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Coordinated generation and transmission expansion planning for a power system under physical deliberate attacks

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ABSTRACT

This paper proposes a static model for coordinated generation and transmission expansion planning (CGTEP). While reducing the cost of investment, operation and energy not served within the system, the model aims to mitigate the vulnerability of power system against physical deliberate attacks in the horizon of planning. Moreover, the peak load of twelve days in a year is taken as a sample of the months to well consider the impacts of load variations over a year. The physical deliberate attacks and their subsequent impacts are also assessed through scenario building procedure. To this end, each scenario in any given month is built as an attack plan targeting transmission system and accordingly they are assigned weights proportional to the consequent damage inflicted on the power system. According to the generated scenarios for physical deliberate attacks, CGTEP is modeled as a mixed integer nonlinear programming problem (MINLP), where the network operation constraints are described by DC power flow equations in different scenarios. Afterward, using some linearization methods, the planning problem is transformed to a mixed integer linear programming (MILP) problem that can be solved by conventional optimization software. Finally, the proposed model is implemented in IEEE 24-bus reliability test system (RTS) and then numerical results are yielded to assess several case studies. The effect of input parameters on the model such as the budget of expansion planning, the number of scenarios, different objective functions, the value of shed load and also different load levels are analyzed. The significance of the proposed approach in mitigating power system vulnerability is well confirmed by numerical results.

1. Introduction

1.1. Motivation

Unexpected blackouts throughout the world may occur by destructive agents that destroy the critical components associated with supply of electricity [1]. Physical deliberate attacks might lead to catastrophic consequences in power system and yet severe impacts on the society, though they less likely occur [2]. As an example, 200 hostile attacks have been occurred at Colombian power network during 1999–2010 [3]. Although any of power system equipment can be the possible targets of the attacks, transmission lines have been the most likely ones due to their simple availability [4,5]. The above concerns have caused the policy-makers and researchers to focus further attention on reinforcing power systems against physical deliberate attacks on transmission systems.

1.2. Literature review

To strengthen transmission system against physical deliberate attacks, a methodology is suggested in [6] that identifies the key network components or critical transmission lines. More precisely, the interactions between the attacker and system operator are formulated as a maximum-minimum programming model where the attacker intends to attack those transmission lines that would yield the maximum damage to the network. The attacker's decision is made while considering the subsequent corrective actions taken by the system operator to minimize the inflected damage. Then in [7,8], a bi-level model has been proposed for identifying the key elements of the power system. The capability of defining different objective functions for attacker and defender is one of the advantages of the bi-level model over the maximum-minimum model. In addition, in the bi-level model, it is possible to define the constraints in the first level of the problem in such a way that these constraints depend on the variables of both levels of the optimization problem. These features make the bi-level model more flexible than the maximum-minimum model. Line switching is proposed as a mechanism

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Nomenclature

A. Indices

f	index of prospective generating units
g	index of existing generating units
l	index of transmission lines
n	index of buses
t	index of time intervals
ω	index of scenarios

B. Sets

G	set of indices of generators
G_n	set of indices of generators connected to bus n
L^O	set of indices of transmission lines in the original transmission network
L^P	set of indices of prospective transmission lines
N	set of indices of buses
Ω_{n_A}	set of scenarios with n_A destroyed transmission lines
Ω_{n_T}	set of scenarios at time interval n_T
Ω'_{n_T}	set of time interval n_T

C. Variables

C_{EENS}	cost of expected energy not served
C_{inv}	total investment cost
C_{ope}	total operation cost
$EENS$	expected energy not served
$p_g^G(\omega,t)$	power output of existing generating unit g in scenario ω at time interval t
$p'^G_{f,n}(\omega,t)$	power output of prospective generating unit f at bus n and scenario ω at time interval t
$p_l^L(\omega,t)$	power flow in transmission line l and scenario ω at time interval t
s_l^L	binary variable that is equal to 1 if prospective transmission line l is built, being 0 otherwise
v_l	binary variable that is equal to 0 if transmission line l is destroyed, being 0 otherwise
$z^G_{f,n}$	number of prospective generating units of type f that are built at bus n
$\delta_n(\omega,t)$	phase angle at bus n and scenario ω at time interval t
$\delta_n^A(\omega,t)$	variable used in the linearization
$\delta_n^Q(\omega,t)$	variable used in the linearization
$\Delta p_n^D(\omega,t)$	load shed at bus n and scenario ω at time interval t
$\Delta p^D_{Total}(t)$	total system load shed at time interval t

D. Constants

C_T	expansion planning budget
$C^G_{f,n}$	investment cost of generating unit f at bus n
C_l^L	investment cost of prospective transmission line l
$I(\omega,t)$	number of destroyed transmission lines in scenario ω at time interval t
$K_g^G(t)$	operation cost of existing generating unit g at time interval t
$K'^G_{f,n}(t)$	operation cost of prospective generating unit f at bus n at time interval t
n_A	counter of destroyed transmission lines
n'_A	number of destroyed transmission lines
n_G	number of generators
n_L	number of transmission lines in the original transmission network
n_N	number of buses
n_P	number of prospective transmission lines
n_S	counter of scenarios
n_T	counter of time intervals
n'_T	number of time intervals
n_Ω	number of scenarios
$O(l)$	origin or sending bus of transmission line l
$P_n^D(t)$	demand at bus n at time interval t
$\overline{P}_g^G$	capacity of existing generating unit g
$\overline{P}'^G_f$	capacity of prospective generating unit f
$\overline{P}_l^L$	capacity of transmission line l
Q_n^G	maximum number of prospective generating unit that can be built at bus n
$\overline{Z}^G_{f,n}$	Maximum number of prospective generating unit f that can be built at bus n.
$R(l)$	destination or receiving bus of transmission line l
$V(\omega,t)$	vector representing the attack plan of scenario ω at time interval t
$V_l(\omega,t)$	component l of $V(\omega,t)$ that is equal to 0 if transmission line l is destroyed in scenario ω at time interval t, being 1 otherwise
$VOSL_n$	value of shed load at bus n
X_l	reactance of transmission line l
γ	binary parameter that is equal to 0 if economic objective function is selected, being 1 if vulnerability-based objective function is selected
$\overline{\delta}$	upper bound for the nodal phase angles
$\underline{\delta}$	lower bound for the nodal phase angles
$\Delta P^D_{n_A,n_T}$	maximum load shed with n_A down transmission lines at time interval n_T
$\Delta P^D_{Total}(\omega,t)$	total system shed load in the original network associated with scenario ω at time interval t
$\pi(\omega,t)$	probability or weight of scenario ω at time interval t

to lessen the destructive effects of physical deliberate attacks in [9,10]. In these references, the system operator, in addition to the corrective actions available in the models proposed in [6–8] (such as load shedding and generation redispatch), can modify the network topology to minimize damage to the network.

The authors of [11–13] have claimed that further development of transmission system mitigates the vulnerability of power network. In these works, the uncertainties involved in physical deliberate attacks are firstly modeled through a scenario strategy generation and then traditional transmission expansion planning (TEP) is devised for all scenarios with regard to their probabilities in which minimizing expansion investment cost and load shedding is considered as the objective function. In [11–13], only one load level in the horizon year is assumed and the impacts of load variations during the year is not considered, whereas, considering load variation can significantly change the optimal transmission expansion plan. It is worth to mention that, the operating costs of the power system equipment is not considered in these models. Making an investment to further increase capacity of transmission lines and power plants within the network is introduced to lessen the adverse impacts of physical deliberate attacks in [2]. Furthermore, a tri-level programming model is developed in [14–20] to model the behavior of defender-attacker-operator in a power system where the defender attempts to minimize the power system vulnerability through optimal resource allocation policies among the limited assets or defense of critical components. This is formulated according to the likely actions taken by attackers and system operators. In these references, uncertainties in physical deliberate attacks are not considered and only the worst attack is taken into