A Review of Transmission Switching and Network Topology Optimization

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***Abstract*--Currently, there are multiple national directives that call for the development of a smarter electrical grid. This includes, but is not limited to, the development of advanced transmission technologies as well as optimizing the use of transmission. Transmission control has been identified as a valuable mechanism for a variety of benefits, from improving the system reliability to improving the market surplus. However, the use of transmission as a controllable asset today is limited. This paper provides a literature review on transmission control and discusses current industry practices involving transmission control; the goal of this paper is to reemphasize the importance of transmission control in order to initiate future research and development in this area so that we are able to truly build and operate a smarter, more flexible transmission grid.**

***Index Terms*—Power system economics, power system reliability, power transmission control, power transmission economics, smart grid, transmission switching.**

I. Introduction

MULTIPLE national directives call on research related to creating a smarter, more flexible grid. The Federal Energy Regulatory Commission (FERC) order 890 calls for improved economic operations of the electric transmission grid. The USA Energy Policy Act of 2005, Sec.1223.a.5, includes: "encourage… deployment of advanced transmission technologies" and "optimized transmission line configuration." The Energy Independence and Security Act of 2007, under Title 13: Smart Grid, has: "increased use of… controls technology to improve reliability, stability, and efficiency of the grid" and "dynamic optimization of grid operations and resources." FERC held a conference in the summer of 2010 on: "Increasing Market and Planning Efficiency through Improved Software," Docket No. AD10-12-000. The motivation of this conference was to promote the development of smarter software to improve the efficiency of the electric industry and to transform the software to better utilize flexible assets (including the modeling of dispatchable networks), new resources, etc; this initiative is a part of FERC's 2009-2014 Strategic Plan. Furthermore, new transmission infrastructure can be expensive and hard to site [1]. Therefore, optimal use of the existing transmission system and optimal expansion should be a priority.

The Optimal Power Flow (OPF) problem is a complex and unique mathematical problem; due to Kirchhoff's laws, changing a transmission asset's impedance (or taking a transmission line offline) changes the power flows over the meshed network. However, the mathematical modeling of the network is not as complex as it could be and various control mechanisms have yet to be harnessed in traditional OPF formulations. Traditionally, the system operator treats transmission assets (lines or transformers) as static assets within OPF formulations. This traditional view does not describe transmission assets as assets that operators have the ability to control. However, it is acknowledged, both formally and informally, that system operators can and do change the grid topology to improve voltage profiles, increase transfer capacity, and even improve system reliability.

These ad-hoc procedures are determined by the system operators, rather than in an automated or systematic way. Furthermore, such flexibility is not incorporated into day-ahead dispatch optimization problems today. This is a shortcoming regarding today's electric grid operations; due to the physics that govern the flow of electric energy and due to the complexities within this network flow problem, it is extremely unlikely that there is a single optimal network topology for all periods and possible market realizations over a long time horizon.

Network topology optimization is a promising option because it uses existing assets to achieve important and timely goals: increased grid flexibility and efficiency. The motivation of this paper and presentation is to reemphasize literature and industry practices that use the flexibility of transmission assets (lines and transformers) to improve system reliability and operational efficiency. This paper is organized as follows. The following section presents a thorough literature review on how transmission assets have been proposed as controllable assets for a variety of uses for well over twenty-five years. Section III presents an overview on current industry practices of transmission control. Section IV discusses recent research that has demonstrated that substantial improvements to operational efficiency can be achieved by co-optimizing the generation dispatch with the network topology; Section IV also discusses how transmission switching differs from transmission planning, how network topology optimization creates a superset of feasible dispatch solutions, and on how network topology optimization affects system reliability. Section V then provides an overview on potential Financial Transmission Rights (FTRs) market implications due to

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network topology optimization. Section VI discusses a list of future research challenges that should be addressed and Section VII concludes this paper.

II. Literature Review

A. Transmission Switching as a Corrective Mechanism

Past research has explored transmission switching as a control method for a variety of problems. The primary focus of past research has been on proposing transmission switching as a corrective mechanism when there is line overloading, voltage violations, etc. While this past research acknowledges certain benefits of harnessing the control of transmission, they do not use the flexibility of the transmission grid to co-optimize the generation along with the network topology. Such co-optimization, as will be discussed in the Section IV, can provide substantial economic savings even while maintaining N-1 reliability standards.

Glavitsch [2] gives an overview of the use of transmission switching as a corrective mechanism in response to a contingency. He discusses the formulation of the switching problem and provides an overview on search techniques to solve the problem. Mazi *et al.* [3] propose a method to alleviate line overloading due to a contingency by the use of transmission switching as a corrective mechanism and they employ a heuristic technique to solve the problem due to the computational challenges of solving such a difficult problem at that time. Gorenstin *et al*. [4] study a similar problem concerning transmission switching as a corrective mechanism; they use a linear approximate Optimal Power Flow (OPF) formulation and solve the problem based on branch and bound. Bacher *et al*. [5] further examine transmission switching in the AC setting to relieve line overloads; they assume that the generation dispatch is already determined and fixed in order to make the problem more tractable. Bakitzis *et al*. [6] examine transmission switching as a corrective mechanism both with a continuous variable formulation for the switching decision as well as with discrete control variables.

Schnyder *et al.*, [7] and [8], proposed a fast corrective switching algorithm to be used in response to a contingency. The benefit of this algorithm over past research is that they simultaneously consider the control over the network topology and the ability to redispatch generation whereas other methods would assume that the generation is fixed when trying to determine the appropriate switching action. Due to the complexity of this problem for its time, this method does not search for the actual optimal topology but rather considers limited switching actions. Rolim *et al*. [9] provide a review of past transmission switching methods, the solution techniques used, the objective at hand, etc. Shao *et al*. [10] continued previous research on the use of transmission switching as a corrective mechanism to relieve line overloads and voltage violations. They propose a new solution technique to find the best switching actions. Their technique employs a sparse inverse technique and involves a fast decoupled power flow in order to reduce the number of required iterations. In Shao *et al*. [11], a binary integer programming technique is used for the same motivation: to use switching actions as a corrective mechanism to relieve line overloads and voltage violations.

B. Transmission Switching and Line Losses

It is well known that if one of two parallel lines is taken out of service, then the line losses will increase if the amount of power transferred across these two points stays the same as compared to when both lines are in service. As a result, it is often assumed that taking a line out of service results in higher system-wide (line) losses. However, this is not the case and, in fact, it is possible to decrease line losses through transmission switching. Modifying a meshed network topology allows the system operator to choose generator dispatch solutions that would otherwise be infeasible given the initial topology. It is, therefore, possible to not only change the topology but change the dispatch solution. With a completely different generator dispatch solution, it is not possible to guarantee that losses increase with fewer lines in service because the power flows throughout the network may be drastically different.

The simplest theoretical example to demonstrate this fact is to take any network and add infinite generators with extremely high costs to every bus. The optimal dispatch with all lines in service will be the same as without these infinite generators and the system will have some level of line losses (if there are any line flows). If all lines are now taken out of service, there will be no line losses but the system still satisfies all of the load since these infinite, expensive generators are dispatched. This solution is obviously more expensive and it obviously will not exist in the practical world; however, this example demonstrates that once you allow for both the topology and the generation to simultaneously change, it is not possible to guarantee that the losses will increase or decrease. Furthermore, past research has already demonstrated that transmission switching can be used to minimize system losses. Bacher *et al.* [12] and Fliscounakis *et al.* [13] both examined the problem of modifying the grid topology in order to minimize system losses.

C. Transmission Switching as a Congestion Management Tool

Transmission switching can even be used as a congestion management tool. Granelli *et al*. [14] propose transmission switching as a tool to manage congestion in the electrical grid. The objective of the model is to minimize the amount of overloads in the network. They discuss ways to solve this problem by genetic algorithms as well as deterministic approaches.

III. Current Industry Practices

A. Transmission Switching to Improve Voltage Profiles and Transfer Capability

It is a common industry practice to switch select transmission lines offline during lightly loaded hours. The capacitive component of a transmission line is the predominant component during low load levels whereas the reactive component is predominant at higher load levels. Consequently, during low load levels there can be situations where a transmission line causes voltage violations in the network, i.e., the voltage levels are too high. Therefore, one simple protocol that operators are aware of is to select key transmission lines that are not currently needed for reliability considerations and they take these lines out of service in order to alleviate voltage violations. Such a protocol is acknowledged as a procedure within the PJM network, [15] and by Excelon, [16]. Likewise, the Northeast Power Coordinating Council includes "switch out internal transmission lines" in the list of possible actions to avoid abnormal voltage conditions, [17] and [18]. Another ad-hoc transmission switching protocol that is at times used by grid operators is to identify key transmission lines that can be taken out of service in order to improve the transfer capability on other high voltage transmission lines. This is a protocol implemented in the PJM network, [15].

B. Special Protection Schemes (SPSs)

Special Protection Schemes (SPSs), also known as Remedial Action Schemes (RASs) or System Integrity Protection Schemes (SIPSs), are an important part of grid operations. SPSs are used to improve the reliability of the grid and improve the operational efficiency. SPSs are primarily identified and developed based on ad-hoc procedures. The development of such corrective mechanisms like SPSs reflects a shift, a push by the industry to switch from preventive approaches to the use of corrective approaches. The use of transmission switching as a corrective mechanism can be a powerful tool. For instance, PJM has a number of SPSs that involve post-contingency transmission switching actions [19]. For example, the following action is listed in [19] on page 184:

"The 138 kV tieline L28201 from Zion to Lakeview (WEC) can be opened to relieve contingency overloads for the loss of either of the following two lines: Zion Station 22 to Pleasant Prairie (WEC) 345 kV Red (L2221), Zion Station 22 to Arcadian (WEC) 345 kV Blue (L2222)."

Such operational protocols like these SPSs are often viewed as a necessary protocol to maintain system reliability. While these transmission switching SPSs do help maintain system reliability, there are alternatives that the operator can employ instead. Possible alternatives may include: re-dispatching the system after the contingency occurs, choosing a different steady-state (no-contingency) dispatch prior to the contingency occurring to ensure there is no overloading, or upgrading the equipment so that it is able to handle these contingency flows. Re-dispatching the system is likely to increase the operating costs. Choosing a different dispatch solution for steady-state operations will increase the operating cost as, otherwise, that dispatch solution would have been initially chosen. Investing in new equipment increases the capital cost of the system.

While this corrective switching action is seen as a necessary mechanism to maintain reliability, the decision to choose this mechanism over these alternative options is economic. Hence, these transmission switching SPSs demonstrate the industry's practice to employ ad-hoc network topology reconfiguration actions for the purpose of improving the operational efficiency while maintaining reliability standards. The concept of network topology optimization, which is covered in Section IV, simply improves upon this current practice with the motive to optimally determine the network topology configuration on a period by period basis while maintaining reliability.

C. Transmission Line Maintenance Scheduling

Transmission line maintenance scheduling is not new but what recently has changed is the perception regarding the importance of considering operational efficiency. The Independent System Operator of New England (ISONE) recently began to focus not only on reliability but also on the dispatch efficiency when determining the appropriate periods to take transmission lines out of service for maintenance. As a result, ISONE estimates that they will save roughly $50 million a year [20]. This ISONE study was based on estimating prices instead of using a mathematical scheduling program that optimizes total system cost while maintaining system reliability. While there are many published papers on transmission line maintenance scheduling, this result reemphasizes the need to develop sound, practical maintenance scheduling problems as well as algorithms to solve such challenging mathematical programs.

D. Seasonal Transmission Switching

In the state of California, the load requirements are lower in the winter and the probability of an outage is higher due to winter storms. The summer is the exact opposite; during the summer, the load is the highest in the year but the probability of outages is lower since there are fewer and less severe storms. As a result, some utilities have determined that it is beneficial to leave certain transmission lines in service during the winter when there is a greater chance of winter storms but yet these lines are taken out of service during summer periods since the threat of an outage is lower.

These lines are primarily redundant transmission lines in the lower voltage network. Such redundancies are less important during summer periods when the probability of an outage is lower. Furthermore, these redundant lines can cause overloading concerns during summer periods since the load conditions during the summer are higher. For instance, there can be two parallel lines with different thermal capacity ratings. The lower capacity line, generally a part of the lower voltage network, may reach its capacity first and, therefore, inhibit the higher voltage network from transferring as much power as desired. Due to the higher loading conditions, it is, therefore, preferred to take the redundant, lower capacity line out of service, as long as the line is not necessary to maintain system reliability. Since the outage rates are lower during the summer periods, the operators are able to take the line out of service without jeopardizing system reliability. In contrast, having these redundancies in service during the winter is integral to maintaining system reliability since the probability of an outage is greater. In addition, the redundancies do not cause overloading concerns during the winter since the winter loading levels are lower.

While this operation is acknowledged by utilities today, the tradeoff between protecting against potential contingencies versus the potential for overloads is not well understood. Seasonal transmission switching models that are capable of answering these questions do not exist today, thereby emphasizing the need for further research and development in the area of seasonal transmission switching.

IV. Network Topology Optimization

A. Transmission Switching's Impact on the Feasible Set of Dispatch Solutions

Co-optimizing the network topology with the generation dispatch allows the operator to simultaneously choose the network topology with the generation. By having the ability to optimize the network topology, the operator now has the ability to choose any dispatch that is feasible given the original topology but also has the ability to choose additional dispatch solutions that are feasible for any of the other topologies. It is possible that a generation dispatch solution is feasible for one topology but not feasible for a different topology since changing the topology changes the power flows in a meshed network due to Kirchhoff's laws. As a result, co-optimizing the generation with the network topology creates a superset of feasible dispatch solutions. Obviously, if there is no congestion in the network then temporarily taking lines out of service will not improve the operational efficiency of the system.

B. Transmission Switching and Reliability

It is often thought that taking a transmission line out of service degrades system reliability. First, the right question to ask is not whether the system reliability degrades but whether the system is still capable of meeting the established reliability requirements. The system operator has the objective to operate the grid at least cost (or in a market context: maximize the market surplus) subject to network (power flow) constraints and subject to meeting established reliability requirements. With two generation dispatch solutions that both meet the reliability requirements and the power flow constraints, the operator chooses the one that has a lower cost, not the one that provides the highest level of reliability. For instance, a grid may be N-k[1] reliable with all lines in service and then it may be N-j ($j < k$) reliable if the operator chooses to temporarily open a few lines. If making this decision reduces the operational cost of the system and $j \geq 1$, then this is the preferred choice since the grid is still maintaining the established reliability requirement of *N-1* but now the operational efficiency has improved. Section III already presented a number of industry practices where transmission lines are temporarily taken out of service, thereby confirming that system operators can and do take transmission lines out of service to improve system operations while still being able to maintain established reliability requirements.

Furthermore, it is possible to improve system reliability by temporarily taking a line out of service. System reliability not only depends on the network topology but it also depends on the generation dispatch solution, e.g., available generation capacity, ramping capabilities of the generators, etc. Since modifying the topology changes the feasible set of dispatch solutions, it is possible to obtain a different generation dispatch solution that was infeasible with the original topology but is feasible with the modified topology. Even though there may be a line(s) temporarily out of service, this new generation dispatch solution may make the system more reliable if it has more available capacity with faster generators. This is shown by a theoretical example in [21].

C. Transmission Switching and Transmission Planning

The concept of optimally reconfiguring the network topology in the short term is often misunderstood to conflict with transmission planning or, in other words, applying transmission switching to reduce costs may seem counter-intuitive as it seems to contradict the purpose of transmission planning. Transmission lines are built to maintain system reliability and/or to improve the operational efficiency, i.e., reduce operating costs. Therefore, there is a common misconception that short-term network reconfiguration will only reduce operating costs for poorly planned transmission networks.

Optimal transmission switching and transmission planning are two different optimization problems with different objectives. Transmission planning is a long-term problem that looks to find the optimal line(s) to build over a long time horizon. On the other hand, optimal transmission switching is a short-term problem that looks to find the optimal network configuration for a specific period. The optimal transmission expansion plan provides the most *aggregate* benefits over a long time horizon; the optimal plan does not guarantee that it benefits the system during *each individual* operating period. As a result, a network can be perfectly planned but yet still benefit from short-term network reconfiguration.

Furthermore, it is next to impossible to determine a single optimal topology over such a long time horizon due to the high level of uncertainty regarding future network conditions. As network conditions change, it should be expected that the optimal topology may change from one period to the next; it is highly unlikely that there is one perfectly planned topology for all possible network conditions over a long planning horizon. Finally, transmission expansion planning is a very difficult optimization problem, which limits the modeling complexity and further decreases the accuracy of the solution. These factors further argue in support of short-term network topology optimization.

D. Optimal Transmission Switching

The electric transmission network is built to be a redundant network in order to ensure mandatory reliability standards and these standards require protection against worst-case scenarios. However, it is well known that these network redundancies can cause dispatch inefficiency and, furthermore, a network branch that is required to be built in order to meet reliability standards during specific operational periods may not be required to be in service during other periods. Consequently, due to the interdependencies between network branches (transmission lines and transformers), it is possible to temporarily take a branch out of service during

[1] *N-k* reliability means that the system can survive the simultaneous failure of any *k* elements (non-radial transmission or generation) without violating any constraints on the surviving network and without the need for load shedding.

certain operating conditions and improve the efficiency of the network while maintaining reliability standards.

The concept of optimal transmission switching states that Optimal Power Flow (OPF) formulations should be modified to incorporate the choice to temporarily have a transmission asset in service or out of service. The operator is then able to co-optimize the generation dispatch with the network topology while maintaining reliability requirements. Due to practical limitations, this concept is proposed to be incorporated into typical day-ahead optimization models and the operator would determine what topology is best for the following day for each hour.

The concept of a dispatchable network was first introduced by O'Neill *et al.* [22], which lead to the following work on optimal transmission switching, [21] and [23]-[30]. This past research has shown that substantial economic savings can be obtained even for models that explicitly incorporate N-1. For instance, [26]-[27] showed that savings on the order of 4-15% can be obtained even while maintaining N-1. If this concept can be implemented and it can obtain even a tenth of these earlier estimated savings, such a result would be immense for the $300 billion dollar electric energy industry in the USA. This past research has been based on the Direct Current Optimal Power Flow (DCOPF) formulation, a linear approximation to the ACOPF problem. As a result, future research is needed to examine the impacts on the ACOPF. Though these DCOPF transmission switching models are lossless models, the fact that losses are ignored is not expected to change the general conclusions: that co-optimizing generation with the network topology creates a superior dispatch solution since it creates a superset of feasible solutions. Furthermore, since the estimated percent savings are so high, even if losses increase it is likely to not outweigh the cost savings by being able to obtain a previously infeasible dispatch solution.

V. Financial Transmission Rights

Many restructured electric energy markets include a Financial Transmission Rights (FTRs) market. FTRs are instrumental in the electric energy markets since they are used to hedge congestion risk and they allow market participants to speculate on price differences. In most electric energy markets, the ISO auctions off the FTRs subject to what is known as the Simultaneous Feasibility Test (SFT). Given a set of assumptions, the SFT guarantees that the FTR market is revenue adequate, i.e., the ISO collects enough congestion rent so that the ISO is able to settle all FTR positions, fully compensate all FTR holders.

One of the assumptions of the SFT is that the network topology is not modified. Therefore, by modifying the network topology there can be revenue inadequacy in the FTR market. Typically, when there is revenue inadequacy, the ISO will derate the payments to the FTR holders; obviously, this decreases the value of the FTRs. In [21], it was shown that network topology optimization can cause revenue inadequacy problems even over a long time horizon. Such research demonstrates that new smart grid technologies that reconfigure the network topology may undermine prevailing market design mechanisms that rely on the premise of a fixed network topology. Future research should investigate a side-payment scheme to maintain revenue adequacy or develop a new form of financial rights that allow the hedging of congestion risk without relying on the assumption of a fixed network topology; this discussion is continued in [21].

VI. Future Challenges

A. ACOPF Transmission Switching and Computational Complexities

One of the main challenges with network topology optimization is the computational challenges. As has been demonstrated by earlier research, [23], solving a DCOPF optimal transmission switching problem is challenging. The DCOPF is a linear approximation of the ACOPF problem, which is a difficult non-convex optimization problem. Adding binary variables to a challenging non-convex, non-linear program like the ACOPF will create an even more challenging problem. As a result, it is likely that network topology optimization may have to be solved using an approximation of the ACOPF problem, the DCOPF. Future research should examine the inaccuracies of solving a network topology optimization technique with an ACOPF approximation, the DCOPF. Likewise, fast heuristic techniques that can speed up the solution time of the DCOPF transmission switching problem are needed as well. Current research, [31], has already shown that fast heuristics can perform close to optimal.

B. Proxy Limits

System operators rely on proxy limits, i.e., surrogate limits, within dispatch optimization models. The DCOPF problem is a crude linear approximation to the ACOPF problem formulation. The DCOPF is commonly used as the OPF formulation for unit commitment problems today. Since the DCOPF does not incorporate voltage variables, many formulations use proxy limits to ensure that there are no voltage stability problems; these are known as voltage stability interface limits. Future research should investigate whether these proxy limits are in unison with future smart grid technologies that reconfigure the network topology and, if not, research will be needed to propose alternative proxy limits.

C. Transient Stability

Even though transmission switching can cause a transient stability concern, transmission switching has been shown to be a possible control mechanism to alleviate transient stability issues, [32]-[33]. Future research is needed to determine whether more frequent transmission switching actions will cause transient stability concerns.

D. Relay Settings

Reconfiguring the network topology may require the changing of relay settings. Future research is needed to evaluate and determine the necessary protocols required for smart grid technologies that may frequently reconfigure the network as well as identify any potential limitations.

VII. Summary

Previous research has demonstrated that harnessing the control of transmission assets can provide substantial benefits. The use of transmission switching as a corrective mechanism has been the most frequently proposed use of transmission control; such research has demonstrated its ability to help alleviate line overloading, voltage violations, etc. Furthermore, past research has demonstrated the ability for transmission switching to help reduce system losses, increase transfer capability, and manage congestion. Even though past research has emphasized the substantial benefits that can be obtained from transmission switching, for the most part transmission assets are still viewed as static assets; today, transmission switching is primarily limited to ad-hoc procedures and special protection schemes. Recent research on network topology optimization, [21] and [23]-[30], proposes that the way in which transmission assets are viewed in economic dispatch optimization models should change, that the state of a transmission asset should be seen as a discrete decision variable in optimal power flow formulations. This previous research has demonstrated that, indeed, the network redundancies that are built into the electrical grid, in order to survive a multitude of contingencies, cause economic dispatch inefficiency. Furthermore, this past research showed that it is possible to improve the operational efficiency of the system while maintaining N-1 by co-optimizing the network topology with the generation.

With more sophisticated modeling of transmission assets, it is possible to better utilize the current infrastructure to improve system reliability and improve the operational efficiency of the system, i.e., improve the social welfare. Further research and development is needed regarding the modeling and use of transmission assets in order to truly obtain a smarter, more flexible grid.

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