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Loading margin calculation with line switching: A decomposition method

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ABSTRACT

This paper presents a model for loading margin calculation integrated with transmission line switching. A mixed-integer nonlinear optimization model is developed which maximizes the loading margin of the system subject to various operational system constraints. An iterative algorithm, based on the Benders decomposition method, is used to solve the problem. The proposed method is tested on medium and large scale test systems and optimization results are compared with that of a non-decomposed method to show the efficacy of the proposed approach.

Introduction

The problem of maximum loading margin intends to compute the maximum load that system can meet given security constraints defined by thermal limits, bus voltage limits, and voltage stability limits. This problem can be cast as an optimization model whose objective is to maximize loading margin of the system considering security constraints, pre-specified loading conditions, and network topology [1].

Recent studies have revealed the benefits of optimal transmission switching in reducing operating costs and improving system performance [2,3]. This paper presents a new application of transmission line switching in the calculation of system loading margin. Mathematically, this problem can be formulated as an optimal power flow model that maximizes system loading margin subject to security constraints. The inclusion of topology changes through transmission switching will produce a mixed-integer nonlinear programming (MINLP) model in which binary variables model the status (in/out) of transmission lines. Practical MINLP models are generally intractable if directly solved by traditional MINLP solvers. To solve realistic large-scale MINLP models, efficient solution algorithms are needed. Generalized Benders decomposition provides an efficient technique for solving large-scale MINLPs in an iterative fashion. This technique decomposes the original model into tractable linear and nonlinear problems that can be solved more efficiently. In the context of power system, Benders decomposition has been applied to solve various MINLP models [4–8]. A Benders technique with restarts is developed in [4] for optimal SVC placement in the transmission network in which system loading margin is maximized subject to security constraints. A bilevel optimization problem is developed in [5] and a decomposition method is used to solve the problem. Transmission switching is incorporated in the lower-level problem as a corrective action for eliminating operating violations. Ref. [6] presents a decomposition method for solving the optimal power flow problem of a distribution system considering network reconfiguration. The model seeks to find the optimum system configuration that minimizes losses under various operating constraints. In [7] Benders method is proposed for solving the available transfer capability problem subject to security constraints in normal and contingency conditions. In [8] authors formulate the daily generation scheduling problem as an MINLP model with time coupling. They use Benders technique to solve the problem by making use of a full ac network model. Ref. [9] provides a comprehensive list of applications of this technique in power systems.

In the Benders method, the original problem is partitioned into a master (mixed-integer) problem and a (nonlinear) subproblem and these problems are iteratively solved until the optimal solution is found [10]. From a mathematical standpoint, this partitioning procedure needs a convex feasible region to ensure optimality. Given the non-convexity of the OPF subproblem, a restart procedure (denoted as multiple restarts) is incorporated in the original Benders algorithm that restarts the Benders loop with an appropriate number of randomly-generated starting points. This technique

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Nomenclature

Indexes and sets

N	set of nodes
L	set of lines
I	set of indices of generating units
Ω_n	set of lines connected to node n
Ψ_n	set of generating units placed at node n
i	index of generating units
n,m,k	indices denoting line k between nodes n and m

Variables

λ	loading margin
K_G	variable used for modeling a distributed slack bus
Q_{gi}	reactive power generation of generating unit i in p.u
V_n	voltage magnitude of bus n in p.u
θ_{nm}	voltage angle difference of bus n and m in radians
p^d_{nmk}, q^d_{nmk}	real and reactive power flow from bus n to bus m (direct flow) in line k in p.u
p^r_{mnk}, q^r_{mnk}	real and reactive power flow from bus m to bus n (reverse flow) in line k in p.u
w_{nmk}	binary variable denoting the switching status of line (n,m,k); 1 is closed, 0 is open

Parameters

P_{gi}	initial active power generation of generating unit i in p.u
$P^{\max}_{gi}$	capacity of generating unit i in p.u
P_{Dn}	real power load at bus n in p.u
Q_{Dn}	reactive power load at bus n in p.u
$s^{\max}_{nmk}$	MVA limit of line (n,m,k) in p.u
g_{nmk}	real part of line admittance (n,m,k) in p.u
b_{nmk}	imaginary part of line admittance (n,m,k) in p.u
g^{sh}_n	shunt conductance connected to bus n in p.u
b^{sh}_n	shunt susceptance connected to bus n in p.u
b_{Cnmk}	capacitive susceptance of line (n,m,k) in p.u
X_{nmk}	series reactance of line (n,m,k) in p.u
L_0	number of lines that can be switched out
b_{fi}, a_{fi}	coefficients of linear approximation of field heating limit of generating unit i in p.u
b_{ui}, a_{ui}	coefficients of linear approximation of under-excitation limit of generating unit i in p.u

is used in [4,5] for solving non-convex OPF subproblems in the Benders algorithm.

As previously stated, significant benefits with negligible costs can be achieved by switching transmission lines in and out. Published works on transmission switching, mainly use optimal dc power flow models in order to reduce the complexity of the problem and improve computational performance [11]. While DC models are fast and efficient, they cannot capture the voltage and reactive power issues that have significant impacts on the loading margin of the system. Thus, exact determination of this parameter should be carried out based on a full ac power flow model in which voltage and reactive power constraints are accounted for. On the other hand, direct solution of such MINLP models by standard solvers is very challenging and time consuming specially in the case of large scale systems, as demonstrated in this work. Therefore, an efficient solution algorithm that can handle large-scale models should be developed.

In view of the above discussion, the main objectives and contributions of this paper are:

(1) To develop a full ac-OPF model for loading margin calculation integrated with optimal transmission line switching.
(2) To develop a solution algorithm based on the Benders decomposition method that can efficiently solve the resulting MINLP model.
(3) To compare the result of the decomposed method with that of a non-decomposed method as well as with the results of a dc power flow model.

The rest of the paper is organized as follows. Section 'Problem formulation' describes the problem formulation of the loading margin determination and the resulting MINLP model. Section 'Solution algorithm' presents the solution algorithm and describes the formulation of the master problem and the subproblem. Section 'Tests systems and results' provides optimization results of test systems and discusses the computational issues of the decomposed and nondecomposed methods. Concluding remarks are provided in Section 'Conclusion'.

Problem formulation

The maximum loading margin problem integrated with transmission switching can be written as an MINLP model with a linear objective function and binary and continuous decision variables, as described below:

$$\text{Minimize } X = -\lambda \quad \text{s.t.} \tag{1}$$

$$\sum_{i\in\Psi_n} P_{gi}(1+\lambda+K_G) - P_{Dn}(1+\lambda) - \sum_{(m,k)\in\Omega_n} p^d_{nmk} - \sum_{(m,k)\in\Omega_n} p^r_{mnk} - g^{sh}_n V_n^2 = 0 \quad \forall n \tag{2}$$

$$\sum_{i\in\Psi_n} Q_{gi} - Q_{Dn}(1+\lambda) - \sum_{(m,k)\in\Omega_n} q^d_{nmk} - \sum_{(m,k)\in\Omega_n} q^r_{mnk} + b^{sh}_n V_n^2 = 0 \quad \forall n \tag{3}$$

$$\left({p^d_{nmk}}^2 + {q^d_{nmk}}^2\right)^{1/2} \leqslant s^{\max}_{nmk} \quad \forall (n,m,k) \tag{4}$$

$$\left({p^r_{mnk}}^2 + {q^r_{mnk}}^2\right)^{1/2} \leqslant s^{\max}_{nmk} \quad \forall (n,m,k) \tag{5}$$

$$p^d_{nmk} = w_{nmk}(g_{nmk}V_n^2 - g_{nmk}V_nV_m\cos\theta_{nm} - b_{nmk}V_nV_m\sin\theta_{nm}) \quad \forall (n,m,k) \tag{6}$$

$$p^r_{mnk} = w_{nmk}(g_{nmk}V_m^2 - g_{nmk}V_nV_m\cos\theta_{nm} + b_{nmk}V_nV_m\sin\theta_{nm}) \quad \forall (n,m,k) \tag{7}$$

$$q^d_{nmk} = w_{nmk}(-(b_{nmk}+b_{Cnmk})V_n^2 - g_{nmk}V_nV_m\sin\theta_{nm} + b_{nmk}V_nV_m\cos\theta_{nm}) \quad \forall (n,m,k) \tag{8}$$

$$q^r_{mnk} = w_{nmk}(-(b_{nmk}+b_{Cnmk})V_m^2 + g_{nmk}V_nV_m\sin\theta_{nm} + b_{nmk}V_nV_m\cos\theta_{nm}) \quad \forall (n,m,k) \tag{9}$$

$$Q_{gi} \leqslant b_{fi}P_{gi}(1+\lambda+K_G) + a_{fi} \quad \forall i \tag{10}$$

$$Q_{gi} \geqslant b_{ui}P_{gi}(1+\lambda+K_G) + a_{ui} \quad \forall i \tag{11}$$

$$P_{gi}(1+\lambda+K_G) \leqslant P^{\max}_{gi} \quad \forall i \tag{12}$$

$$V_n^{\min} \leqslant V_n \leqslant V_n^{\max} \quad \forall n \tag{13}$$

$$\sum_{(n,m,k)\in L} (1-w_{nmk}) \leqslant L_0 \tag{14}$$