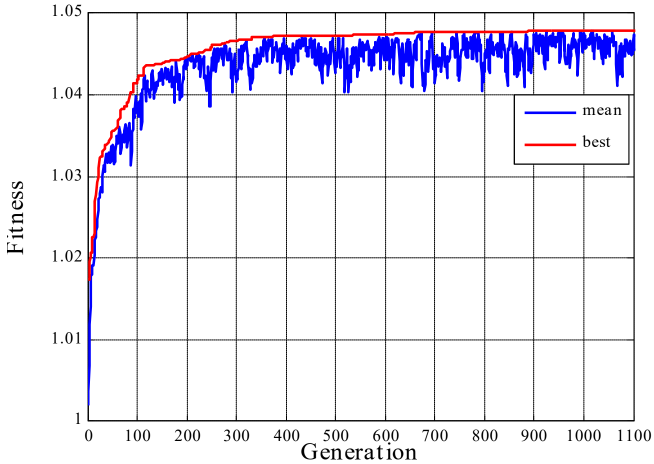

Fig. 3 Fitness over generation on the optimization of the Time of Delivery Schedule and Factor.

4.2 Optimization of the control's law of a battery-based storage system

An operation of an energy storage system may be summarized as: when de demand is lower than the mean value then system should store energy; when the demand is higher than the mean the storage system should delivery its energy. The Fig. 7 illustrate this kind of operation, which can be applied when the capacity of storage energy is not a restriction like occurs in some pumped storage system. When the capacity of storage energy is a restriction the problem of optimal operation may be treated as proposed in Section III. To present the optimal operation of a battery based storage system the generation profile presented at Fig. 8 will be considered. The storage system with 1 MVA and 1 MWh as restrictions and using the proposed modeling of the Section III has an optimal control as printed out in the Fig. 9. The storage energy along the operation is presented in the Fig. 10.

As observed in Fig. 9 the maximum power observed is lower than the nominal. Therefore, the power of the energy storage system is overestimated.

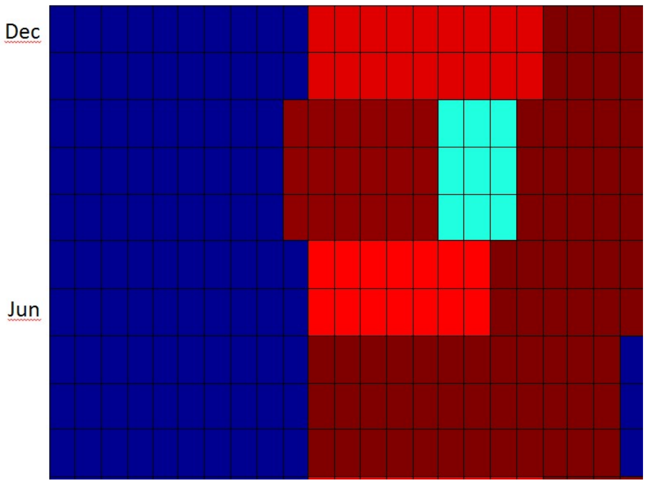

Fig. 4 Time of delivery factors of optimization algorithm.

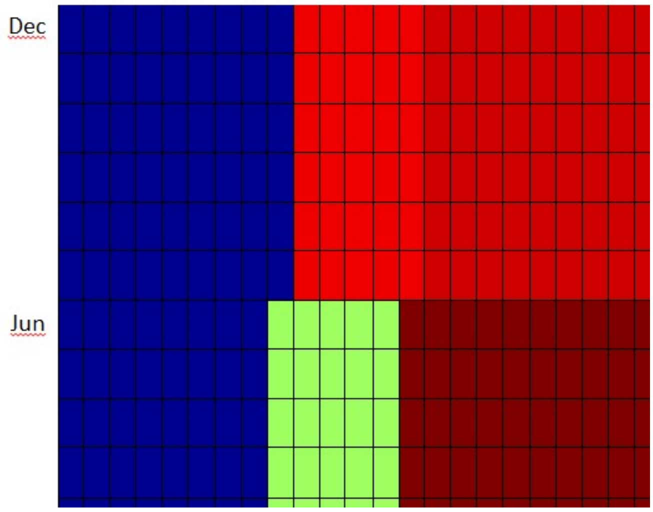

Fig. 5 Time of delivery factors of optimization algorithm with reduced degree of freedom.

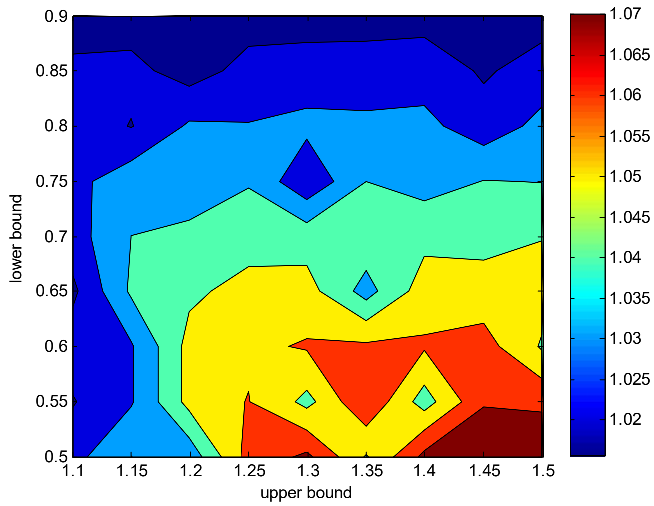

Fig. 6 Relation between the mean returns in relation of the lower and upper bound of the energy price factors.

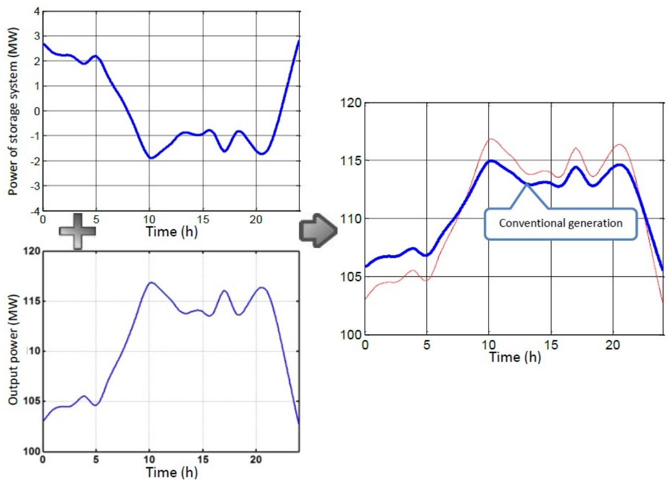

Fig.7 Summary of an energy storage system operation without restriction in the capability of storage energy.

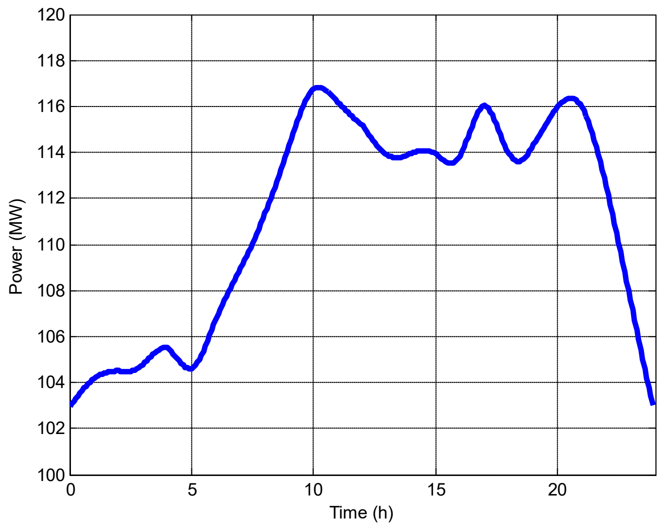

Fig.8 Generation profile.

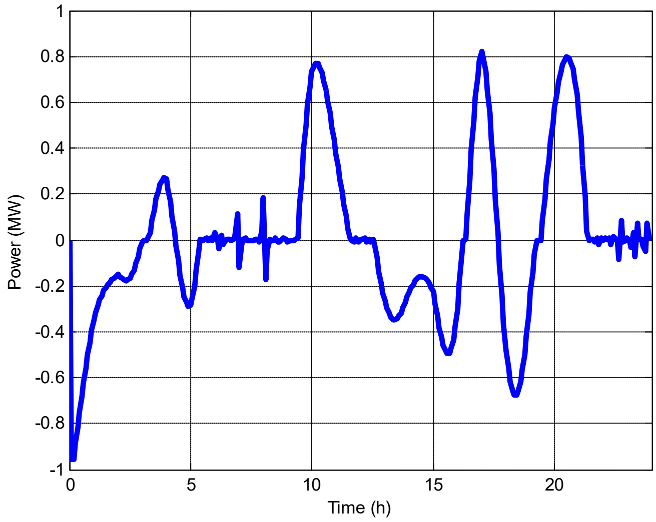

Fig. 9 Optimal operation of a battery-based energy storage system with 1 MVA and 1 MWh.

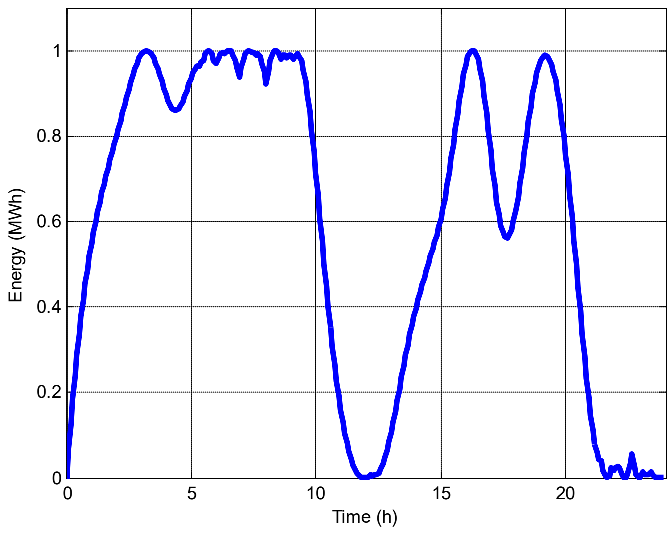

Fig. 10 Stored energy.

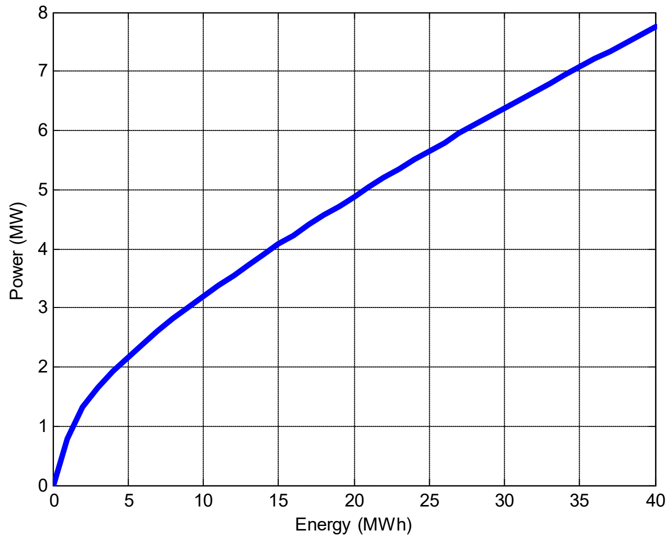

Fig. 11. Optimum relation between power and storage capability.

In fact, there is an optimum relation between power and energy of a storage system. This relation depends on the generation profile and could be estimated by the optimum operation estimated by the algorithm. Considering the generation profile of the Fig. 8 the optimum relation between the power and the energy can expressed as done in the Fig. 11.

5. CONCLUSIONS

This paper presented an evolutionary algorithm that could help in the Time of Delivery Schedule and Factor optimization. Another contribution is the modelling the operation of an energy storage system as an optimization problem that could be solved by applying the SQP method. With the obtained results, it is possible to dimension the best relation between power and storage capability of the storage system. This entire process could be repeated every time when the generation profile change. As the battery-based storage systems has a modular architecture it is possible time to time tuning the best arrangement.

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