Enhanced Security-Constrained OPF With Distributed Battery Energy Storage

Yunfeng Wen, *Student Member, IEEE*, Chuangxin Guo, *Member, IEEE*, Daniel S. Kirschen, *Fellow, IEEE*, and Shufeng Dong

***Abstract*—This paper discusses how fast-response distributed battery energy storage could be used to implement post-contingency corrective control actions. Immediately after a contingency, the injections of distributed batteries could be adjusted to alleviate overloads and reduce flows below their short-term emergency rating. This ensures that the post-contingency system remains stable until the operator has redispatched the generation. Implementing this form of corrective control would allow operators to take advantage of the difference between the short- and long-term ratings of the lines and would therefore increase the available transmission capacity. This problem is formulated as a two-stage, enhanced security-constrained OPF problem, in which the first-stage optimizes the pre-contingency generation dispatch, while the second-stage minimizes the corrective actions for each contingency. Case studies based on a six-bus test system and on the RTS 96 demonstrate that the proposed method provides effective corrective actions and can guarantee operational reliability and economy.**

***Index Terms*—Benders decomposition, energy storage, optimal power flow, security-constrained optimal power flow.**

NOMENCLATURE

Indices and Sets:

i	Index to the set of generators.
j	Index to the set of cost curve segments.
k	Index of contingencies in the long-term period.
k'	Index of contingencies in the short-term period.
l	Index to the set of transmission lines.
m	Index to the set of batteries.
n	Index to the set of load buses.
N_{C}	Set of contingencies.
N_D	Set of load buses.
N_{G}	Set of generators.
N_{L}	Set of transmission lines.
N_{S}	Set of batteries.
N_Z	Set of segments of the piecewise linear generator cost function.

Parameters:

$E_m^{\max}$	Energy capacity of battery m [MWh].
$F^{\max}$	Vector of long-term flow limits [MW].
$F_{\mathrm{G}i}^{\min}$	Fixed cost of generator i [$].
$PC_m^{\max}$	Maximum charging power limits of battery m [MW].
$PD_m^{\max}$	Maximum discharging power limits of battery m [MW].
$PG_i^{\max}$	Maximum active power output of generator i [MW].
$PG_i^{\min}$	Minimum active power output of generator i [MW].
PL	Vector of load injections [MW].
PL_n	Load at bus n [MW].
T^0, T^k	Shift factor matrices for the base case and kth contingency conditions.
z_{ij}	Marginal cost of generator i on segment j [$/MW].
τ_1	Response time of the generators [min].
τ_2	Ramping time of the generators [min].
γ	Vector of factors relating the short- and long-term ratings of the branches.
$\Delta PG_i^{\max}$	Maximum possible redispatch of generator i during the ramping period (τ_2) [MW].
$\Delta PG_{ij}^{\max}$	Length of segment j of the output curve of generator i [MW].
$\Delta u^{\max}$	Vector of maximum allowed adjustments of control variables.

Manuscript received June 10, 2013; revised October 02, 2013, December 20, 2013, and March 04, 2014; accepted April 28, 2014. Date of publication May 19, 2014; date of current version December 18, 2014. The work of Y. Wen, C. Guo, and S. Dong was supported in part by the State Key Development Program for Basic Research of China (2013CB228206), in part by the National Natural Science Foundation of China (51177143), and in part by the Zhejiang Province Natural Science Key Foundation (LZ12E07002); The work of D. S. Kirschen was supported in part by the Department of Energy ARPA-E GENI program under research grant DE-AR0000232 and by the State of Washington STARS program . Paper no. TPWRS-00756-2013.

Y. Wen, C. Guo, and S. Dong are with the College of Electrical Engineering, Zhejiang University, Hangzhou, Zhejiang Province 310027, China (e-mail: yunfeng.8681@163.com).

D. S. Kirschen is with the Department of Electrical Engineering, University of Washington, Seattle, WA 98195 USA (e-mail: kirschen@uw.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2014.2321181

Variables:

u^0, u^k	Vector of control variables for the base case and long-term period following contingency k.
x^0	Vector of state variables for the base case.
$x^{k'}$, x^k	Vector of state variables for the post-contingency short- and long-term period.
E_m	Energy stored in battery m [MWh].
EC_m	Maximum energy that battery m must be able to charge to cope with all contingencies [MWh].
ED_m	Maximum energy that battery m must be able to discharge to cope with all contingencies [MWh].
$PC^{k'}$	Vector of battery charging power [MW].
$PC_m^{k'}$	Power that battery m must charge to deal with contingency k [MW].
$PD^{k'}$	Vector of battery discharging power [MW].
$PD_m^{k'}$	Power that battery m must discharge to deal with contingency k [MW].
PG^0	Vector of power output of generators for the base case [MW].
$PG^{k'}$	Vector of power output of generators immediately following an outage [MW].
PG^k	Vector of generator injections following redispatch [MW].
ΔPG_{ij}^0	Power produced by generator i on segment j of its cost curve [MW].
ΔPG_i^{k+}	Long-term increase in the output of generator i following contingency k [MW].
ΔPG_i^{k-}	Long-term decrease in the output of generator i following contingency k [MW].

I. Introduction

POWER systems are usually operated according to the preventive security paradigm which requires that, following any credible contingency, all flows and voltages should remain within prescribed limits [1]. These limits are set in such a way that: 1) the post-contingency system will remain stable until operators take any actions; 2) no protection actions would occur prior to operators take these actions. However, this preventive security paradigm is costly because it often involves scheduling or dispatching generating units in a less than economically optimal manner for long periods of time to guard against contingencies that occur rarely. For some difficult operating conditions and severe contingencies, preventive security may not even be possible. Interest in corrective security has thus been growing in recent years [2]–[4]. Under the corrective security paradigm, post-contingency corrective actions may be necessary to remove overloads and correct unacceptable voltages that could trigger cascading outages. Since these actions are taken only in the event of a contingency, corrective security is cheaper than preventive security because the system can be operated closer to its economic optimum most of the time. However, the post-contingency relief of overloads usually depends on the availability of generating units that can be redispatched quickly. If there are not enough of these units or if their ramp rates are relatively slow, the scope for post-contingency corrective control is limited.

The availability of battery energy storage systems would considerably increase this scope because these devices have much faster ramp rates and could be distributed across the transmission network. They would therefore be able to relieve more and larger overloads faster and could therefore support the implementation of corrective control on a more ambitious scale. However, the effectiveness of batteries for corrective control is constrained not only by their ramp rate and power rating but also by the amount of energy that they are able to inject or store before other control actions take effect.

This paper describes how the operation of distributed battery energy storage for corrective control can be optimized as part of an enhanced security constrained optimal power flow (SCOPF).

II. Literature Review

Batteries can be used for a variety of applications in power systems. Several battery energy storage systems have been installed to provide load following and peak shaving [5], [6]. A method for the dimensioning of a battery energy storage system to provide a primary frequency reserve was presented in [7]. In [8], a PV/battery combination is introduced into a security constrained unit commitment that manages the economics and security of the grid. Arabi and Kundur [9] discuss the modeling and data requirements for batteries used in power system stability studies. Batteries are also an attractive means of providing the flexibility needed to support the integration of stochastic and intermittent renewable energy sources [10], [11].

This paper considers only the additional benefits that fast response of batteries [12], [13] could provide in terms of corrective power system security. Except under special circumstances, the financial benefits that might be derived from the use of batteries for corrective control are unlikely to justify the cost of buying and installing these batteries. However, using these batteries for corrective control is not incompatible with other applications, such as arbitrage, frequency control and providing reserve for generator contingencies. Adding the benefits of these various applications (while taking into account the constraints that they place on each other) might be sufficient to justify investments in distributed batteries.

The operation of batteries for post-contingency corrective control must be part of the solution of an SCOPF. Alsac and Stott were the first to formulate the SCOPF problem [14]. A comprehensive review of recent developments in this area can be found in [15].

Utilities define several thermal limits, such as normal (continuous) rating, short-term emergency rating and long-term emergency rating, in order to avoid damaging power equipment by causing excessively high temperatures in components [16]. This feature can be modeled in the SCOPF as follows:

$$\min_{x^0,u^0,x^{k'},x^k,u^k} \quad f^0(x^0,u^0) \tag{1a}$$

$$\text{s.t.} \quad g^0(x^0,u^0)=0 \tag{1b}$$

$$h^0(x^0,u^0)\le F^{\max} \tag{1c}$$

$$g^{k'}(x^{k'},u^0)=0 \tag{1d}$$

$$h^{k'}(x^{k'},u^0)\le \gamma F^{\max} \tag{1e}$$

$$g^k(x^k,u^k)=0 \tag{1f}$$

$$h^k(x^k,u^k)\le F^{\max} \tag{1g}$$

$$\left|u^k-u^0\right|\le \Delta u^{\max} \tag{1h}$$

where variables with the superscript 0 denote state and control variables in the base case, variables with apostrophes denote post-contingency short-term state and control variables (i.e., immediately after the contingency and thus before the start of the generation redispatch), variables without an apostrophe denote post-contingency long-term state and control variables. Note that in SCOPF, the long-term emergency ratings are usually set to be the same as normal ratings.

When no post-contingency corrective actions are allowed ($\Delta u^{\max}=0$), the SCOPF operates in preventive mode and is then often called PSCOPF. On the other hand, when such corrective actions are possible ($\Delta u^{\max}>0$), the SCOPF operates in corrective mode and is called CSCOPF.

The standard CSCOPF formulation [considering the pre-contingency and post-contingency long-term constraints (1b)–(1c), (1f)–(1h)] [2]–[4], [17], [18], implicitly assumes that the immediate post-contingency state of the system is sufficiently stable to endure until the operator redispatches generation or implements other corrective control actions. In this formulation, which is denoted CSCOPF-I hereafter, the short-term emergency rating (γ) of the lines and transformers is assumed to be sufficiently large that the post-contingency short-term security constraints (1d), (1e) can be ignored during this emergency period (typically 15 min [19]).

A drawback of the CSCOPF-I formulation is that under stressed conditions, post-contingency flows may exceed their short-term emergency ratings. This could result in cascading lines outage before corrective actions have taken effect. To mitigate this problem, some authors have proposed a combined preventive/corrective CSCOPF formulation (CSCOPF-II) that imposes existence and viability constraints (1d), (1e) on the short-term state. In [20], constraints enforce both the post-contingency short-term (emergency) limits and the long-term (normal) operating limits. The authors of [21] propose an adjustable relaxation of the post-contingency limits, which allows them to explore the tradeoff between the cost and the level of security provided by the CSCOPF solution. CSCOPF-II is therefore more likely than CSCOPF-I to appeal to system operators because it does not ignore the short-term emergency ratings. However, in the absence of fast control resources, it relies on preventive measures to ensure security during the short-term emergency period, and these preventive measures increase the cost of the solution.

The following section describes an enhanced SCOPF (ESCOPF) that takes into account the fast-response corrective capability of distributed batteries. The ESCOPF is a two-stage optimization problem: the first-stage optimizes the pre-contingency generation dispatch, while the second-stage minimizes the corrective actions for each contingency state. These corrective actions include both short-term injections from batteries and the long-term redispatch of generators. For the sake of simplicity, contingencies due to a generator outage are not considered, and it is assumed that the contingencies do not cause transient or voltage instabilities.

III. Corrective Control Strategy

The operation strategy of batteries for corrective security purpose is proposed as follows:

Step 1) Following the occurrence of contingency k at time t_0, one or more fast-response distributed batteries inject power (PS^k) starting at time t_1 to bring the branch flows back down within their emergency rating.

Step 2) The power injections from the batteries remain constant until time t_2 when the generators start ramping.

Step 3) During the ramping period from time t_2 to t_3, the batteries continuously reduce their injections until they reach zero, while the generators ramp their output up or down.

Step 4) The flows in the overloaded lines decrease linearly until they reach their continuous rating at time t_3.

The response time of the batteries (from t_0 to t_1) is very small compared to the other time periods and can be ignored. The amount of energy that a battery must be able to discharge or charge to help deal with the kth contingency is thus

$$ES^k=(\tau_1+0.5\tau_2)PS^k \tag{2}$$

where $\tau_1=t_2-t_1$ and $\tau_2=t_3-t_2$.

Figs. 1–4 illustrate this model using a two-bus system. Immediately after the outage of line L_{12}^b at time t_0, the post-contingency flow $F_{12}^{a'}$ on line L_{12}^a exceeds its short-term emergency rating (F_{ST}). At time t_1 battery S2 starts discharging and injects *PS* to bring the flow in line L_{12}^a back to its short-term emergency rating. To keep the system in balance, battery S1 starts charging and thus extracts the same amount of power *PS* from the system. These coordinated injections maintain the stability of the system for a period τ_1, which gives generators time to start ramping. From time t_2 onwards, the flow F_{12}^a on the overloaded line decreases as generator G2 ramps up and generator G1 ramps down while the two batteries reduce their injection or extraction. At time t_3 the flow in line L_{12}^a reaches its continuous rating F_{LT}. Battery S2 must therefore be able to deliver an amount of energy proportional to the area ABDFA, while battery S1 must be able to store an amount of energy proportional to the area ACEFA.

IV. ESCOPF Formulation

Fig. 5 shows the two-stage structure of the ESCOPF. The first-stage problem determines the optimal state and control variables for the pre-contingency state ($t\le t_0$), and ensures the feasibility of the corrective post-contingency states. Based on

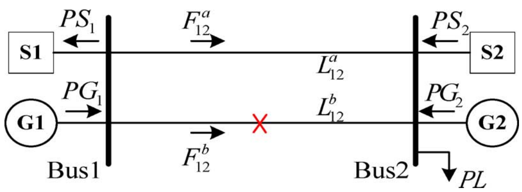


Fig. 1. Two-bus system.

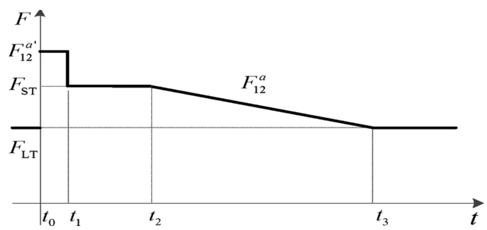


Fig. 2. Flow in line L_{12}^{a}.

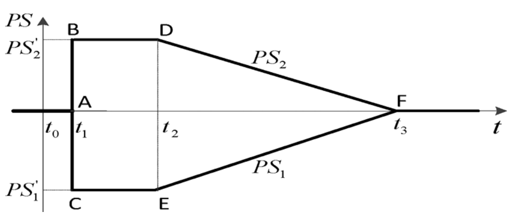


Fig. 3. Power injections by the two batteries.

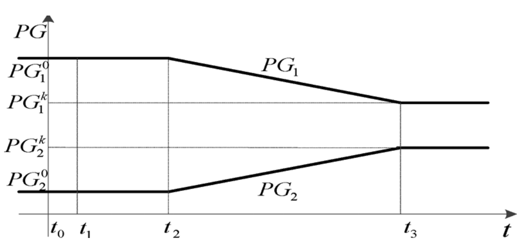


Fig. 4. Power output of the two generators.

the pre-contingency dispatch (PG^0) obtained in the first-stage problem, for each contingency, two types of second-stage problems seek the optimal corrective actions at operating points t_1 (immediately following the occurrence of a contingency) and t_3 (when the generators and batteries have stopped ramping). Given the corrective actions at these two key operating points, the post-contingency short- and long-term violations on all branches can be alleviated within their respective timeframes.

It is assumed that the energy that the batteries must be able to inject or extract to cope with the contingencies in the short-term is small compared to their overall energy rating because the deployment of batteries will usually be justified based on their use for arbitrage, which requires considerably more energy than the type of corrective actions that we are considering, therefore the state of charge of batteries along the operational timeframe is not included in the ESCOPF.

In addition, since the post-contingency flows on all the branches would be kept below their short-term emergency rating during the ramping period (t_2 to t_3, see Fig. 2), as in the traditional CSCOPF problems, the security constraints

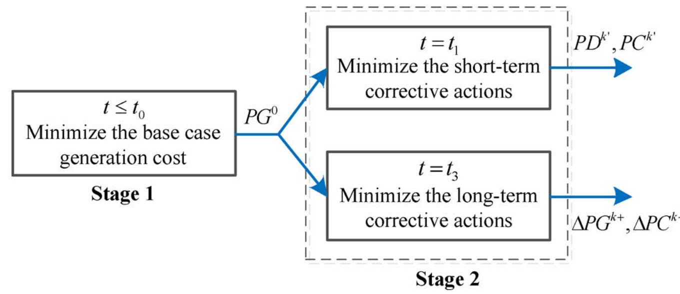


Fig. 5. Structure of the ESCOPF problem.

associated with the ramping process are not considered in the ESCOPF model.

A. Stage 1: Minimization of the Generation Cost

The first-stage problem determines a most cost-effective operating point (PG^0) for the pre-contingency state. If the operating cost of the generators is represented using a piecewise linear cost curve, the objective function of this problem is

$$\min_{\Delta PG_{ij}^{0}, PD_m^{k'}, PC_m^{k'}, \Delta PG_i^{k+}, \Delta PG_i^{k-}} \sum_{i\in N_{\mathrm{G}}} \Big(F_{\mathrm{G}_i}^{\min} + \sum_{j\in N_Z} z_{ij}\Delta PG_{ij}^{0}\Big). \tag{3a}$$

The feasibility space of PG^0 is not only constrained by the pre-contingency operational limits but also by the post-contingency limits required to ensure the feasibility of the second-stage problems:

1) Base Case Constraints: The total power output of generator i must be equal to the sum of the power generated in each segment of the cost curve plus its minimum power output:

$$PG_i^0 = PG_i^{\min} + \sum_{j\in N_Z} \Delta PG_{ij}^0, \forall i \in N_{\mathrm{G}} \tag{3b}$$

where the power generated in each segment of the cost curve should be within its limits:

$$0 \le \Delta PG_{ij}^0 \le \Delta PG_{ij}^{\max}, \forall i \in N_{\mathrm{G}}, \forall j \in N_Z. \tag{3c}$$

The total power output should meet the load demand:

$$\sum_{i\in N_{\mathrm{G}}} PG_i^0 = \sum_{n\in N_D} PL_n. \tag{3d}$$

The pre-contingency power flows on all lines should be within their continuous rating:

$$-F^{\max} \le T^0(PG^0 - PL) \le F^{\max}. \tag{3e}$$

2) Post-Contingency Short-Term Constraints: Immediately following a contingency, in order to relieve short-term overloads at operating point t_1, some batteries located downstream from the overloaded lines will inject power in the network. However, to maintain the power balance in the system, other batteries located upstream from these lines must extract power from the network:

$$\sum_{m\in N_{\mathrm{S}}} PD_m^{k'} = \sum_{m\in N_{\mathrm{S}}} PC_m^{k'}, \forall k' \in N_{\mathrm{C}}. \tag{3f}$$

The generator injections ($PG_i^{k'}$) do not change immediately after a line outage:

$$PG_i^{k'} = PG_i^0, \forall i \in N_{\mathrm{G}}, \forall k' \in N_{\mathrm{C}}. \tag{3g}$$

The power injections and extractions of the batteries must keep the flows in all branches within their short-term emergency rating:

$$\left| T^k[(PG^{k'} + PD^{k'}) - (PL + PC^{k'})] \right| \leq \gamma F^{\max}, \forall k' \in N_{\mathrm{C}}. \tag{3h}$$

The battery energy storage is assumed to be capable of transitioning continuously from zero to full output [22]–[24]. The discharging and charging power are bounded by

$$0 \leq PD_m^{k'} \leq PD_m^{\max}, \forall m \in N_{\mathrm{S}}, \forall k' \in N_{\mathrm{C}} \tag{3i}$$
$$0 \leq PC_m^{k'} \leq PC_m^{\max}, \forall m \in N_{\mathrm{S}}, \forall k' \in N_{\mathrm{C}}. \tag{3j}$$

3) Post-Contingency Long-Term Constraints: At operating point t_3, generators have been completely redispatched. The real power output of the generators can be represented as the sum of the base case power and the increased power:

$$PG_i^k = PG_i^0 + \Delta PG_i^{k+} - \Delta PG_i^{k-}, \forall i \in N_{\mathrm{G}}, \forall k \in N_{\mathrm{C}}. \tag{3k}$$

To maintain the system power balance, the total output change of all the generators must be balanced:

$$\sum_{i \in N_{\mathrm{G}}} \Delta PG_i^{k+} = \sum_{i \in N_{\mathrm{G}}} \Delta PG_i^{k-}, \forall k \in N_{\mathrm{C}}. \tag{3l}$$

After generation redispatching, the power flow on each line should be within its long-term limits:

$$\left| T^k(PG^k - PL) \right| \leq F^{\max}, \forall k \in N_{\mathrm{C}}. \tag{3m}$$

The redispatching amount of a generator should be within its ramping limits:

$$0 \leq \Delta PG_i^{k+} \leq \Delta PG_i^{\max}, \forall i \in N_{\mathrm{G}}, \forall k \in N_{\mathrm{C}} \tag{3n}$$
$$0 \leq \Delta PG_i^{k-} \leq \Delta PG_i^{\max}, \forall i \in N_{\mathrm{G}}, \forall k \in N_{\mathrm{C}}. \tag{3o}$$

The power output of a generator should be within its capacity:

$$PG_i^{\min} \leq PG_i^k \leq PG_i^{\max}, \forall i \in N_{\mathrm{G}}, \forall k \in N_{\mathrm{C}}. \tag{3p}$$

B. Stage 2: Minimization of the Corrective Actions

Since the first-stage problem aims at minimizing the base case generation cost, the feasible corrective control solutions ($PD^{k'}$, $PC^{k'}$, ΔPG^{k+}, ΔPG^{k-}) obtained tend to be large and close to their maximum limits. Therefore, it is necessary to resolve the two-types of second-stage problems to seek the minimum amount of adjustments of the batteries and generators to comply with each corrective post-contingency state. The formulations of the two types of post-contingency optimization problems are given as follows:

1) Short-Term Corrective Actions Optimization: The first type is the short-term corrective actions optimization problem, which handles the immediate aftermath of the contingency. At this operating point (t_1), the overloads must be limited to the short-term emergency rating by controlling the batteries. For each contingency, the objective of the problem is to minimize the power that must be injected or extracted instantly by the batteries to alleviate the short-term emergency overloads:

$$\min_{PD_m^{k'}, PC_m^{k'}} \sum_{m \in N_{\mathrm{S}}} (PD_m^{k'} + PC_m^{k'}). \tag{4}$$

This optimization is subject to the constraints (3f)–(3j).

2) Long-Term Corrective Actions Optimization: The second type is the long-term corrective actions optimization problem. For each contingency, the problem determines how generation should be redispatched to bring the branch flows back within their continuous rating at operating point t_3. The objective of the problem is to minimize the amount of redispatching needed:

$$\min_{\Delta PG_i^{k+}, \Delta PG_i^{k-}} \sum_{i \in N_{\mathrm{G}}} (\Delta PG_i^{k+} + \Delta PG_i^{k-}). \tag{5}$$

The constraints (3k)–(3p) must be considered.

C. Remarks on the ESCOPF

After solving the proposed two-stage ESCOPF, the global optimal solution of the pre-contingency state is achieved. However, the post-contingency solutions (corrective actions) are not globally optimal, because we do not include the weighted sum of the expected operating costs of corrective control for the two types of second-stage problems in the objective function (3a). The reasons why we do not consider these costs are as follows:

1) The actual implementation of corrective actions occurs in real time, thus the proposed ESCOPF problem is concerned about minimizing the base case generation cost while ensuring security.
2) The probability that an outage will occur over the time frame covered by a particular OPF solution is very small. Therefore the value of the expected recourse function would be very small compared to the base case generation cost [25].
3) Battery energy storage has a high investment cost but a relatively low operating cost [22], leading other researchers to ignore this operating cost in their optimization models [24], [26]. Since contingencies that would violate the short-term emergency ratings are relatively rare events, the amount of energy involved is likely to be a small fraction of the amount of energy that would be cycled through the battery for other purposes (e.g., arbitrage). We therefore believe that neglecting the cost of operating the batteries for corrective purpose is a reasonable assumption. If we assume that the system operator owns the batteries, the cost of this energy could be tallied as part of the cost of maintaining security. If the battery is owned by a merchant operator, it would make more sense to compensate this merchant operator for providing a reliability service. The energy consumed following a contingency could then be invoiced to the system operator ex-post.

D. Calculation of the Energy Required for Corrective Control

Once the ESCOPF problem has been solved, the minimum amount of energy that each battery must be able to store or deliver to cope with all the contingencies is given by

$$EC_m = \max\{(\tau_1 + 0.5\tau_2)PC_m^{k'}\}, \forall m \in N_{\mathrm{S}}, \forall k' \in N_{\mathrm{C}} \tag{6a}$$

$$ED_m = \max\{(\tau_1 + 0.5\tau_2)PD_m^{k'}\}, \forall m \in N_{\mathrm{S}}, \forall k' \in N_{\mathrm{C}}. \tag{6b}$$

The energy stored in battery m during the operating period under consideration is therefore bounded by

$$ED_m \leq E_m \leq E_m^{\max} - EC_m, \forall m \in N_{\mathrm{S}}. \tag{6c}$$

These constraints are not used in the ESCOPF but should be passed to the tool used to schedule the charging and discharging of the batteries (e.g., day-ahead unit commitment with distributed battery energy storage). This will ensure that the use of the batteries for post-contingency corrective control is compatible with other applications of the batteries, such as arbitrage.

V. Solution Method

The two-stage ESCOPF problem is solved serially: solve the first-stage problem first, then take the solution of the first-stage problem as parameters and resolve the second-stage problems. Note that both the two-stage problems are convex because their objective functions and all the constraints are linear. Since both the two-types of second-stage problems are DC OPF, and can be solved easily using linear programming techniques, this section only explains the solution method of the first-stage problem.

The proposed first-stage problem cannot be solved directly, as a large number of $\mathrm{N}-1$ contingencies must be considered. Instead, the first-stage problem can be solved using Benders decomposition [27], [28]. The primal first-stage problem is decomposed into a master problem for minimizing the base case generation cost, and two sets of sub-problems for checking, if under the pre-contingency dispatch, corrective control resources (batteries, generators) are sufficient to alleviate the post-contingency short- and long-term violations. Both the two sets of post-contingency transmission security check sub-problems are run for all the contingencies. Feasibility Benders cuts are generated during each iteration, and the optimal solution is obtained when all the sub-problems are feasible.

The formulation of the master and sub-problems are given as follows:

A. Master Problem: Pre-Contingency Optimization

The master problem corresponds to equations (3a)–(3e) of the first-stage problem. It is a DC OPF augmented by the Benders cuts generated by the sub-problems. It can thus be solved using linear programming.

B. Sub-Problem 1: Short-Term Transmission Security Check

Sub-problems of type 1 check whether under the current dispatch solution of the master problem, distributed batteries can be operated to alleviate all the short-term emergency violations. For contingency k', non-negative slack variables $s^{k'}$, $r^{k'}$ are introduced to ensure that the optimization problem is feasible. The objective of this sub-problem is to minimize the sum of the slack variables

$$\min_{PD_m^{k'}, PC_m^{k'}, s_l^{k'}, r_l^{k'}} f^{k'} = \sum_{l \in N_{\mathrm{L}}} (s_l^{k'} + r_l^{k'}). \tag{7}$$

This optimization is subject to constraints (3f)–(3j). Slack variables $s^{k'}$ and $r^{k'}$ are used to relax constraints (3h):

$$T^k[(PG^{k'} + PD^{k'}) - (PL + PC^{k'})] - s^{k'} \leq \gamma F^{\max} \tag{8}$$

$$-T^k[(PG^{k'} + PD^{k'}) - (PL + PC^{k'})] - r^{k'} \leq \gamma F^{\max}. \tag{9}$$

If, after solving a sub-problem 1, the sum of slack variables is equal to 0, the short-term violations after the occurrence of contingency k' can be removed using distributed batteries. Else, the corrective control of batteries cannot bring the post-contingency flows back to their short-term emergency rating, which means the preventive dispatch of the generators has to be adjusted, a Benders cut is generated and added to the master problem for the next iteration. The linear form of the Benders cut is

$$\begin{aligned} f^{k'} &+ \sum_{i \in N_{\mathrm{G}}} \lambda_i^{k'}(PG_i^0 - PG_i^{0*}) \\ &= f^{k'} + \sum_{i \in N_{\mathrm{G}}} \lambda_i^{k'}\Big[(PG_i^{\min} + \sum_{j \in N_Z} \Delta PG_{ij}^0) \\ &\quad - (PG_i^{\min} + \sum_{j \in N_Z} \Delta PG_{ij}^{0*})\Big] \\ &= f^{k'} + \sum_{i \in N_{\mathrm{G}}} \sum_{j \in N_Z} \lambda_i^{k'}(\Delta PG_{ij}^0 - \Delta PG_{ij}^{0*}) \leq 0 \end{aligned} \tag{10}$$

where PG_i^{0*} and ΔPG_{ij}^{0*} are the base case trial operating point obtained from solving the master problem, $\lambda_i^{k'}$ is the multiplier associated with the constraints (8), (9), and can be determined as follows:

$$\lambda_i^{k'} = \left.\frac{\partial f^{k'}}{\partial PG_i^0}\right|_{PG_i^0 = PG_i^{0*}}. \tag{11}$$

C. Sub-Problem 2: Long-Term Transmission Security Check

Sub-problems of type 2 check whether under the current dispatch solution of the master problem, generators can be redispatched to deal with all the contingencies. Non-negative slack variables s^k, r^k are introduced to ensure feasibility for contingency k. The objective of this sub-problem is

$$\min_{\Delta PG_i^{k+}, \Delta PG_i^{k-}, s_l^k, r_l^k} f^k = \sum_{l \in N_{\mathrm{L}}} (s_l^k + r_l^k). \tag{12}$$

This optimization is subject to constraints (3k)–(3p). Slack variables are added to relax constraints (3m):

$$T^k(PG^k - PL) - s^k \leq F^{\max} \tag{13}$$

$$-T^k(PG^k - PL) - r^k \leq F^{\max}. \tag{14}$$

If, after solving a sub-problem 2, the sum of slack variables is equal to 0, the long-term violations after the occurrence of contingency k can be cleared through generation redispatch. Else, the corrective control of generators cannot bring the post-contingency flows back to their long-term rating, a Benders cut is generated and added to the master problem for the next iteration. The linear form of the Benders cut is

$$f^k + \sum_{i \in N_G} \sum_{j \in N_Z} \lambda_i^k (\Delta PG_{ij}^0 - \Delta PG_{ij}^{0*}) \leq 0 \qquad (15)$$

where λ_i^k is the multiplier associated with the constraints (13), (14), and is determined by

$$\lambda_i^k = \left. \frac{\partial f^k}{\partial PG_i^0} \right|_{PG_i^0 = PG_i^{0*}}. \qquad (16)$$

D. Solution Procedure

Fig. 6 shows the flowchart of the Benders decomposition based algorithm for the first-stage problem.

Step 1) Solve the master problem to determine an initial operating point; set the contingency index $K = 1$.

Step 2) For contingency K, calculate the post-contingency power flows.

Step 3) Check if the post-contingency flows are within their short-term emergency limits, if not, solve sub-problem 1 and generate a Benders cut for each sub-problem that is not feasible.

Step 4) Check if all the post-contingency flows are within their long-term limits; for those that are not, solve a sub-problem of type 2 and generate a Benders cut when the problem is not feasible.

Step 5) Let $K = K + 1$, and repeat steps 2 to 4.

Step 6) When $K > NC$ and all sub-problems are feasible, stop and record the base case dispatch; else, add the Benders cuts generated for each infeasible sub-problem to the master problem and repeat steps 1 to 5.

VI. Case Studies

The proposed ESCOPF model and algorithm have been tested using a 6-bus system and a modified RTS 96 system. The response time (τ_1) of the generators is assumed to be 5 min, their ramping time (τ_2) 10 min, and the short-term emergency rating of all lines is assumed to be 1.2 times larger than the continuous ratings. All $\mathrm{N}-1$ line outage contingencies are considered. The CSCOPF-I, CSCOPF-II and ESCOPF are solved using Matlab and CPLEX. All the experiments were performed on a personal computer with 4 Intel (R) Core (TM) i7-4700 MQ CPU (2.4 GHz) and 8 Gb of memory.

A. Six-Bus System

Fig. 7 shows the six-bus system used to illustrate the proposed method. This system consists of 3 generators, 6 buses, and 11 transmission lines. The total load is 199.5 MW, equally distributed between the three load buses. Batteries are installed at buses 1, 5, and 6.

1) Comparison Between ESCOPF and Conventional CSCOPF: Table I compares the solutions produced using the two variants of CSCOPF and the ESCOPF. NSC and NLC are

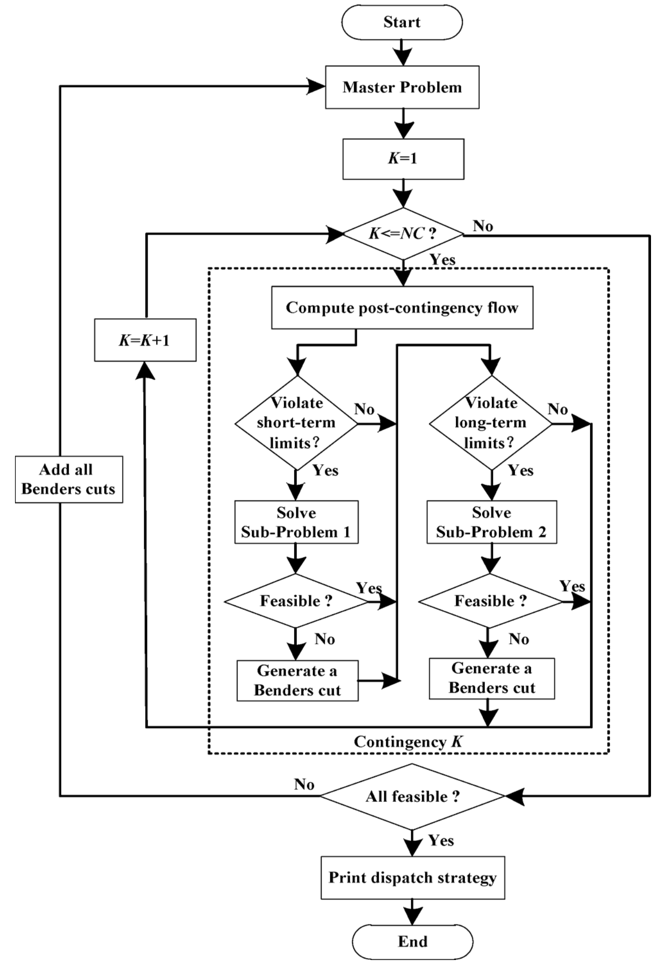


Fig. 6. Flowchart of the proposed algorithm.

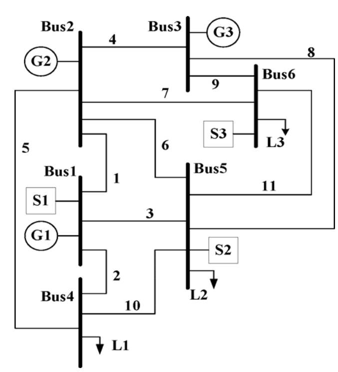


Fig. 7. Six-bus system.

the numbers of contingencies that result in a violation of the short-term and long-term limits, respectively.

CSCOPF-I is relatively cheap because it ignores the two contingencies (outages of lines 1, 2) that would violate the short-term emergency ratings. Four contingencies (outages of lines 1, 2, 3, 5) require post-contingency generation redispatch to avoid a violation of the continuous line rating. Since the CSCOPF-II formulation enforces the short-term emergency limits, no short-term violations would occur. However this solution costs more than the one obtained with the CSCOPF-I formulation. These

TABLE I
OPTIMAL SOLUTIONS PRODUCED BY THE CSCOPF AND ESCOPF

Model	PG1 MW	PG2 MW	PG3 MW	COST $	NSC	NLC
CSCOPF-I	117	37.5	45	3334.3	2	4*
CSCOPF-II	103.7	50.8	45	3352	—	4*
ESCOPF(10 MW)	112.5	42	45	3340.2	1*	4*
ESCOPF(20 MW)	117	37.5	45	3334.3	2*	4*

* means that these contingencies can be dealt with using corrective actions.

TABLE II
CORRECTIVE CONTROL ACTIONS OBTAINED BY THE FIRST-STAGE PROBLEM

Cont.	Short Term			Long Term		
	PS1 MW	PS2 MW	PS3 MW	PG1 MW	PG2 MW	PG3 MW
L1	+2.5	-20	+17.5	-50	0	+50
L2	-14	-6	+20	-50	0	+50
L3	—	—	—	-50	0	+50
L5	—	—	—	-50	0	+50

+ indicates a discharge, - indicates a charge.

TABLE III
CORRECTIVE CONTROL ACTIONS OBTAINED BY THE SECOND-STAGE PROBLEM

Cont.	Short Term			Long Term		
	PS1 MW	PS2 MW	PS3 MW	PG1 MW	PG2 MW	PG3 MW
L1	-0.3	0	+0.3	-20.9	0	+20.9
L2	-15	0	+15	-30.4	0	+30.4
L3	—	—	—	-18.9	0	+18.9
L5	—	—	—	-40.3	0	+40.3

CSCOPF formulations assume that batteries are not used for corrective actions.

The performance of the ESCOPF is tested in two cases: 1) the power and energy capacity of each battery is set to be 10 MW/10 MWh; 2) the power and energy capacity of each battery is set to be 20 MW/20 MWh. In the 10 MW/10 MWh case, the ESCOPF achieves a solution that is more expensive than CSCOPF-I but cheaper than CSCOPF-II. In the 20 MW/20 MWh case, the ESCOPF achieves the same cost as the CSCOPF-I because the total power capacity of the batteries is sufficient to deal with all two contingencies resulting in short-term constraint violations using corrective actions only. On the other hand, when the three batteries have only a 10 MW capacity each, one of the two contingencies that result in short-term constraint violations requires preventive actions, i.e., generation redispatch in the base case solution. In all cases, generation redispatch is required to correct the long-term constraint violations. The CSCOPF-II formulation requires less post-contingency redispatch because it implements a more secure preventive dispatch.

Tables II and III show the evolution of the corrective actions, which are obtained by solving the first-stage and second-stage problems, respectively. These corrective actions are provided by the 20 MW/20 MWh batteries immediately after each contingency and the long-term generation redispatch for the same contingencies. This demonstrates that, after solving the second-stage problems of the ESCOPF, smaller corrective actions of the batteries and generators are required to relieve overloads.

TABLE IV
PRE-CONTINGENCY LINE FLOWS IN THE SIX-BUS SYSTEM

Line No.	CSCOPF-I	CSCOPF-II	ESCOPF
L1	0.75	0.61	0.7
L2	0.84	0.76	0.81
L3	0.74	0.69	0.73
L4	0.13	0.15	0.14
L5	0.36	0.42	0.38
L6	0.30	0.32	0.31
L7	0.52	0.53	0.52
L8	0.24	0.26	0.25
L9	0.55	0.55	0.55
L10	0.16	0.16	0.16
L11	0.08	0.05	0.07

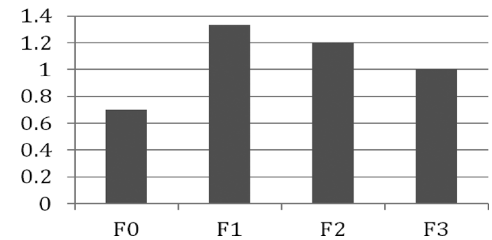


Fig. 8. Flow on line 1 before and after an outage of line 2.

As can be seen from Table III, if line 1 were to be disconnected, battery S1 at Bus 1 would charge at a rate of 0.3 MW while the battery S3 at Bus 6 would discharge at the same rate. Similarly, if line 2 were disconnected, the batteries at buses 1 and 6, would respectively charge and discharge at a rate of 15 MW. The outage of line 2 is thus the worst case and would require that $(5/60 + 0.5 * 10/60) * 15 = 2.5$ MWh of energy be kept in reserve in battery S3 and that the same amount of spare energy capacity be available in battery S1.

2) Pre- and Post-Contingency Power Flow Analysis: Table IV shows the pre-contingency loading level in each line for the CSCOPF-I, CSCOPF-II and ESCOPF (10 MW) solutions. The ESCOPF's ability to dispatch distributed batteries for short-term corrective action makes possible higher power flows in most lines under pre-contingency conditions than the CSCOPF-II. Using batteries for corrective actions thus increases the utilization factor of the existing transmission infrastructure and reduces the need for investments in new facilities.

Fig. 8 shows how the ESCOPF adjusts the line flows for an outage of line 2. F0 corresponds to the pre-contingency line flows, F1 to the flow immediately after the outage and before any action by the batteries, F2 to the flow when batteries provide short-term corrective actions, and F3 to the flows after generation redispatch has been fully implemented. After the outage of line 2, the flow on line 1 would violate the short-term emergency rating. However, this flow is first reduced below this emergency rating using the batteries and then below the continuous rating through generation redispatch.

B. RTS 96 System

The proposed algorithm was also tested on a modified RTS 96, which consists of three interconnected RTS 79 networks,

TABLE V
LOCATION OF THE BATTERIES IN THE RTS96

Case 1	(108,113),(208,213),(308,313)
Case 2	(106,108,113),(206,208,213),(306,308,313)
Case 3	(106,108,113,114),(206,208,213,214),(306,308,313,314)

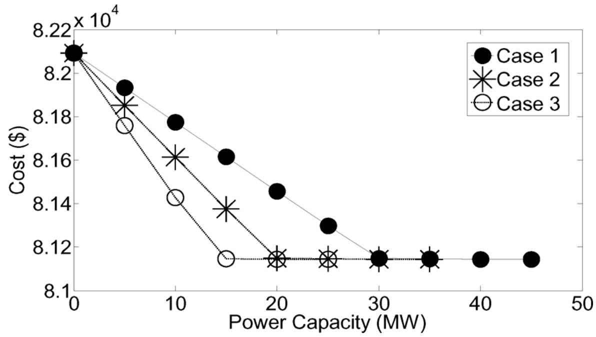


Fig. 9. Minimum cost achieved by the ESCOPF as a function of the number of batteries and their individual power capacity.

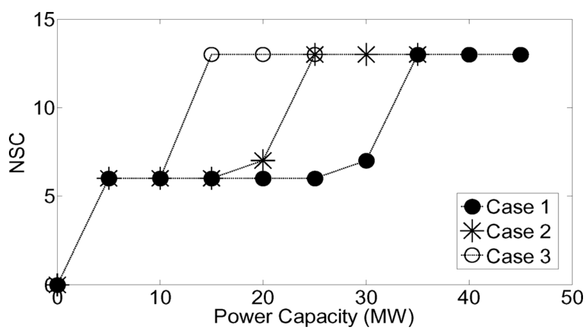


Fig. 10. Number of short-term line flow limit violations as a function of the number of batteries and their individual power capacity. These violations are handled using post-contingency corrective actions involving these batteries.

with 96 generators, 73 buses, and 120 lines. The contingency set includes 120 N − 1 lines outage.

1) Effect of the Number and Power Capacity of the Batteries: Three cases with 6, 9 and 12 batteries were considered. These batteries were located as indicated in Table V. In each case, the power rating of each battery was varied from 0 to 45 MW.

Fig. 9 shows how the generation cost, as calculated using the ESCOPF, decreases as the power rating of the batteries increases. The same lowest cost is achievable in all three cases, albeit with different battery power ratings. As one would expect, a smaller total battery power capacity is required when the batteries are more widely distributed. The optimal trade-off between additional investment costs in batteries and higher generating costs would depend on the per MW cost of the batteries.

Fig. 10 shows how the number of post-contingency short-term line flow limit violations varies with the number of batteries and their power capacity. As the number of batteries increases and they are spread more widely, the ESCOPF has to take less preventive security measures and can allow more short-term violations to be handled using corrective actions.

Table VI shows the detailed results and running time obtained with the ESCOPF when the power rating of each the batteries installed in case 3 is varied from 5 to 20 MW. As the maximum power capacity increases, the ESCOPF allows more short-term and long-term violations to be removed by corrective actions using the batteries and the generators. Note that this requires more computing time.

TABLE VI
DETAILED RESULTS OF ESCOPF

$PS^{\max}$ MW	COST $	NSC	NLC	Time s
5	81759	6*	36*	2.4
10	81428	6*	38*	2.5
15	81145	13*	45*	4.3
20	81144	13*	78*	4.7

TABLE VII
COMPARISON OF CSCOPF AND ESCOPF

Model	COST $	NSC	NLC	ED MWh	EC MWh	Time s
CSCOPF-I	81144	13	78*	—	—	4.6
CSCOPF-II	82091	—	29*	—	—	2.3
ESCOPF	81144	13*	78*	34.5	30	4.7

Table VII compares the results obtained with the ESCOPF and the two variants of CSCOPF when twelve 20 MW/20 MWh batteries have been installed as described in case 3. Under these conditions, the ESCOPF has enough resources to achieve the same cost as the CSCOPF-I attains by neglecting the short-term limit violations. All 13 post-contingency short-term limit violations and all 78 long-term limit violations are removed using corrective actions at a lower cost than can be achieved by CSCOPF-II. The total energy (ED) that should be stored for all batteries is 34.5 MWh, and the total energy storage margin (EC) that should be maintained is 30 MWh, which are smaller than the values (40 MWh for both ED and EC) calculated if only the first-stage problem of the ESCOPF was solved. The last columns of Tables VI and VII show that the computing time for the ESCOPF varies with the power rating of the batteries. When this power rating is small, the ESCOPF is faster than the CSCOPF-I because it is able to deal with fewer long-term limit violations. However, when ESCOPF has enough resources, the computing time is larger but very close to the computing of the CSCOPF-I. Note that CSCOPF-II is the fastest as it has the fewest NLC.

Fig. 11 shows how much energy should be stored and how much energy capacity margin should be reserved in each battery to cope with all the contingencies. The configuration of the RTS is such that batteries 4 and 7 only need to provide corrective actions in the form of discharges while battery 12 only needs to charge following outages. The other batteries must charge or discharge depending on the outage.

2) Effect of the Short-Term Emergency Rating: The value of the ESCOPF depends on the difference between the short-term and long-term ratings of the lines. Table VIII shows the results obtained with the ESCOPF when 12 batteries with an individual capacity of 10 MW/10 MWh have been installed as described in case 3. As the ratio between the short-term and long-term ratings increases, fewer contingencies lead to short-term violations. This means that the generation cost calculated

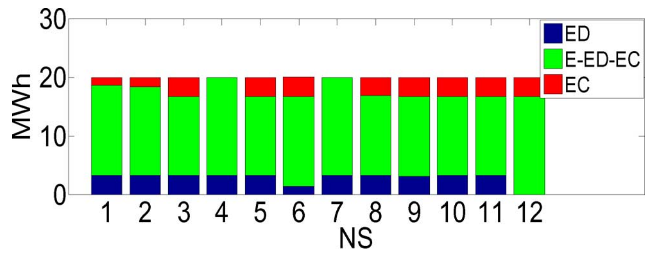


Fig. 11. Energy and energy margin required in each battery for corrective actions.

TABLE VIII
EFFECT OF THE RATIO BETWEEN THE SHORT- AND LONG-TERM EMERGENCY RATINGS

γ	COST \$	NSC	NLC	ED MWh	EC MWh	Iter	Time s
1.05	83819	13*	22*	20	20	3	3.2
1.1	82842	10*	23*	20	20	3	2.6
1.15	82082	10*	31*	20	20	2	2.4
1.2	81428	6*	38*	20	20	2	2.5
1.25	81145	7*	79*	15.8	12.5	4	4.7
1.3	81144	1*	78*	1.1	1.1	4	4.5
1.35	81144	0	78*	0	0	4	4.4

by the ESCOPF as well as the total energy and energy margin that the batteries must keep in reserve decrease. Table VIII also shows how the number of iterations and the running time of the ESCOPF change with the increasing of the ratio between the short-term and long-term ratings.

VII. CONCLUSION

Contingencies can cause some branch flows to exceed not only their continuous rating but also their short-term emergency rating. Ignoring such short-term violations of operating constraints could cause cascading outages. On the other hand, preventively dispatching the generating units to avoid such short-term overloads can be costly. Alternatively, distributed batteries could provide very fast corrective actions aimed at quickly eliminating these violations of the emergency limits. Generating units can then be redispatched to bring these flows back under their long-term or continuous rating.

This paper has described an enhanced, two-stage security constrained OPF (ESCOPF) problem that incorporates the fast response capability that distributed battery energy storage systems provide. The two-stage ESCOPF can be solved serially: First, solve the first-stage problem (minimization of the generation cost) using Benders decomposition; Then, solve the second-stage problems (minimization of the corrective actions) using linear programming.

Implementing this form of corrective security would allow operators to take advantage of the difference between the short- and long-term ratings of the branches and would therefore increase the available transmission capacity. In the long run, this would reduce the need for investments in additional transmission facilities.

Test results demonstrate the effectiveness of this problem formulation and illustrate the effects of the number of batteries, their power rating and the difference between the short- and long-term line ratings.

While the proposed two-stage ESCOPF problem has been illustrated assuming that the batteries are connected directly to the transmission network, it is also applicable to batteries connected to the distribution network. The proposed technique could also be used for other distributed resources that are able to respond quickly after a contingency, such as some types of demand response.

REFERENCES

[1] B. Stott, O. Alsac, and A. J. Monticelli, "Security analysis and optimization," *Proc. IEEE*, vol. 75, no. 12, pp. 1623–1644, Dec. 1987.
[2] F. Capitanescu and L. Wehenkel, "A new iterative approach to the corrective security-constrained optimal power flow problem," *IEEE Trans. Power Syst.*, vol. 23, no. 4, pp. 1533–1541, Nov. 2008.
[3] F. Capitanescu and L. Wehenkel, "Optimal power flow computations with a limited number of controls allowed to move," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 586–587, Feb. 2010.
[4] J. Condren, T. W. Gedra, and P. Damrongkulkamjorn, "Optimal power flow with expected security cost," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 541–547, May 2006.
[5] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, "Value analysis of battery energy storage applications in power systems," in *Proc. IEEE Power Systems Conf. Expo.*, 2006, pp. 2206–2206.
[6] K. C. Divya and J. Østergaard, "Battery energy storage technology for power systems-an overview," *Elect. Power Syst. Res.*, vol. 79, no. 4, pp. 511–520, Apr. 2009.
[7] A. Oudalov, D. Chartouni, and C. Ohler, "Optimizing a battery energy storage system for primary frequency control," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1259–1266, Aug. 2007.
[8] B. Lu and M. Shahidehpour, "Short-term scheduling of battery in a grid-connected PV/battery system," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 1053–1061, May 2005.
[9] S. Arabi and P. Kundur, "Stability modelling of storage devices in FACTS applications," in *Proc. IEEE Power Engineering Society Meeting*, 2001, pp. 767–771.
[10] A. Gabash and P. Li, "Flexible optimal operation of battery storage systems for energy supply networks," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2788–2797, Aug. 2013.
[11] Q. Li, S. S. Choi, Y. Yuan, and D. L. Yao, "On the determination of battery energy storage capacity and short-term power dispatch of a wind farm," *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 148–158, Apr. 2011.
[12] *Outlook of Energy Storage Technologies*, [Online]. Available: http://www.storiesproject.eu/docs/study_energy_storage_final.pdf
[13] H. I. Su and A. El-Gamal, "Modeling and analysis of the role of fast-response energy storage in the smart grid," in *Proc. Commun. Control Comput. Conf.*, 2011, pp. 719–726.
[14] O. Alsac and B. Stott, "Optimal load flow with steady-state security," *IEEE Trans. Power App. Syst.*, vol. PAS-93, no. 3, pp. 745–751, May 1974.
[15] F. Capitanescu, J. L. M. Ramos, P. Panciatici, D. Kirschen, A. Marano, L. Platbrood, and L. Wehenkel, "State-of-the-art, challenges, and future trends in security constrained optimal power flow," *Elect. Power Syst. Res.*, vol. 81, no. 8, pp. 1731–1741, Aug. 2011.
[16] L. Platbrood, S. Fliscounakis, F. Capitanescu, P. Panciatici, C. Merckx, and M. Ortega-Vazquez, Deliverable D3.2: Development of Prototype Software for Steady State Optimization of the ETN [Online]. Available: http://www.fp7-pegase.com/pdf_ddl/D3.2_dev.pdf
[17] A. Monticelli, M. V. F. Pereira, and S. Granville, "Security-constrained optimal power flow with post-contingency corrective rescheduling," *IEEE Trans. Power Syst.*, vol. 2, no. 1, pp. 175–180, Feb. 1987.
[18] T. Gomez, I. J. Perez-Arriaga, J. Lumbreras, and V. M. Parra, "A security-constrained decomposition approach to optimal reactive power planning," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 1069–1076, Aug. 1991.
[19] PJM Manual 03: Transmission Operations [Online]. Available: http://www.pjm.com/~/media/documents/manuals/m03.ashx
[20] F. Capitanescu, J. L. Martinez-Ramos, D. Kirschen, L. Wehenkel, M. Ortega-Vazquez, A. Marano, H. Crisciu, S. Fliscounakis, L. Platbrood, P. Panciatici, and Y. Hassaine, Deliverable D3.1: State of the Art and Modelling Requirements for Steady State Optimization of the ETN [Online]. Available: http://www.fp7-pegase.com/pdf/D3.1_part1.pdf

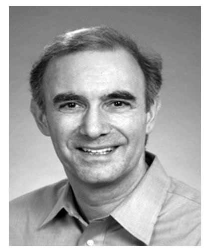
[21] F. Capitanescu and L. Wehenkel, "Improving the statement of the corrective security-constrained optimal power-flow problem," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 887–889, May 2007.
[22] EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications. Palo Alto, CA, USA, EPRI [Online]. Available: http://www.sandia.gov/ess/publications/ESHB%201001834%20reduced%20size.pdf
[23] R. Sioshansi, P. Denholm, T. Jenkin, and J. Weiss, "Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects," *Energy Econ.*, vol. 31, no. 2, pp. 269–277, Mar. 2009.
[24] L. Xie, Y. Gu, A. Eskandari, and M. Ehsani, "Fast MPC-based coordination of wind power and battery energy storage systems," *J. Energy Eng.*, vol. 138, no. 2, pp. 43–53, Jun. 2012.
[25] Contingency Modeling Enhancements. Folsom, CA, USA, California ISO [Online]. Available: https://www.caiso.com/Documents/RevisedStrawProposal-ContingencyModelingEnhancements.pdf
[26] C. H. Lo and M. D. Anderson, "Economic dispatch and optimal sizing of battery energy storage systems in utility load-leveling operations," *IEEE Trans. Energy Convers.*, vol. 14, no. 3, pp. 824–829, Sep. 1999.
[27] A. M. Geoffrion, "Generalized Benders decomposition," *J. Opt. Theory Appl.*, vol. 10, no. 4, pp. 237–260, 1972.
[28] A. J. Conejo, E. Castillo, R. Minguez, and R. Garcia-Bertrand, *Decomposition Techniques in Mathematical Programming-Engineering and Science Applications*. Berlin, Germany: Springer, 2006.

Yunfeng Wen (S'12) received the B.S. degree in electrical engineering from Sichuan University, Chengdu, China, in 2010. He is currently pursuing the Ph.D. degree in electrical engineering at Zhejiang University, Hangzhou, China.

From November 2012 to October 2013, he was a visiting Ph.D. student at the University of Washington, Seattle, WA, USA. His research interests include power system risk-based dispatch and security-constrained optimal power flow.

Chuangxin Guo (M'08) received the B.S., M.S., and Ph.D. degree in electrical engineering from Huazhong University of Science & Technology, Wuhan, China, in 1992, 1994, and 1997, respectively.

From 1997 to 2003, he worked as Director of the Beijing Dongfang Electronics Research Institute and Deputy Chief Engineer of Dongfang Electronics Co., Ltd. He is currently a Professor in the College of Electrical Engineering at Zhejiang University.



Daniel S. Kirschen (M'86–SM'91–F'07) is the Donald W. and Ruth Mary Close Professor of Electrical Engineering at the University of Washington, Seattle, WA, USA. From 1994 to 2010, he was with the University of Manchester, U.K. Prior to joining the academic world, he worked for Control Data Corporation and Siemens-Empros on the development of advanced application software for electric utilities.

Shufeng Dong received the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2009.

He is currently an Assistant Professor in the Department of Electrical Engineering at Zhejiang University, Hangzhou, China. His research interests include power system analysis and control.