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Merchant power flow controllers

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ABSTRACT

The transmission system in the U.S. is under stress, leading to high congestion costs. To address this issue, more efficient utilization of the existing network is a paramount alternative to building new transmission lines. Significant transfer capability enhancement can be readily achieved via a number of mature technologies that enable power flow control. Despite the promise of power flow controllers (PFC), their deployment has been very limited, due to a number of reasons, including heavy economic regulation. This has many drawbacks, including lengthy planning and approval time, lack of incentives for efficient planning and operation, and transfer of the investment risks to the ratepayers. This paper argues that PFCs pose characteristics that fit well within the framework of merchant transmission without its drawbacks, such as lumpy investments. This paper, thus, proposes to assign financial transmission rights (FTR) to merchant PFC owners based on the additional transfer capability that they offer to the system. The owners are expected to recover their investment costs through the revenues they collect from such FTRs. Unlike regulated rate of return payment, the proposed model provides the right incentive for efficient planning and operation of PFCs. The paper also proves FTR revenue adequacy in presence of the PFCs by developing a simultaneous feasibility test model. The performance of the method as well as its revenue adequacy are demonstrated, first, on a two-bus system, and then, on a three-bus system in presence of loop flows. The paper concludes that opening the electricity markets to merchant PFC projects would reveal profitable investment opportunities to improve the efficiency of the system.

1. Introduction

The transmission system in the United States is under stress, which leads to costly congestion in the grid (Spencer, 2002; Snarr, 2009). Fig. 1 shows the annual congestion rent in the U.S. for a select number of independent system operators (ISO) and regional transmission organizations (RTO) in 2015 (California ISO, 2016; Potomac Economics, 2016a; ISO New England Inc. Internal Market Monitor, 2016; Monitoring Analytics LLC, 2016; Potomac Economics, 2016b; Potomac Economics, 2016c; SPP Market Monitoring Unit, 2016). Congestion revenue is presented here as a proxy to congestion cost, on which public data is not available. The total congestion revenue for the presented areas in Fig. 1, adds to five billion dollars. Assuming that congestion rent is a good proxy for congestion cost, this expense will be transferred to electricity ratepayers. The new congestion patterns created by increased penetration from intermittent renewable energy resources is only expected to aggravate this problem (Sang et al., 2018).

While building new transmission lines can offer an effective solution to the congestion problem, new transmission projects are extremely costly, take a long time to complete, and face substantial permitting barriers. Alternatively, power flow controllers (PFC) can significantly enhance the transfer capability over the existing network, through utilizing its unused capacity (Hug, 2008). The increase in transfer capability can be as large as 50% according to the literature (Amin, 2004) and provide substantial savings in terms of avoided congestion costs and deferred transmission investment costs. Power flow control enables rerouting of the power to the paths that are not congested. This is shown schematically for PJM in Fig. 2, where an actual map of real-time prices is presented on the left. Due to the transmission system limits, the prices are very high in the eastern parts of the system near the load centers in Philadelphia and Washington, DC, while the prices are very low in southwest Virginia. This large price difference signals clear inefficiencies, as the cheap energy produced in Kentucky, southwest Virginia, and West Virginia cannot be transferred to the locations with high demand. Thus, local expensive power plants near the load centers are required to produce energy at a much higher cost to meet the energy demand in the system. Additionally, the figure has implications regarding system reliability. As most of the generation capacity in the northeastern part of the system is utilized to produce energy, there is little reserve (extra capacity) left for contingency response. Fig. 2-right shows how PFCs can improve the transfer capability and allow additional flow of power from the cheap resources to the electric load. Enhancement of the transfer capability will improve economic efficiency by replacing some of the expensive power plants near the load centers with cheaper resources in the southwestern part of the

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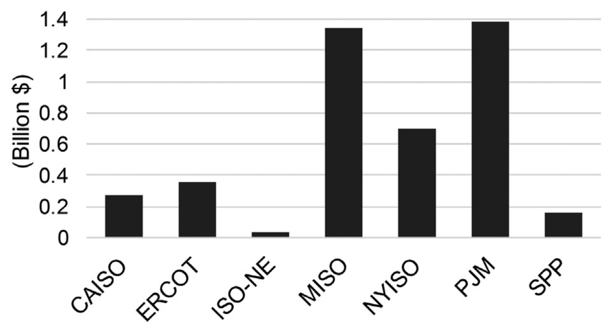

Fig. 1. Annual congestion cost in select U.S. independent system operators and regional transmission organizations in 2015.

system. Consequently, the reserve capacity near the load centers will increase, which would translate in reliability improvements.

Power flow control can be achieved via a number of different technologies, such as topology control, voltage phase shift, or impedance control (Sahraei-Ardakani et al., 2016; Gotham and Heydt, 1998; Zhang and Sahraei-Ardakani, 2018). This paper focuses on the latter technology, as many of the existing PFC devices rely on impedance control. The grid is also expected to be equipped with more variable-impedance PFCs, as a distributed and relatively cheap version of such devices has been successfully introduced to the market (Smart Wires Inc.). PFCs are already a part of the North American grid. To mention a few, five EPRI-sponsored FACTS devices are currently operating in AEP's territory (Kentucky), BPA (Oregon), CSW (Texas), TVA (Tennessee), and NYPA (New York) (Basler et al., 2012). Recently, Smart Wires has also completed the installation of a distributed series reactor device for Minnesota Power (Smart Wires, 2017).

Despite their potential in improvement of transfer capability, PFC installations have been relatively limited. Moreover, the set point of the existing PFCs are not optimized alongside generation dispatch within the energy management systems (Sahraei-Ardakani and Hedman, 2016a; Sahraei-Ardakani and Hedman, 2017). There are two reasons for such underutilization: (i) PFC modeling involves computational complexities that are challenging to handle (Sahraei-Ardakani and Hedman, 2016a; Sahraei-Ardakani and Hedman, 2017); and (ii) PFCs are regulated as a part of monopoly transmission system (Sahraei-Ardakani and Blumsack, 2016; Sahraei-Ardakani and Blumsack, 2012). Effective handling of the computational challenges involved in PFC operation has received significant attention recently (Ziaee and Choobineh, 2017a; Ziaee and Choobineh, 2017b; Sahraei-Ardakani and Hedman, 2016a; Sahraei-Ardakani and Hedman, 2017; Sahraei-Ardakani and Hedman, 2016b; Sang and Sahraei-Ardakani, 2018). However, addressing the inherent inefficiencies of regulation remains to be an unresolved barrier.

The existing PFCs, similar to any transmission asset, receive a fixed regulated rate of return (RoR) on their investment. The RoR compensation structure does not provide any incentive for efficient operation. On the contrary, frequent adjustment of the PFC set point would increase the maintenance costs, which are not desirable. Therefore, PFC owners under an RoR payment structure, would prefer to keep the set point of their devices unchanged for as long as they can. Moreover, a badly located PFC will receive the same compensation as a well-planned PFC, as long as they are both permitted. This paper aims to offer a solution to these problems through a merchant model, where the payments to the PFC owners are based on their performance. We, first, develop a convex model for PFCs and show that financial transmission right (FTR) market revenue adequacy is maintained in presence of PFCs, with such a convex model. Then, we calculate the additional FTRs that can be supported in a network that is equipped with PFCs. This paper argues that the additional FTRs should be assigned to PFC owners, through which they may recover their investment costs and make extra profit. The proposed structure would transfer the investment risks to the PFC owners and provide the right incentive for efficient operation.

The rest of this paper is organized as follows: section II develops a convex model for PFCs. Section III provides a proof for FTR revenue adequacy in presence of PFCs. A Case study on a two-bus system is provided in section IV, and finally section V concludes the paper.

2. PFC modeling and convexification

The power flow on a transmission line can be calculated through the shift factors and nodal injections, according to the linear dc power flow equation, as shown in (1).

$$f_l = \sum_{i=1}^{N} \varphi_{li} I_i \tag{1}$$

f_l is the flow on line l, N is the number of nodes in the network, φ_{li} is the sensitivity of f_l to injection at node i, I_i. For a network with fixed topology, shift factors (φ) are constant, making (1) a linear equation. However, when a transmission line's impedance is controllable through a PFC, (1) is no longer valid, because the shift factors change. To keep the shift factors constant, PFC can be represented via a pair of injections, as shown in Fig. 3 (Sahraei-Ardakani and Hedman, 2017). In the figure, a single line k is shown with its "from" and "to" nodes and its susceptance, b_k. The PFC is represented by the change in the susceptance of the line, Δb_k. This susceptance change is equivalent to an injection pair at the "from" and "to" nodes of line k, as shown in Fig. 3.

The injection pair, representing the PFC, will affect the flow of all the other lines in a meshed network, which have nonzero shift factors

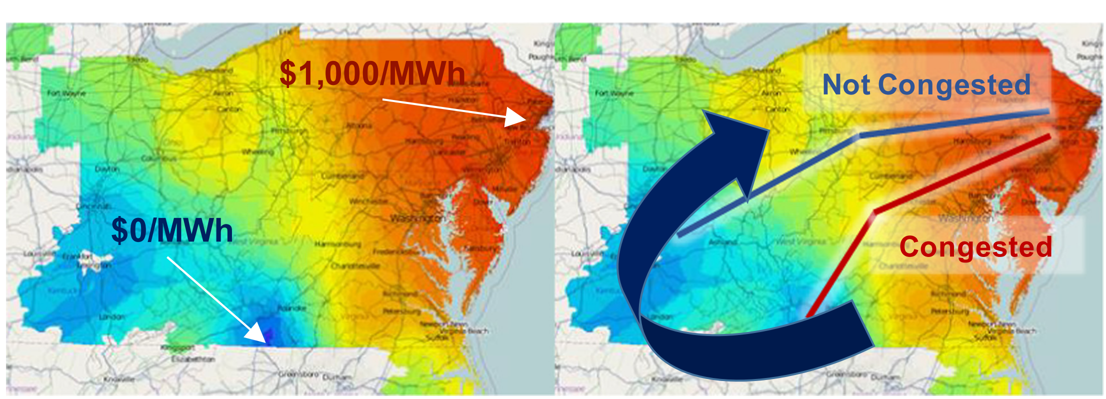

Fig. 2. Left: a map of real-time prices in PJM, with prices as high as $1000/MWh in the east and as low as $0/MWh in the southwestern parts of the system; Right: with power flow control, the unused capacity over the existing transmission system can be utilized to improve both economic efficiency and system reliability.