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Flexible implementation of power system corrective topology control

Payman Dehghanian[a,*], Yaping Wang[b], Gurunath Gurrala[c], Erick Moreno-Centeno[b], Mladen Kezunovic[a]

[a] Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA
[b] Department of Industrial and Systems Engineering, Texas A&M University, College Station, TX, USA
[c] Department of Electrical Engineering, Indian Institute of Science, Bangalore, India

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ABSTRACT

This paper proposes a novel decision making framework for optimal transmission switching satisfying the AC feasibility, stability and circuit breaker (CB) reliability requirements needed for practical implementation. The proposed framework can be employed as a corrective tool in day to day operation planning scenarios in response to potential contingencies. The switching options are determined using an efficient heuristic algorithm based on DC optimal power flow, and are presented in a multi-branch tree structure. Then, the AC feasibility and stability checks are conducted and the CB condition monitoring data are employed to perform a CB reliability and line availability assessment. Ultimately, the operator will be offered multiple AC feasible and stable switching options with associated benefits. The operator can use this information, other operating conditions not explicitly considered in the optimization, and his/her own experience to implement the best and most reliable switching action(s). The effectiveness of the proposed approach is validated on the IEEE-118 bus test system.

1. Introduction

Bulk electric transmission systems have been traditionally characterized with static assets and fixed configuration over time except in the cases of faults and forced outages. Power system topology control, often called transmission switching, offers the system operators an opportunity to harness the flexibility of the transmission system topology by temporarily removing lines out of the system. By changing the way how electricity flows through the system, transmission switching can be employed either in emergency scenarios (to alleviate violations, congestions, and overloading conditions), or during normal operating conditions (for higher economic benefits). Such considerations, which are employed in the operational time frame, make it possible to have more efficient use of the existent network facilities.

Though being performed for decades on a very limited scale with rather focused aims, transmission switching has recently gained further importance with the increased penetration of renewable energy resources and the growing demand for more reliable operation of power systems [1]. It has been shown that various operating conditions can be resolved through transmission switching; amongst, one can mention voltage violations and overloading conditions as a result of possible contingencies [2–4], network losses and congestion management [5,6], security enhancement [7,8], reliability improvements [9], and also cost reduction for economic benefits [10,11].

Reference [12] thoroughly reviewed the existing literature as of the late 1980s and introduced the transmission switching as a corrective mechanism in response to possible contingencies. A branch and bound optimization to handle the linear approximate optimal power flow (OPF) problem for corrective switching actions was also introduced in the late 1980s [13]. Optimal transmission switching, as a mixed integer programming (MIP) problem, based on the DCOPF formulation through which considerable economic savings may be gained, has been analyzed recently in [14]. Transmission switching as a corrective mechanism both with continuous and discrete control variable formulations is addressed in [15]. Flow canceling transactions in order to develop a MIP-based framework for system topology control were used in [16]. Some practical requirements for implementation of topology control applications in real world scenarios are generally introduced in [17]. Some of the mentioned approaches are too computationally intensive to find

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[*] Corresponding author at: Wisenbaker Engineering Research Center, Texas A&M University, College Station, TX 77843-3128, USA. Tel.: +1 9795873095; fax: +1 9798459887.

E-mail addresses: payman.dehghanian@tamu.edu (P. Dehghanian), ypwang@tamu.edu (Y. Wang), gurunath_gurrala@yahoo.co.in (G. Gurrala), e.moreno@tamu.edu (E. Moreno-Centeno), kezunov@ece.tamu.edu (M. Kezunovic).

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Nomenclature

A. Sets

$g \in G$	system generators
$g \in \dot{G}$	generators out of service due to a contingency
$k \in K$	system transmission lines
$k \in \hat{K}$	transmission lines in service
$k \in \bar{K}$	transmission lines out of service
$k \in \dot{K}$	out of service lines due to a contingency
$n \in N$	system buses

B. Decision variables

P_g	power output of generator g
P_k	power flow through line k
s_k	switch action for line k (0: no switch, 1: switch)
θ_n	bus angle at bus n
u_n	unfulfilled demand at bus n

C. Parameters

B_k	susceptance of line k
$B^t(\mathrm{RD}_i)$	incremental benefits obtained via generation re-dispatch-only at node i of the switching tree at time t
$B^t(S_i)$	incremental benefits obtained through successful implementation of switching line i and corresponding generation re-dispatch at time t
c_g	linear generation cost of generator g
d_n	demand (in MW) at bus n
$\mathrm{FP}^t(\mathrm{B}_i)$	failure probability of the CB i at time t
$MB^t(S_i)$	mean benefits obtained through successful implementation of switching and generation re-dispatch at node i of the decision tree at time t
M_k	big M-value for line k
$P^t(S_i)$	availability index of switching line i at time t
$P_k^{\max}$, $P_k^{\min}$	max. and min. line flow limit for line k
$P_g^{\max}$, $P_g^{\min}$	max. and min. generation limit for generator g
$\theta^{\max}$, $\theta^{\min}$	max. and min. bus angle difference
τ	minutes between two switching operations

the solutions fast enough for practical implementations. Some others do not simultaneously consider the control over the network topology and the ability to re-dispatch generation.

Advanced optimization techniques have been recently proposed to determine the transmission switching plans for day to day operations. In [18], heuristics to deal with the optimal switching problem in large-scale power systems are proposed. Fast transmission topology control heuristics in which expert's judgments are exploited in a DCOPF formulation to deal with the global marginal cost of congestion are proposed in [19]. Two fast heuristics for optimal transmission switching, one dealing with a sequence of linear programs (LPs) and the other with a sequence of MIPs taking one line out at a time, have been proposed in [20]. A fast efficient heuristic which selects the switching plan based on the minimum generation cost objective is proposed in [21]. The N-1 reliability criterion is integrated into the DCOPF formulation for the purpose of switching decision making in [22]. Topology control for load shed recovery (LSR) via the DCOPF-based MIP Heuristics (MIP-H) is recently proposed in [23].

An approach to incorporate the transient stability constraints in the ACOPF is proposed in [24] and controlling system stability through line switching is tested on an actual system in [25]. Likewise, for the transmission switching algorithms based on DCOPF formulations to be of practical use, one needs to ensure the AC feasibility and stability of the switching solutions. Reference [26] introduces the concept of robust corrective topology control and presents methodologies for real-time, deterministic planning-based, and robust corrective switching actions. The optimization procedure in [26] provides one switching sequence and involves repetitive solution of transmission switching optimization until a valid switching plan satisfying the AC feasibility and stability is found. However, if the selected lines are not switchable due to the associated circuit breaker (CB) failures, the switching process stops and the operator may need to re-run the optimization engine to obtain a new switching sequence. In practice, line switching implementation involves several operational procedures and clearances at various levels of the utility organizations which are commonly time consuming. So, transmission operators need to be provided with switching plans with high probability of success to minimize the involved time and labor. To the best of the authors' knowledge, none of the existing topology control algorithms address such practical considerations.

Trying to bridge the gap between the theoretical advancements in previous literature and the practical requirements that the operator will have to deal with, this paper proposes an implementation procedure for realizing transmission switching in practice. The main objective of this paper is to demonstrate how such technologies can empower the operator not only to obtain feasible switching actions, but also allow the operator to use his/her experience and personal judgment to decide which feasible set of actions to implement. The proposed framework, to be used in day to day operation planning scenarios in response to probable contingencies, provides several switching options per contingency in a tree-like structure. At each level of the switching tree, the framework suggests the operator a set of AC feasible and stable switching plans based on a selected optimization criterion such as maximum LSR or minimum generation cost, etc. This paper also proposes a decision making support tool based on a CB reliability assessment technique using condition monitoring data. A mean benefit index is proposed to quantify the impacts of failed CBs associated with switching of a transmission line in any substation configuration. The operator can use this information, other operating conditions not explicitly considered in the optimization, and his/her own experience to select the most reliable switching actions at each level of the tree for implementation. It is important to mention that the suggested switching actions will be a temporary solution to recover from the critical contingencies in a timely manner and the switched lines would be returned back to service when the contingency is permanently mitigated.

The rest of the paper is structured as follows. The proposed framework including the optimization algorithm to obtain the switching plans, switching AC feasibility/stability checks, and CB reliability and line availability analyses are introduced in Section 2. The proposed methodology is examined through three case studies on the IEEE 118-bus test system in Section 3, followed by some practical discussions provided in Section 4. The paper is eventually concluded in Section 5.

2. Problem description and the proposed framework

This section elaborates the proposed switching implementation framework containing four main modules: the Binary Switching Tree (BST) algorithm, AC feasibility check, stability check, and CB reliability assessment. The framework is illustrated in Fig. 1 and the details come in the following.

2.1. BST algorithm

The proposed BST algorithm is an extended version of the MIP-H algorithm in [23]. The MIP-H finds one switching operation and