Unlocking reserves with smart transmission switching

Raphael Saavedra a,b, Alexandre Street b,∗, José M. Arroyo c

a Invenia Labs, Cambridge, UK
b Department of Electrical Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil
c Departamento de Ingeniería Eléctrica, Electrónica, Automática y Comunicaciones, E.T.S.I. Industrial, Universidad de Castilla-La Mancha, Ciudad Real, Spain

A B S T R A C T

The consideration of a flexible network topology has been previously shown to produce significant benefits to power system operation. In this paper, we study the effects of considering smart transmission switching actions to unlock flexible generation resources from the network. More specifically, we consider a smart network capable of performing both preventive and real-time corrective topology changes in response to the occurrence of contingencies. The proposed economic dispatch model ensures the co-optimization of energy and reserves with pre- and post-contingency transmission switching actions, thus producing the optimal policy with transmission flexibility. An exact decomposition methodology based on the nested column-and-constraint generation algorithm is devised to address the challenging mixed-integer program arising from the proposed formulation. Numerical simulations show that the incorporation of corrective transmission switching in the optimization process offers significant benefits to system reliability and substantial cost savings.

Nomenclature

The symbols used in this paper are defined in this section. Superscript “m” is used to represent new variables in the single-level approximation of the subproblem. Superscripts “(k)” and “(m)” are used to denote the value of a variable at outer-loop iteration k and inner-loop iteration m, respectively.

Sets and indices

Set of indices

B Set of bus indices b.
b(i) Bus where generator i is located.
C Set of contingency state indices c. The pre-contingency state is represented by c = 0.
fr(l) Origin bus index of line l.
I Set of generator indices i.
Ib Set of indices i of generators located at bus b.
L Set of transmission line indices l.
LTS Set of indices l of switchable transmission lines.
T Set of time period indices t.
tol(l) Destination bus index of line l.

Parameters

Δt Duration of time periods.
εi,c εi,c Initial value of the convergence parameter.
Aci Parameter that is equal to 1 if generator i is available in period t under contingency state c, being 0 otherwise.
Aci Parameter that is equal to 1 if transmission line l is available in period t under contingency state c, being 0 otherwise.
Cf Cost coefficient of power imbalance.
Cdni, Cdip Down- and up-spinning reserve costs offered by generator i in period t.
di,b Power demand at bus b in period t.
C l Rated capacity of transmission line l.
L,UB Lower and upper bounds for the system cost.

Functions

Ci,p(t) Production cost function offered by generator i in period t.
F(c) Vector of linear functions defining the set of contingency states.

Keywords:
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Energy and reserve co-optimization
Nested column-and-constraint generation algorithm
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Decision variables

\( \theta_{it} \) Phase angles at bus \( b \) in period \( t \) under contingency state \( c \) in the lower level of the subproblem.

\( \Phi, \Phi^{\text{op}} \) Levels of system power imbalance resulting from the subproblem and from its single-level approximation.

\( \Phi^{w} \) Worst-case system power imbalance.

\( \Phi_{it}^{\text{dc}}, \Phi_{it}^{\text{pc}} \) Variables used in the linearization of the absolute value of the power imbalance at bus \( b \) in period \( t \) under contingency state \( c \).

\( \Phi_{it}^{\text{dd}}, \Phi_{it}^{\text{up}} \) Variables used in the linearization of the absolute value of the power imbalance at bus \( b \) in period \( t \) in the lower level of the subproblem.

\( a_{it} \) Binary variable that is equal to 1 if generator \( i \) is available in period \( t \), being 0 otherwise.

\( a_{it} \) Binary variable that is equal to 1 if transmission line \( l \) is available in period \( t \), being 0 otherwise.

\( f_{it}^{\text{dl}}, f_{it}^{\text{ul}} \) Power flows of line \( l \) in period \( t \) under contingency state \( c \) and in the lower level of the subproblem.

\( p_{it}^{\text{dc}}, \bar{p}_{it} \) Power outputs of generator \( i \) in period \( t \) under contingency state \( c \) and in the lower level of the subproblem.

\( r_{it}^{\text{dc}}, r_{it}^{\text{up}} \) Down- and up-spinning reserve contributions of generator \( i \) in period \( t \).

\( x_{it}^{\text{dc}}, x_{it}^{\text{up}} \) Binary variables that are equal to 1 if transmission line \( l \) is switched on in period \( t \), being 0 otherwise, under contingency state \( c \) and in the lower level of the subproblem.

Dual variables

\( \rho_{it} \) Dual variable associated with the power balance equation at bus \( b \) in period \( t \) in the lower level of the subproblem.

\( \gamma_{it}, \chi_{it} \) Dual variables associated with the constraints imposing lower and upper bounds for \( \rho_{it} \).

\( \sigma_{it}, \sigma_{it} \) Dual variables associated with the constraints imposing lower and upper bounds for \( f_{it}^{\text{dl}} \).

\( o_{it}, \sigma_{it} \) Dual variables associated with the constraints relating power flows and phase angles for line \( l \) in period \( t \) in the lower level of the subproblem.

1. Introduction

The operation of power systems is deeply rooted in mathematical optimization and is directly affected by numerous sources of uncertainty. In order to supply demand in a reliable fashion, power system planners and operators must take into account the effects of contingencies and nodal injection fluctuations by co-optimizing energy and ancillary services, such as reserves and ramping. In the short-term determination of the optimal economic dispatch, these ancillary services are crucial to secure dispatch feasibility and to minimize the risk of power imbalance scenarios.

Notwithstanding the importance of generation ancillary services, the consideration of a flexible network topology can also produce significant benefits to power system operation. In this context, transmission switching (TS), also known as topology control, represents an operational feature whereby transmission lines can be deliberately switched on and off by the system operator in each time period. Due to Kirchoff's voltage law, every loop in the system represents an additional electrical constraint that can potentially curb certain reserve capabilities. Thus, by switching off one or more specific transmission lines, loops can be removed and, hence, system operation becomes less constrained. In the past decade, TS has been widely studied in the technical literature and shown to potentially reduce operational costs and enhance system reliability [1–13].

Relevant works [1–4,7,9] consider TS actions exclusively in the normal state or base case, i.e., before uncertainty unfold. However, recent works have pointed towards the relevance of corrective or post-contingency TS, conducted in real-time after uncertainty unfolds [5,8,10–12]. In [5,8,10–13], the benefits of post-contingency TS were examined within the context of real-time contingency analysis by employing sequential approaches wherein corrective TS is conducted after generation scheduling. As a consequence, corrective TS is not co-optimized with energy or reserves. On the other hand, a recent literature contribution addressing the contingency-constrained unit commitment problem has shown that the co-optimization of post-contingency TS provides significant benefits for system reliability, thereby reducing system costs and worst-case power imbalance levels [6].

In this paper, we study the effects of considering TS actions within the network- and contingency-constrained economic dispatch to unlock flexible generation resources. More specifically, we focus on the benefits of a smart network capable of performing both preventive and real-time corrective topology changes in response to the occurrence of contingencies. In fact, independent system operators and regional transmission organizations have already utilized corrective TS in practice [8]. However, the employment of such an operational feature, if not co-optimized with preventive actions, leads to inconsistencies between the short-term decision making and the practical implementation, resulting in suboptimal scheduling and dispatch [14].

In order to address this issue, the proposed model co-optimizes energy and reserves while considering both pre- and post-contingency TS actions, thus producing the optimal policy with transmission flexibility. In this paper, we denote this feature by smart TS. This modeling aspect represents a major departure from existing works where the energy dispatch and optimal TS are solved either sequentially or utilizing heuristics that do not guarantee the co-optimization of generation scheduling, reserve allocations, and TS actions [4,5,10–13]. Moreover, as future time periods can affect the decisions that must be made now, single-period formulations may lead to suboptimal scheduling [15]. Thus, as a relevant modeling novelty with respect to [1,2,5,6,9], a multi-period setting with inter-temporal constraints is utilized.

The proposed multi-period network- and contingency-constrained economic dispatch with smart TS takes the form of a challenging mixed-integer program with major complicating factors. First, the explicit consideration of contingencies through a security criterion requires the precise characterization of system operation under each credible contingency state. Second, the utilization of a multi-period setting involves the inclusion of inter-temporal constraints such as ramping limits. Finally, the co-optimization of post-contingency TS leads the problem formulation to feature binary recourse decision variables.

As a consequence, the straightforward application of off-the-shelf commercial solvers for mixed-integer linear programming, as done in [2,3,6], may lead to unacceptable computing times even for moderately sized instances. Moreover, the nonconvexity of the operation under contingency precludes the adoption of usual decomposition methodologies such as Benders decomposition [16] and the standard column-and-constraint generation algorithm (CCGA) [17]. In order to circumvent these methodological and computational issues, we propose an exact solution methodology based on the nested CCGA [18]. To the best of our knowledge, this is the first time that the nested CCGA is applied to power system operation with transmission switching. Numerical results from an illustrative 4-bus system and the IEEE 118-bus system show the benefits provided by smart TS within the economic dispatch.
The main contributions of this paper are:

1. A network- and contingency-constrained economic dispatch model is proposed to co-optimize energy and reserve offers with pre- and post-contingency TS actions. The model is formulated in a multi-period setting and considers inter-temporal constraints such as ramping limits.
2. A novel application of the nested CCGA is presented as a solution methodology to tackle the challenging mixed-integer program arising from the problem formulation. The proposed decomposition algorithm is shown to greatly outperform the direct application of off-the-shelf solvers when the system is under stress.
3. Numerical experience is conducted to show that the co-optimization of post-contingency TS actions allows unlocking reserve capabilities at critical periods of the day. As a result, system costs are reduced while also alleviating worst-case power imbalance. Constraints (2) define the worst-case power imbalance. In (3) and (4), a dc power flow is modeled, characterizing power balances and line flows, respectively, while taking into account the possibility of line outages and TS. Line flows are bounded in (5) according to the line rated capacities. Non-switchable lines are forced to be connected by constraints (6). Constraints (7) and (8) set the production limits. In (9), post-contingency power outputs are bounded by the available reserve contributions. In (10) and (11), up- and down-spinning reserve contributions are respectively limited. In (12) and (13), ramping limitations are enforced in the pre-contingency state, as is customary in the related literature [3,4]. Constraints (14) ensure the non-negativity of the variables used in the linearization of the absolute value of the power imbalance. Finally, TS actions are modeled by binary variables in (15).

Note that, since the problem addressed is an economic dispatch, we assume that unit commitment decisions have already been made, being represented in the formulation by parameters $V_{i,t}$. For unit consistency, the duration of sub-hourly time periods is considered in the objective function (1) and in the ramping constraints (12) and (13). It should also be noted that, in this formulation, the contingency state $c = 0$ represents the pre-contingency state, wherein all generators and transmission lines are available. Furthermore, contingency states are characterized through parameters $A^u_i$ and $A_d^i$. Therefore, any desired security criterion can be utilized through the appropriate definition of $A^u_i$ and $A_d^i$, which can be formulated in a compact way by using a set of linear constrained functions as follows:

$$f_i \left( (A^u_i)_{i \in I}, (A^d_i)_{i \in I} \right) \geq \theta; \quad \forall i \in T, \forall c \in C.$$  

(16)

As an example, the widely used $n - 1$ security criterion can be formulated as follows:

$$\sum_{i \in I} A^u_i + \sum_{i \in I} A^d_i \geq |I| + |C| - 1; \quad \forall i \in T, \forall c \in C.$$  

(17)

3. Solution methodology

Due to the aforementioned complicating factors, it is impractical to directly solve problem (1)–(15) through commercial solvers, while usual decomposition techniques [16,17] fail to guarantee the attainment of optimality. As an alternative, we propose an exact solution methodology based on the nested CCGA [18]. This technique relies on the reformulation of problem (1)–(15) as an equivalent instance of two-stage robust optimization [19]. To that end, parameters $A^u_i$ and $A^d_i$ are respectively replaced with variables $a_i$ and $b_i$, whereas the constraints modeling the operation under contingency are replaced with a max–min problem [20–22]. The solution to the resulting robust counterpart involves two loops, as described next.

The outer loop comprises the iterative solution of a master problem and a subproblem and is responsible for obtaining increasingly tighter bounds for the optimal value of the objective function (1). The master problem consists of a relaxation of the original problem wherein only a subset of contingencies is considered, while the subproblem is a max–min problem aiming to obtain the worst-case contingency for the solution attained by the master problem.

The inner loop is devoted to solving the subproblem, which is an instance of bilevel programming with lower-level binary variables. The inner loop consists in the iterative solution of two problems, namely a single-level approximation of the subproblem and the lower level of the subproblem. Note that the inner loop is run within each outer-loop iteration, thereby giving rise to the nested structure of the algorithm.

3.1. Master problem

The master problem is a relaxation of the original problem (1)–(15) that is iteratively tightened through the addition of contingency states identified by the subproblem. At each outer-loop iteration $k$, $C$ is replaced in (1)–(15) with a subset of $k$ contingency states. Solving the master problem yields decisions $p^u_{i,k} \ast \hat{p}^u_{i,k} \ast \hat{p}^u_{i,k}$ and $p^d_{i,k}$, representing the optimal pre-contingency dispatch, network topology, and reserve allocations for the considered subset of credible contingencies.
The solution of the master problem allows computing the following lower bound for the optimal value of the objective function (1):

\[ L.B^{(k)} = \sum_{i \in I} \sum_{t \in T} \left[ C_{i}^{p} (p_{i}^{(k)}) \Delta t + C_{i}^{a} f_{i}^{(k)} \Delta t + C_{i}^{d} d_{i}^{(k)} \Delta t \right] + C^{f} \Phi^{(k)}. \]  

(18)

3.2. Subproblem

The subproblem for (1)–(15) at outer-loop iteration \( k \) is formulated as follows:

\[ \Phi^{(k)} = \max_{a_{i}, \nu_{i}} \min_{\nu_{i}, \nu_{i}, \nu_{i}} \sum_{m \in B} \left( \Phi_{m}^{(k)} + \Phi_{m}^{(k)} \right) \]

subject to:

\[ a_{i} \in \{0, 1\}; \; \forall i \in I, \forall t \in T \]

(20)

\[ a_{i} \in \{0, 1\}; \; \forall i \in I, \forall t \in T \]

(21)

\[ f \left( \{ a_{i} \}_{i \in I}, \{ a_{i} \}_{i \in C} \right) \geq 0; \; \forall i \in T \]

(22)

\[ \sum_{i \in I} \sum_{t \in T} \sum_{j \in J} \sum_{b \in B} \phi_{i}^{(k)} \geq \delta_{i} \sum_{i \in I} \sum_{t \in T} \phi_{i}^{(k)} - \theta_{i} \sum_{i \in I} \sum_{t \in T} \phi_{i}^{(k)} : \] \( (\theta_{i}) \);

(23)

\[ \psi \phi_{i}^{(k)} \geq \psi \phi_{i}^{(k)} : \] \( (\psi) \);

(24)

\[ f \left( \{ a_{i} \}_{i \in I}, \{ a_{i} \}_{i \in C} \right) \geq 0; \; \forall i \in I, \forall t \in T \]

(25)

\[ a_{i} \geq 0; \; \forall i \in I, \forall t \in T \]

(26)

\[ \Phi^{(k)} \geq 0; \; \forall i \in \mathcal{C}, \forall t \in T \]

(27)

\[ a_{i} \in \{0, 1\}; \; \forall i \in I, \forall t \in T \]

(28)

\[ \nu_{i} \in \{0, 1\}; \; \forall i \in \mathcal{C}, \forall t \in T \]

(29)

\[ \nu_{i} \in \{0, 1\}; \; \forall i \in \mathcal{C}, \forall t \in T \]

(30)

The goal of the subproblem is to identify the worst-case contingency state for given pre-contingency generation schedule and network topology obtained by the preceding master problem. Hence, a bilevel framework is utilized, with binary variables \( a_{i} \) and \( a_{i} \) implicitly modeling all component outages considered in the prescribed security criterion. In this bilevel formulation, the upper level is responsible for finding the contingency state maximizing the power imbalance, while the lower level obtains the optimal system reaction comprising energy redispatch and corrective TS actions. A tilde is used to denote the lower-level variables modeling system operation under contingency, whereas dual variables are shown in parentheses. The solution of the subproblem allows computing the following upper bound for the optimal value of the objective function (1):

\[ U.B^{(k)} = \sum_{i \in I} \sum_{t \in T} \left[ C_{i}^{p} (p_{i}^{(k)}) \Delta t + C_{i}^{a} f_{i}^{(k)} \Delta t + C_{i}^{d} d_{i}^{(k)} \Delta t \right] + C^{f} \Phi^{(k)}. \]

(31)

Expression (31) is identical to (18) except for the term, where \( \Phi^{(k)} \) replaces \( \Phi^{(k)} \). Note that \( \Phi^{(k)} \) is the optimal value of the objective function of the subproblem at outer-loop iteration \( k \). Hence, \( \Phi^{(k)} \) represents the worst-case imbalance resulting from implicitly considering all the contingencies in the prescribed security criterion for the solution identified by the master problem at outer-loop iteration \( k \). By contrast, \( \Phi^{(k)} \) is the worst-case imbalance associated with the reduced set of contingencies explicitly considered in the master problem at outer-loop iteration \( k \).

The outer loop converges once the bounds resulting from the master problem and the subproblem are within a pre-specified tolerance \( \varepsilon^{p} \).

3.3. Algorithm overview

As sketched in Fig. 1, the proposed methodology involves two nested loops and the solution of several problems derived from the original problem. The proposed nested decomposition works as follows:

1) Initialize the outer-loop iteration counter \( k \) to 0 and the contingency set to an empty set.
2) Solve the master problem: obtain a lower bound for the optimal value of the objective function (1).
3) Initialize the inner-loop iteration counter \( j \) to 0 to solve the subproblem (19)–(30).

(a) Solve the single-level approximation of the subproblem (32)–(40) to obtain an upper bound for the optimal value of the objective function of the subproblem (19).
contingency TS, and then post-contingency TS is utilized in response wherein the economic dispatch is first co-optimized only with pre-TS, denoted by No TS; 2) a sequential approach, referred to as Seq-TS, in [24].

areas in which the system can be split [23]. System data are available capacity above 200 MW and for the 12 tie lines connecting the three contingencies were considered for the 17 generators with rated power and every single line at every time period. For the 118-bus system, the security criterion accounted for the outage of every single generator standard with peaks at around 10:00 and 19:00 was employed. In both cases, the following hour; thus, \( \Delta t = 0.25 \) h. A typical daily load curve considered with the goal of solving the economic dispatch for the reduction of certain line capacities. Four time periods of 15 min were the modifications include the increase in nodal consumption and the version of the IEEE 118-bus system. In order to stress the system, the first is an illustrative 4-bus system, while the second is a modified dispatch, numerical simulations were conducted over two benchmarks. In order to investigate the benefits of smart TS within the economic method described in Section 3 was employed to address Smart TS. No TS was solved through a standard single-loop CCGA, i.e., the nested CCGA excluding the inner loop. Seq-TS was solved through a single-loop CCGA followed by the resolution of a single instance of the subproblem (19)–(30) to find the corresponding worst-case contingency and its associated optimal reaction. The execution of the decomposition procedures was stopped when a solution was found within a 1% optimality tolerance. All tests were conducted utilizing Julia and CPLEX 12.8 on an Intel Core i7-490K processor at 4.00 GHz with 32 GB of RAM.

4. Numerical results

In order to investigate the benefits of smart TS within the economic dispatch, numerical simulations were conducted over two benchmarks. The first is an illustrative 4-bus system, while the second is a modified version of the IEEE 118-bus system. In order to stress the system, the modifications include the increase in nodal consumption and the reduction of certain line capacities. Four time periods of 15 min were considered with the goal of solving the economic dispatch for the following hour; thus, \( \Delta t \) is equal to 0.25 h. A typical daily load curve with peaks at around 10:00 and 19:00 was employed. In both cases, the standard n−1 security criterion was adopted. For the 4-bus system, the security criterion accounted for the outage of every single generator and every single line at every time period. For the 118-bus system, contingencies were considered for the 17 generators with rated power capacity above 200 MW and for the 12 tie lines connecting the three areas in which the system can be split [23]. System data are available in [24].

Three approaches were compared, namely 1) a model disregarding TS, denoted by No TS; 2) a sequential approach, referred to as Seq-TS, wherein the economic dispatch is first co-optimized only with pre-contingency TS, and then post-contingency TS is utilized in response to contingencies; and 3) the proposed model with smart TS, denoted by Smart TS. The solution methodology described in Section 3 was employed to address Smart TS. No TS was solved through a standard single-loop CCGA, i.e., the nested CCGA excluding the inner loop. Seq-TS was solved through a single-loop CCGA followed by the resolution of a single instance of the subproblem (19)–(30) to find the corresponding worst-case contingency and its associated optimal reaction. The execution of the decomposition procedures was stopped when a solution was found within a 1% optimality tolerance. All tests were conducted utilizing Julia and CPLEX 12.8 on an Intel Core i7-490K processor at 4.00 GHz with 32 GB of RAM.

4.1. 4-bus example

For the illustrative 4-bus system, we have compared the three approaches at distinct hours of the day: 03:00–04:00, when the demand is at its lowest level; 10:00–11:00, when the demand is at its peak; and 22:00–23:00, when the demand is at an intermediate level. Table 1 summarizes the results, which were attained in less than 1 s. In this table, \( \Phi^o \) represents the worst-case percent system power imbalance in terms of system load. It can be seen that, for the low-demand hour, TS has no effect on solution quality. When the demand is higher, the worst contingencies lead to significant power imbalance for both No TS and Seq-TS. Smart TS, on the other hand, is capable of ensuring power balance under all contingencies considered in the security criterion.

The reported disparities in system costs and power imbalance levels are a consequence of the different reserve allocations provided by the three approaches. The sums of up- and down-spinning reserves resulting from each approach for each 15-minute time period in the critical 10:00–11:00 interval are listed in Table 2. The results show that Smart TS allows unlocking up-spinning reserve capabilities that were constrained under No TS and Seq-TS. Additionally, Smart TS also avoids the need for allocating down-spinning reserves.

4.2. 118-bus system

For the 118-bus system, we have investigated the performance of the three approaches for every hour of the day. Fig. 2 depicts the hourly system costs. It can be seen that, in the low-demand hours, the three
approaches resulted in similar system costs. However, during the peak hours, Smart TS obtained significant cost savings when compared to No TS and Seq-TS. This behavior is a direct consequence of the results displayed in Fig. 3, which shows the hourly worst-case power imbalance percent levels in terms of system load. While Smart TS attained a 0% worst-case power imbalance in all hours, No TS and Seq-TS featured power imbalance levels of up to 1.6% and 0.5%, respectively.

Regarding the computational effort of Smart TS, Table 3 lists the computing times resulting from the direct application of commercial branch-and-cut software, denoted by BC, and from the proposed solution methodology based on the nested CCGA, referred to as NCCGA. Note that a 900-s (i.e., 15 min) time limit was employed. The results show that the computing times are similar for the low-demand hours. However, when the system is under stress, NCCGA significantly outperformed BC. Furthermore, the computing times resulting from NCCGA are well within the required time frame for the short-term economic dispatch with 15-minute time periods.

### 5. Conclusion

This work has addressed the incorporation of smart transmission switching into the network- and contingency-constrained economic dispatch. The related literature has mainly focused on approaches wherein post-contingency transmission switching is either disregarded or implemented sequentially after the energy dispatch. By contrast, the proposed formulation ensures the co-optimization of generation dispatch, reserve allocations, and both preventive and corrective transmission switching. Thus, the inclusion of smart transmission switching within the economic dispatch provides the optimal operation considering network flexibility.

Straightforwardly solving the proposed formulation with off-the-shelf commercial software is shown to yield unacceptable computing times for the short-term economic dispatch when the system is under stress even for moderately sized instances. Additionally, the solution methodologies presented in the related literature fail to cope with the binary recourse variables characterizing corrective transmission switching. To address these issues, an exact decomposition methodology based on the nested column-and-constraint generation algorithm is proposed. The solution methodology involves an outer loop wherein the original problem is decomposed into a master-subproblem structure. The resulting bilevel subproblem is responsible for obtaining the worst-case contingency state for given pre-contingency generation schedule and network topology. Finally, an inner loop is devised to handle the presence of lower-level binary variables in the subproblem.

Numerical simulations allow drawing four main conclusions:

1) The co-optimization of post-contingency transmission switching within the economic dispatch benefits system operation by consistently reducing system costs and decreasing power imbalance levels in the worst contingency states during the periods when the system is under stress.

2) The co-optimization of post-contingency transmission switching allows unlocking reserve capabilities that would otherwise be unused due to operational constraints.

3) From a computational perspective, the proposed solution technique significantly outperforms the direct application of off-the-shelf commercial software when the system is under stress.

4) The computational effort required by the proposed solution methodology for a medium-sized benchmark such as the IEEE
118-bus system is within industry standards for the one-hour-ahead network- and contingency-constrained economic dispatch using a 15-minute time resolution.

Further work will address the extension of the formulation to consider an ac load flow model.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

As explained in [25], a linear equivalent for the product of a binary variable $z \in \{0, 1\}$ and a continuous variable $\beta \in [\bar{\beta}, \overline{\beta}]$ can be obtained as follows: 1) replace the product $\beta z$ with a new continuous variable $y$, and 2) introduce new constraints $\beta z \leq y \leq \overline{\beta} z$ and $\overline{\beta}(1 - z) \leq \beta - y \leq \overline{\beta}(1 - z)$. As a consequence, if $z$ is equal to 0, $y$ is also equal to 0 while $\beta$ is bounded by its upper and lower limits. Conversely, if $z$ is equal to 1, $y$ is equal to $\beta$ and is bounded by the upper and lower limits for $\beta$.

References