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A deterministic approach to locating series flow-controllers within transmission systems to alleviate congestion

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ABSTRACT

This paper proposes a new technique to intelligently split busbars within a meshed power system, to facilitate the insertion of series active power flow-controllers into the high voltage transmission systems. Such flow-controllers have historically been placed at system and national boundaries to modulate cross-border flows for regulatory, commercial and security purposes. The present work proposes a new concept for power system control, and embeds series flow-controllers *within* meshed transmission networks to gauge the extent to which their dispatchable flows can be used to alleviate thermal congestion. To articulate the value that such flexibility might provide, a new simplified unit commitment and dispatch formulation is presented, which integrally uses series flow-controllers to manage congestion and thus reduce operating costs. While both the siting and operation methodologies are shown to be practical, the achieved cost savings are modest at best, even on systems which are weakened to have significant levels of thermal congestion.

1. Introduction

Congestion in high voltage transmission systems is costly and undesirable [1,2]. The thermal limits of certain lines can prohibit the utilization of the most cost-effective generators, meaning more expensive generation elsewhere must be brought online instead, which increases the cost of serving the demand in the system. As noted by Han and Papavasiliou [3] "*the physical laws that govern power flows have traditionally presented a range of challenges both in the operation and the market design of electricity systems. These challenges can be mitigated to a certain extent by an array of transmission control technologies.*"

Taking its cue from this, the present paper proposes a novel method of managing congestion in a meshed power system, by inserting series active power *flow-controllers* at carefully selected locations within the network. The traditional use for active power control flow-controllers, historically implemented as a phase-shifting transformer, was at national and system boundaries, where they were used to regulate cross-border flows for commercial or security purposes [4]. For instance, quadrature boosters have been used at area boundaries in the UK to regulate market flows [5].

Modern power electronic devices (the review in [6] discusses several) offer new ways to use smart flow-controllers to unlock flexibilities *within* power networks [7,8]. However, published approaches to siting such power electronic devices have typically considered direct series or shunt connections to existing lines or buses. To extend the search space of potential installation locations, the present work describes a novel technique for *exhaustively sectionalizing* buses and evaluating the flow-controlling coverage offered by straddling each split. This represents the first research question addressed by the present work: how much additional flexibility is realized by expanding the search space for flow-controller insertions in this way?

The methodology described is largely technology-agnostic: for instance, such a flow-controller could be realized as a pair of back-to-back HVDC converters [9], or perhaps as an interline power flow-controller [10]. The ability to dispatchably withdraw active power at one terminal, and inject it at the other, is the functional characterization of the flow-controller that will be embraced in this work (this *power-injection model* follows [11]). Cheaper generator dispatch schedules should be possible when such a flow-controlling flexible resource is both strategically located and fully integrated with the unit commitment and dispatch procedure. The present paper treats both topics, to gauge the incremental cost savings that may be attainable by installing these flow-controller to straddle carefully chosen splits in existing bus-bars.

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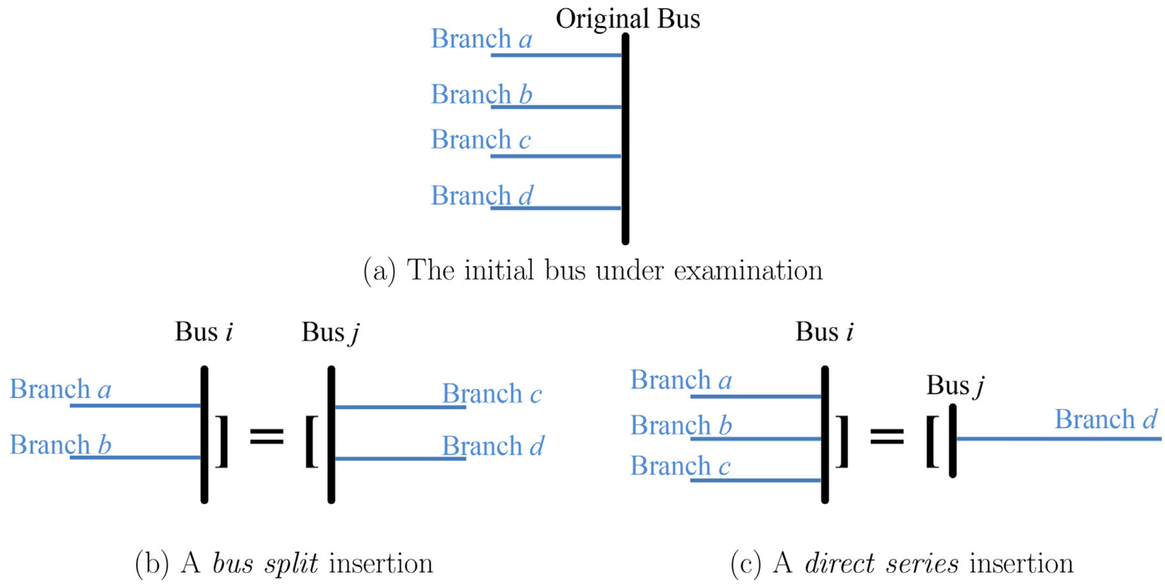

Fig. 1. The two broad types of bus sectionalization considered in this work. The **]=[** symbol represents the flow-controller.

There is a substantial extant literature on locating power electronics devices to improve power system operation (partial reviews can be found in [12–15]). Such devices can be located in power systems using diverse strategies and in pursuit of various objectives. There are three general approaches to placement: analytic and sensitivity methods [16], formal optimization techniques [17], and computational approaches using metaheuristics [18]. Alleviation of congestion is a common theme [19–24].

A substantial shortcoming of prior work on locating series devices is that they generally consider extant branches as candidate installation locations. By contrast, the present work enumerates *all* possible ways of *splitting* the existing buses in a system, to find many more candidate divisions for the flow-controller to bridge, and to articulate what additional value this approach offers.

Optimal transmission switching is another way to add flexibility to the generator scheduling formulation so that it may intelligently avoid congestion [25,26]. The optimal transmission switching approach exploits the counter-intuitive phenomenon whereby weakening a transmission system, by selectively removing certain branches from service, can ameliorate congestion and facilitate cheaper generation schedules.

Optimal transmission switching schemes can achieve substantial generation cost savings. One influential work [27] introduced a basic optimal transmission switching model and found generator cost savings up to 25%, though this was only on one particular test system under notional conditions (given the high, ongoing costs of operating power systems, savings of even a fraction of percent are meaningful, and figures such as the foregoing only point out the potential here) The biggest limitation to optimal transmission switching schemes is that they become computationally intractable on systems of realistic scale [28,29]. This is because each branch in the network must be associated with a binary status decision variable, which can cause a combinatorial explosion of complexity on large systems.

By contrast, the present scheme here only proposes to add a small number of flow-controllers to a system, which does not substantially increase the number of decision variables. Additionally, the flow through the controller is a continuous, bounded variable, and so can be optimally fine-tuned to suit the prevailing circumstances. The binary nature of the optimal transmission switching decision does not enjoy such finesse. Conversely, the ability to switch every single line inherently offers system-wide flexibility, whereas a finite number of flow controllers can only offer flow flexibility on a certain subset of branches.

Novel contributions of the present work include an original technique for appraising the suitability of a split in a power system for hosting a series flow-controller and a unit commitment and dispatch formulation that directly exploits the flexibility such controllers afford.

Methodologies for both siting and operating the flow-controllers are presented in Section 2. The placement technique is applied to two test systems in Section 3, and is trialled operationally in Section 4 to determine the value of such novel flexibility. A simple sensitivity analysis is conducted in Section 5. Conclusions are drawn in Section 6.

2. Methodology

The proposed methodology seeks to add flow-controllers to a power system so their dispatchable cross-flow has the maximum possible influence on branches throughout the network. Each flow-controller is placed by enumerating every available way to split busbars in the system, and then analysing the effect a controllable cross-split flow would have at that location. This technique can be applied sequentially until the desired number of controllers have been added to the system. The selected locations depend only on the system's basic connective structure: this siting methodology is not specific to any particular generation dispatch schedule.

2.1. Siting flow-controllers

2.1.1. Flow-controller model

Conceptually, a series power flow-controller can be thought of as two coupled generators, constrained so that one injects active power into the network, and the other withdraws an equal quantity. This framework models, for instance, two HVDC controllers placed back-to-back in a network. The present work rejects the common implicit assumption that such flow-controller can *only* be placed in direct series with an existing branch in the network. Rather, this work assumes that these flow controllers can be physically located at any existing substation in the network, for instance bridging a split created by strategically sectionalizing a bus bar there. This exhaustive technique considers both the conventional case of *direct series* connection, where the flow-controller is connected with just

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