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Battery energy storage systems as a way to integrate renewable energy in small isolated power systems

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ABSTRACT

Isolated power systems present high levels of Renewable Energy Sources (RES) curtailment as intermittency and isolation impose challenging difficulties regarding the integration of this energy into the electrical grid. The recent developments in electrical vehicles have decreased the kWh cost of lithium-ion batteries below a threshold value that was previously prohibitive for grid-scale applications. Therefore, the integration of RES considering the installation of a Battery Energy Storage System (BESS) into an isolated power grid is an up-to-date research topic and is assessed in this paper. The BESS is inserted into the Unit Commitment and Economic Dispatch (UC + ED) platform and regarded as another dispatchable generator. To keeps the costs down, the BESS is mainly used to provide a portion of the spinning reserve needs and secondly to alleviate the load of the thermal generators, using the free modules. The BESS configurations that maximises the economic viability and minimises the RES curtailment are presented. The results suggest that the investment in this technology may be profitable and considerably decreases the levels of RES curtailment.

Introduction

All over the world, power systems are currently being challenged with the growing integration of Renewable Energy Sources (RES). RES are environmentally friendly and, in many situations, are cheaper than conventional technologies. However, most of RES, mainly wind and solar, have the disadvantage of being variable in a way that is not controllable. For instance, PhotoVoltaic (PV) or wind turbines are able to generate electricity if the sun is shining or if the wind is blowing. Additionally, as they depend on weather conditions, oscillations on the available power do occur without warning. This profile of RES defines the so-called intermittency.

In large interconnected power systems, this is an issue (perhaps not a problem) that is being currently dealt with by the system operators with success. However, in small isolated system this is certainly a problem. By isolated systems it is meant islanded systems i.e. micro-grids (a few tens of MW installed generating capacity) that are not interconnected to other power systems, interconnected systems being the case of mainland power systems. The electrification of small rural areas using, for instance, RES and batteries is outside the scope of this approach.

The problem gets even more complicated when the portion of renewable power injected into the grid is relatively high as compared to the power assigned to the conventional, usually thermal, generators. To solve this problem, utilities may be forced to curtail the output of renewable power plants to a level that does not interfere with the system's constraints. This technique may result in curtailing a considerable percentage of environmentally friendly renewable energy, which is replaced by more reliable power sources, such as fossil fuel fired thermal generators, but environmentally harmful.

Islanded power systems with a significant penetration of RES power have to deal not only with intermittency, but also with their isolation. If there is a surplus or a deficit of energy, the grid operator cannot transfer the energy to or from any other place, namely neighbour countries. Additionally, isolated power systems require a considerable margin of spinning reserve due to the intermittency of RES. Spinning reserve is generation capacity that is online but unloaded and that can rapidly respond to compensate for generation outages or load deviations and is normally ensured by thermal generators. Islanded power systems are usually composed by small diesel generators that generate expensive electrical power. All these factors combined are the reason why these islanded power systems show the highest levels of RES curtailment. As a consequence, these utilities are the most interested ones in finding solutions for this problem, because increasing the integration of RES results in reducing the fuel costs of running thermal generators and has environmental benefits.

In island isolated systems, one of the main challenges is to avoid RES curtailment. This is particularly challenging because, as the RES power injected into the grid increases, the power assigned to conventional

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Nomenclature

t is the time period index
i is the thermal generator index
j is the state index
k is the year index
$TotalCost$ is the most economic sequence of feasible states (€)
$StateCost$ is the cost of each feasible state that composes the sequence (€)
S_{upci} is the start-up cost of thermal generator i (€)
S_{dwci} is the shutdown cost of thermal generator i (€)
$Cost_i$ is the production cost for thermal generator i, given by a quadratic function $Cost_i = a_i + b_i P_i(t) + c_i P_i^2(t)$ (€)
$D(t)$ is the residual demand assigned to the thermal generators at time t (MW)
$P_i(t)$ is the output power of the thermal generator i at time t (MW)
$D_L(t)$ is the total demand required by customers at time t (MW)
$P_{RES}(t)$ is the RES output power at time t (MW)
$P_{state_j}{}^{\min}$ is the technical minimum power output of state j (MW)
$P_{state_j}{}^{\max}$ is the maximum power output of state j (MW)
$P_i^{\max}$ is the maximum output power of thermal generator i (MW)
$P_i^{\min}$ is the technical minimum power output of thermal generator i (MW)
$SR_{total}(t)$ is the total spinning reserve needs at time t (MW)
$SR_{gen}(t)$ is the rated power of the largest online thermal generator at time t (MW)
$SR_{RES}(t)$ is the spinning reserve requirements to ensure reliable RES power at time t (MW)
$W_{speed}(t)$ is the average wind speed at the wind parks at time t (m/s)
Pr_{WG} is the rated power of the wind parks at time t (MW)
$Pg_{WG}(t)$ is the total output power at the wind parks at time t (MW)
$lbP_i(t)$ is the lowest output power of thermal generator i, at time t (MW)
$ubP_i(t)$ is the upper operating bound of thermal generator i, at time t (MW)
$RPdwn_i$ is the ramp-down power rate of thermal generator i (MW/h)
$RPup_i$ is the ramp-up power rate of thermal generator i (MW/h)
$X_i(t)$ is an integer variable that indicates the time periods in which the generator is online or offline
$Gmindwn_i$ is the minimum downtime of thermal generator i, which is the minimum time that the generator must remain stopped once it is shutdown (h)
$G\min up_i$ is the minimum uptime of thermal generator i, which is the minimum time that the generator must remain operating once it is running (h)
$E(t)$ is the energy stored in the BESS at time t (MWh)
$E_{BESS}^{\max}$ is the nominal storable energy of the BESS (MWh)
N_{mod} is the number of modules that compose the BESS
P_{BESS} is the rated power of the BESS (MW)
P_{inv} is the inverter rated power (MW)
$N_{\mathrm{mod}}^{used}(t)$ is the number of used modules at time t
$ceil$ is the ceiling division function; $ceil(x) = \lceil x \rceil$ is the least integer greater than or equal to x
$P_{BESS}^{C}(t)$ is the power charged to the BESS (MW)
$P_{BESS}^{D}(t)$ is the power discharged from the BESS (MW)
P_{BESS}^{in} is the power absorbed from the grid to the BESS (MW)
P_{BESS}^{out} is the power released to the grid from the BESS (MW)
η_{BESS}^{C} is the charging efficiency of the BESS (%)
η_{BESS}^{D} is the discharging efficiency of the BESS (%)
δ_{DoD} is the depth of discharge (%)
N_{cycles} is the number of cycles of the BESS
f is the probability density function of the Beta distribution
F is the cumulative distribution function of the Beta distribution
Γ is the gamma function
SR_{used} is the effective utilisation of spinning reserve
$SR_{\min}$ is the minimum spinning reserve down
$SR_{\max}$ is the maximum spinning reserve up
$BESS_{SR}(t)$ is the portion of spinning reserve assigned to the BESS at time t (MW)
$N_{M1}(t)$ is the number of modules used by the FPF at time t
$P_{Curt}(t)$ is the RES curtailed power at time t (MW)
$P_{FREE\_CH}(t)$ is the sum of the power of the available modules for charging purposes at time t (MW)
$N_{FREE\_CH}(t)$ is the number of available modules to charge at time t
$N_{M2}(t)$ is the number of modules used by the SPF at time t
$P_{AV\_DISCH}(t)$ is the power available to be lowered from generators at time t (MW)
$P_{FREE\_DISCH}(t)$ is the sum of the power of the available modules, for discharging purposes at time t (MW)
$N_{FREE\_DISCH}(t)$ is the number of available modules to discharge at time t
$N_{M3}(t)$ is the number of modules used by the TPF at time t
$\xi_{Curtail}$ is the total reduction in curtailment (%)
$Curt_{w/oBESS}$ is the yearly RES curtailment without BESS (MWh)
$Curt_{w/BESS}$ is the yearly RES curtailment with BESS (MWh)
N_{cycles}^{used} is the total number of cycles used in one year
E_{ch} is the energy charged into the BESS in one year (MWh)
NPV is the net present value of the project (€)
n is the equipment lifetime
CF_k is the cash flow for year k (€), equal to the net yearly profit
a is the discount rate (%)
I_0 is the investment cost (€)
R_k is the gross revenue at year k (€)
$FC_{w/oBESS_k}$ is the total fuel costs of the thermal generators without BESS at year k (€)
$FC_{w/BESS_k}$ is the total fuel costs of the thermal generators with BESS at year k (€)
$O\,\&\,MC_{BESS_k}$ is the operation & maintenance cost of the BESS at year k (€)

generators decreases, which may lead to infringements of the thermal generators technical minimum related constraints. In case of infringement, RES power curtailment is the solution at hand, as it increases the power assigned to the conventional generators.

The main conventional generators' constraint states that the power system should operate with a combination of thermal generators that is able to simultaneously generate their assigned power and ensure the total spinning reserve requirements. If the selected combination of generators does not comply with this constraint, the system searches for another combination of generators, by turning on or shutting down units, which exhibit a higher technical minimum power output and can supply both the demand and spinning reserve. If this new technical minimum is higher than the previous demand assigned to the generators, the system is obliged to incur into RES curtailment. The required curtailment power is the difference between the previous demand assigned to the generators and the technical minimum power of the combination of generators selected now.

The recent developments of electrical vehicles have decreased the kWh cost of lithium-ion (Li-Ion) batteries below a threshold value that