Power Flow Control in Electric Distribution Systems Integrating Storage Devices

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Abstract: - Battery Energy Storage Systems (BESS) can nowadays be used for many applications on the electric distribution grids. They can lead to significant technical and economic benefits such as continuity of service, improvement of power quality levels, smart load management and power flow control between different interconnected electric networks. Their applications can be implemented thanks to efficient algorithms aimed to evaluate many different operating sceneries under several technical constraints. In this paper, a methodology for optimizing the power flow between different levels of electric distribution grids through the use of BESS is proposed. The problem is solved by convex optimization approach and optimal control algorithms.

Key-Words: Battery Energy Storage System (BESS); electrical distribution networks; power flow optimization; Renewable Energy Source (RES) management

1 Introduction

The increasing penetration within electrical systems of Renewable Energy Sources (RES) and Distributed Generation (DG) involves a significant innovation in the management of transmission and distribution electrical networks based on both concepts of "intelligence" and "flexibility".

In this perspective, energy storage technologies will surely bring many economic and technical benefits in terms of efficiency and functionality of today and foreseeable future electrical grids. In fact, storage devices are meant to accumulate energy and provide it during specified time periods, according to needs and management targets set by operating, functional and economic conditions.

An energy storage device can operate with the following purposes:

- to exchange high power for short times, by fractional of a second to a few tens of seconds *(power performances)*;
- to exchange power continuously for several hours *(energy performances)*;

in both cases, however, it must be able to operate at the correct power charging/discharging level as well as switch its own operating status from charging to discharging phase very quickly.

In terms of installed power, the main, traditional and widespread energy storage system is represented by pumping hydroelectric systems.

This proven technology is typically used at the level of the transmission network in order to store large amount of energy. Its use is on the rise globally.

Interesting and alternative modern technologies are represented by Battery Energy Storage System (BESS), (Compressed Air Energy Storage (CAES) and (Superconducting Magnetic Energy Storage (SMES). Due to their own feature, these are mainly used on electric distribution grids.

Actually, BESSs are experiencing a substantial growth in performances together with a simultaneous price reduction. Compared to other storage systems, their use is very interesting because a significant amount of energy can be stored easily and effectively inside the batteries and subsequently discharged during long time periods

In this context many applications have been proposed [1-3] and it is easy to predict a growing penetration of BESSs for transmission as well as distribution networks, particularly in areas with a high presence of RES plants (large wind and/or photovoltaic generators) or with weak infrastructure network. For such uses, the best performances seem to be guaranteed by Na/S and Na/NiCl high temperature batteries. Innovative technologies based on lithium ions, redox/vanadium and metal/air are actually developing.

Currently, studies are focusing on the increase of specific power of each single cell, the improvement of control systems and the overall safety and the reduction of production costs [4-7].

BESSs can also be extremely important to simultaneously provide many ancillary services such as electric energy time-shift, load following and frequency control, area regulation, electric supply reserve capacity, voltage support, power quality, demand charge management, time-of-use energy cost management, etc. [8-11].

The BESSs are extremely versatile and have proved to be a good solution in particular for microgrids with renewables and/or cogeneration units. They may be essential for the development of smart grids, not only thanks to their ability to store surplus energy and then deliver it in the most economically advantageous moments, according to a demand response logic, but also for the consequent significant increases of the levels of quality and continuity of supply of energy. Obviously, type and size of BESSs strictly depends on the services to which they will be allocated.

In recent years various methods of optimization to maximize the benefits of storage devices have been developed. These studies have involved the use of these devices inside electric system on both high and medium voltages, together with their possible insertion inside smart energy districts environments and, consequently, in urban and on low voltage lines.

The operational planning of an electrical system including traditional generators (diesel groups), RES generation (in this case wind and photovoltaic), controllable loads and BESS systems has been proposed in [12]. Tabu Search methodology and Genetic Algorithms have been developed to determine the operability of controllable loads and BESS systems within the limits of manufacturability scheduled for RES generators, using the storage to offset the cost and differences between supply and demand of electric energy.

An algorithm to maximize the use of RES reducing the running of traditional diesel generators by means of BESS systems has been proposed in [13]. The optimal dimensioning of each component was focused; the technical-economic benefit deriving from the maximization of the different types of RES is highlighted and the use of traditional generators can be reduced until 85%.

Studies have been also conducted about optimal control strategies in residential context, in order to increase synergy between the electric storage systems and mechanisms of demand response within a smart grid. The storage management is solved through dynamic programming techniques and control policies based on price thresholds and energy variables [14-16] or through convex optimization algorithms [17-19].

In this paper a methodology for the optimization of the energy flows of interchange between two electrical networks through the use of a system of nickel-sodium storage system has been developed. The BESS is used to provide services of "electric supply capacity". The storage of abundant energy and the subsequent supply at the right moment to the grid with generation deficit can avoid the use of traditional and expansive generators and lead to a global appropriate power management of network. The problem is solved by convex optimization approach.

2 Mathematical Formulation

The schematic representation of the simulated electrical system is shown in Fig. 1.

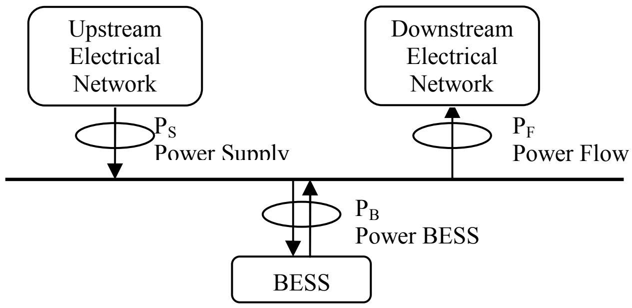

Fig. 1. Representation of electrical system

The BESS has to balance power flowing from upstream to downstream electrical network depending on:

- power deficit between generation and loads in the downstream network;
- power supply from upstream network;
- available compensating power from/to BESS;
- technical limits imposed by a system operator in order to avoid congestion of the electricity networks.

The aim is to minimize the operational costs of the BESS and, at the same time, reduce its wear and consequently extend its operational life.

The objective function to be minimized is a nonlinear function of the BESS compensating power:

$$\min \int_{t_0}^{t_f} C_B \, p_B(t) \, dt \tag{1}$$

subject to the technical constraints related to active power that upstream electrical network can supply:

$$\begin{aligned} & p_S(t) = p_F(t) \pm p_B(t) \\ & P_S^{min} \le p_S(t) \le P_S^{max} \end{aligned} \tag{2}$$

where:

- $p_S(t)$ is the power supplied by upstream electrical network according to rules of the electricity market;
- $p_F(t)$ is the power flowing to downstream electric network which depends on the difference between generation and internal energy demand;
- $p_B(t)$ is the compensating power stored inside the BESS;
- C_B is the cost per kW of BESS;
- P_S^{min} and P_S^{max} are minimum and maximum power that can be supplied by upstream electrical network;
- t_0 and, t_f are the starting/final times of operation.

The control of power flow from upstream to downstream electric networks takes into account operational limits of transmission/distribution lines imposed by the operator. Obviously, the roles of two networks are interchangeable even if such a case is not been considered in this paper.

The mathematical formulation of problem describes the behavior of BESS during charge/discharge operations by means of the state variable represented by the amount of energy stored in the BESS.

The following differential equation are provided:

$$\dot{q}_B(t) = f(p_B(t), q_B(t)) \tag{3}$$

subject to the constraints of min/max charge level and charge/discharge power:

$$\begin{aligned} & Q_B^{min} \le q_B(t) \le Q_B^{max} \\ & P_B^{discharge} \le p_B(t) \le P_B^{charge} \end{aligned} \tag{4}$$

where:

- $q_B(t)$ is the BESS capacity (storable energy);
- Q_B^{min} and Q_B^{max} are the min and max storable energy in the BESS;
- $P_B^{discharge}$ and P_B^{charge} are the power discharge and charge level of the BESS.

The optimal control can be solved as a problem of nonlinear programming by discretizing (1).

This approach leads to the following formulation:

$$\min \sum_{j=1}^{T} C_B \, P_B^j \tag{5}$$

subject to inequalities:

$$\begin{aligned} & P_S^{min} \le P_B^j \le P_S^{max} \\ & Q_B^{min} \le Q_B^j \le Q_B^{max} \\ & P_B^{discharge} \le P_B^j \le Q_B^{charge} \end{aligned} \tag{6}$$

It is assumed that, during the generic j-th time period, the state Q_B and control P_B variables remain constant. The duration of the j-th time period is considered equal to fixed period of analysis Δt.

The stored energy will be given by the following equation:

$$Q_B^j = Q_B^0 + \sum_{k=1}^{j} F_B \, P_B^k \, \Delta t \tag{7}$$

where:

- $Q_B^0 = q_B(t_0)$ is the initial charge of the BESS;
- Q_B^j is the charge of the BESS at the end of j-th period;
- P_B^k is the compensating power of the BESS during the k-th period;
- F_B is a matrix whose elements are constants and related to the charging/discharging power of BESS, its efficiency and compensating power flow

The cost per kW of BESS C_B can be expressed as:

$$C_B = \frac{C_B^{rep}}{\left(Q_B^{max} - Q_B^{min}\right) n_{cycle}} P_B^j \, \Delta t \tag{8}$$

where:

- C_B^{rep} is the cost of replacing the BESS;
- n_{cycle} is the total number of full charge/discharge cycles of BESS before its replacement.

3 Numerical Examples

The mathematical formulation has been implemented through the use of Matlab software. In particular, the optimization problem was solved by means of the "fmincon" function, which allows to search for the minimum of a multivariable constrained nonlinear function. This function uses an "interior point" mathematical structure.

The control algorithm is of predictive type in order to forecast future energy fluctuations of the downstream network and the handling of BESS in order to compensate the power passing through. Every constraint of nonlinear programming have been imposed by appropriate programming formulations taking into account the round-trip efficiency η (efficiency of the cycle of charge/discharge) of the installed BESS to obtain a simulation as reliable as possible. The optimization procedure was implemented by considering a time period of 24 h.

Test case 1

The proposed methodology was tested on the system configuration represented in Fig. 1.

A 1.5 MWh BESS recently marketed by one of the most important electric devices manufacturing companies was assumed for test simulations. The total energy production and load curves have been detected and provided by an Italian distribution system operator and represent real data recorded on its electric grids on the day 06.14.2014

In order to exploit the advantages of optimization procedure, an initial state of charge equal to 100% for the batteries has been hypothesized. The input data are shown in Tables 1 and 2.

TABLE 1. Upstream electrical network data

Minimum power supply	P_S^{min}	500 [kW]
Maximum power supply	P_S^{max}	2.000 [kW]

TABLE 2. Technical and economical data of BESS

Capacity	Q_B	1.500 [kWh]
Maximum charge power	P_B^{charge}	750 [kW]
Maximum discharge power	$P_B^{discharge}$	750 [kW]
Maximum charge level	Q_B^{max}	1.500 [kWh]
Minimum charge level	Q_B^{min}	450 [kWh]
Initial charge level	Q_B^0	100%
Life cycles	n_{cycle}	4.500
Roundtrip efficiency	η	80 [p.u.]
Replacing Cost	C_B^{rep}	1.500 [k€]

In Fig. 2 the charging/discharging/level power of BESS and the power flow transiting towards the downstream network are shown, for the whole 24 hours period.

The power supply by upstream network meets the technical constraints imposed as well as the global energy balance of the primary station distribution. It was possible to achieve this objective through a correct sizing of the battery capacity and an optimal management which guarantee the best possible use. The predictive control has fundamental importance in order to ensure the flow of compensating power necessary to balance the flows transiting between the two networks at any time of the day.

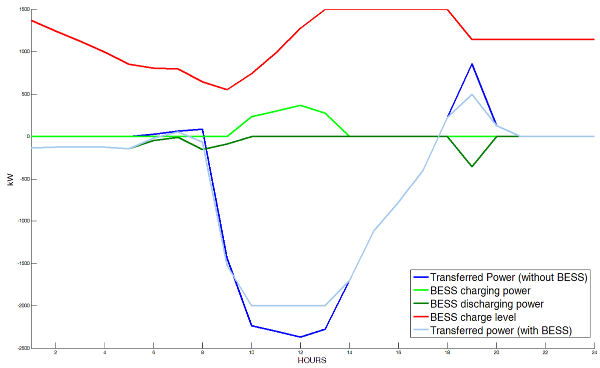

Fig. 2. Power flows from upstream to downstream network

In fact, the control algorithm provides for the need between 10.00 and 13.00 on balance the power flow in transit, caused by an excess production of the downstream network, draining the battery and preparing to absorb and store the power flow in excess. It may be noted also as the power flow of the battery never reaches values close to the maximum discharge power or charge. This result translates into a lower risk of failure of the battery system.

The simulation was performed within 24 hours of a working day; expanding the simulation period could most likely provide better results, due to the possibility of the predictive control algorithm to optimize the flow of power and compensating the state of charge for a broader time period.

Test case 2

A second simulation was executed considering the presence of RES (photovoltaic and wind generators) inside the distribution systems. In this case, the BESS system is used not only to balance power between the electric networks but also for an optimal management of additional RES generation by storing energy during time periods of highest generation and releasing it in case of profitable economical or technical conditions.

The PV and wind production has been estimated considering historical data provided by the same Italian network operator. The data are referred to a 2013 summer day, with high solar radiation and moderate winds. The maximum power output reached by the Distributed Generation units is equal to 1000 kW.

As shown in Fig. 3, the optimal control approach has been able to assure a reliable management of loads and both generated and stored energy.

However, it is noteworthy that the high O&M cost of BESS causes some curtailments regarding interruptible loads. These situations, however, took place for very limited timeframes.

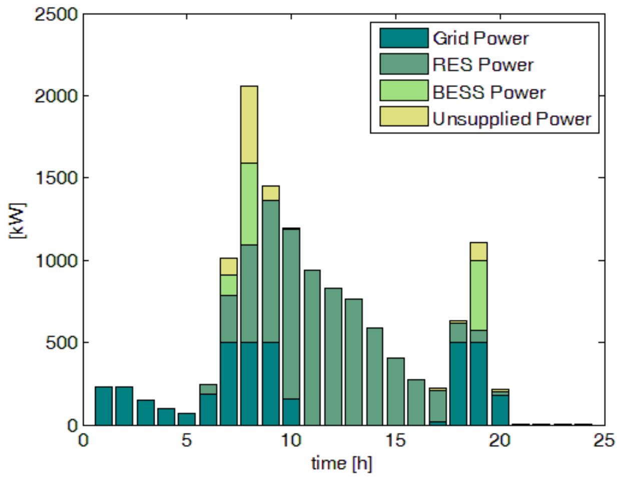

Fig.3. Grid, RES and BESS supplied power

Figure 4 gives a representation of power exchanges between the two electric networks during the optimization window. Positive values indicate that the flow was going from upstream to downstream network, while negative values indicate that downstream grid was able to feed the upper level network thanks to stored energy and/or abundant production from RES.

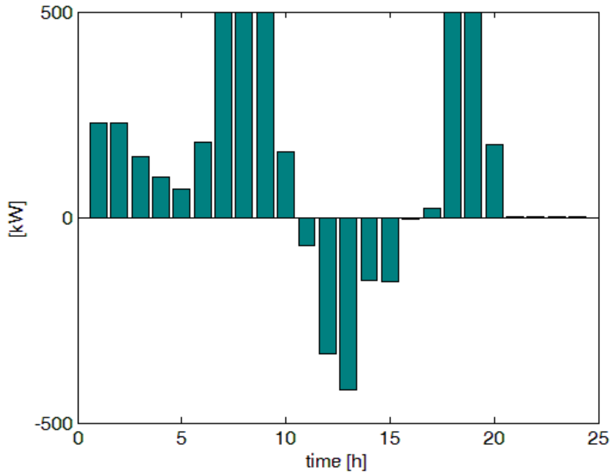

Fig. 4. Power streams between the grids

Figures 5 and 6, finally, point out the different charge levels and the charge/discharge power of BESS system during the simulation periods.

The test cases show optimal economic results and real technical possibility to control power flow in electric distribution system by using BESSs.

The only inconvenient is represented by still high replacing cost of BESS but the nowadays price reduction trend opens up new and interesting perspectives. In fact, this issue is destined to be eliminate in a very next future thanks to expected technical improvements in storage technologies, that will assure to them a longer life, and necessary lower purchase prices.

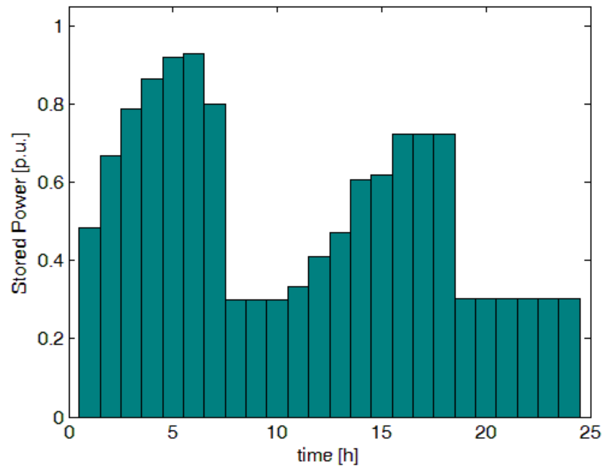

Fig.5. BESS charge level

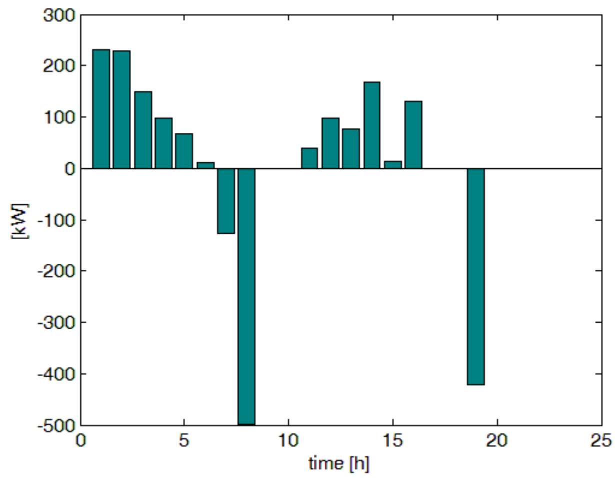

Fig. 6. BESS Charge/Discharge Power

4 Conclusions

In this paper, a methodology for the optimization of energy flows between different grids through the use of Battery Energy Storage Systems (BESSs) has been discussed. A convex optimization approach, based on optimal control theory, has been pursued.

Simulations were developed according two possible scenery, including or not the presence of RES inside the electric networks. Results show how BESSs are able to assure a better management of power flows between two connected grids.

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