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Use of New Generation of Power Flow Controllers to Defer Transmission Investment

A. DEL ROSSO[1], S. UPPALAPATI[1], T. HEIDEL[2]
[1]Electric Power Research Institute (EPRI)
[2]ARPA-E
USA

SUMMARY

Four new technologies for controlling power flow in transmission and distribution grids have been developed under the auspice of ARPA-E's GENI program. This new hardware advancement is intended to more efficiently and cost effectively direct the flow of power on the grid to reduce congestion, help minimize energy losses, increase network flexibility to better accommodate renewable generation, and enable the grid to be more responsive and reliable. Some of these new power flow control devices are reaching a point of maturity where they may be ready for installation on utility systems in the near future, while others are already commercially available in various models and types.

A study was performed to assess the capabilities and benefits that these technologies can provide to the electric grid. Among the many possible applications of power flow controllers, the study dealt with the most important anticipated uses of this technology, namely; congestion cost reduction, and deferral of transmission expansions needed for reliability. This paper focusses on the second aspect. We analyse through concrete case studies on a real power system, the use of power router technologies to potentially defer transmission expansion projects. The case studies were selected from actual transmission expansion plans developed by the Southwest Power Pool (SPP). A companion paper titled Congestion Reduction Benefits of New Power Flow Control Technologies used for Electricity Market Operations, describes results of the congestion reduction analysis conducted on a practical, large-scale power system.

KEYWORDS
Power flow control – transmission – expansion – investment deferral – reliability - flexibility

INTRODUCTION

A new generation of power flow control technologies (PFC) have been developed under the auspice of the ARPA-E's GENI program [1]. A brief description of these technologies and their main characteristics is provided in Table 1 [2]. Some common characteristics include fast response times and flexible operation and control. Some of these technologies are also mobile, and can be moved from one location of the grid to another in a relatively straightforward way. These technologies in addition to traditional technologies like phase angle regulators (PAR), high voltage direct current

adelrosso@epri.com

(HVDC) lines, and flexible AC Transmission Systems (FACTS) can provide control of the amount of power flowing on different paths on the transmission grid.

Table 1: New power flow technologies

Device	Developer	Characteristics
Distributed Series Reactors (DSR)	Smart Wires Inc.	• Increases line impedance on demand by injecting the magnetizing inductance of the Single-Turn Transformer. • Functions as a current limiter to divert current from the overloaded lines to underutilized ones • Local or centralized control are possible • Various device models and types
Compact Dynamic Phase Angle Regulators (CD-PAR)	Varentec Inc.	• Power converter integrated with a transformer • Special modulation technique allows for control of angle and module of series injected voltage, thus providing smooth and continuous control of P and Q flows over the line.
Transformer-less Unified Power Flow Controller (UPFC)	Michigan State University	• Cascaded multi-level inverters (CMIs) to eliminate transformers • Fractional MVA rating (10-20%) for >1p.u. (raise/lower/reverse) power swing on typical line • Modular scalable design
Magnetic Amplifier (MA)	Oak Ridge National Lab SPX Waukesha	• Inserts a controlled variable inductance in the line • Power electronics isolated from the HV line • Low power dc source controls the high voltage ac inductance • Smooth reactance regulation, acceptable harmonics • Uses standard transformer manufacturing methods

Power delivery systems are to be planned, built, and operated so that sufficient transmission capacity exists to deliver electricity from the available generation to the consumption points in a reliable and economic manner. Load growth and generation additions can lead to increased loading on lines and transformers, to the point where transmission capacity investments become necessary. In some cases, PFCs can be used to divert power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and, consequently, potentially reducing the need for transmission upgrades. Examples of common transmission reinforcements or upgrades include increased capability of a transmission corridor or transmission interface, increased import capability into a load pocket, and increased export capability of an area with surplus generation.

This paper presents an analysis of the use of power flow control technologies to potentially defer transmission expansion projects. The concept is illustrated through several use cases from consolidated transmission expansion plans developed by Southwest Power Pool (SPP).

APPROACH

Transmission expansion needs are identified as part of the transmission planning process. Based on these needs, transmission expansions are designed with the final goal of achieving optimal solutions that meet the required reliability level with the lowest cost possible. In some cases, expansion projects needed for reliability also have economic benefits or help facilitate societal goals such as the achievement of renewable portfolio standards.

The transmission expansion process is a very complex and extensive process that involves not only planning engineers but also a number of stakeholders, depending on the geographic footprint (utility planning, regional planning, or interregional planning), and type of entities involved (utility, ISO/RTO, market participants, local and federal commissions and regulatory entities, and so forth). In deregulated jurisdictions, the process can be complicated because various entities have responsibility for various parts of the solution development process [3]. Considering the complexity of transmission planning, this work does not attempt to identify and design solutions for transmission expansion needs on the study system but rather to analyse whether a PFC-based solution can potentially substitute for an expansion project that is already defined in an existing transmission plan. For this purpose, transmission planning reports published by SPP were reviewed in order to find potential use cases. The main objective of the SPP expansion plans is to create an effective long-range plan for the SPP footprint that identified NERC, SPP, and local planning criteria violations and developed appropriate mitigation plans to meet the reliability needs of the SPP region. In addition, SPP evaluates projects that might produce economic benefits to the stakeholders in the SPP footprint.

In general terms, the approach that was taken in this analysis is as follows:

- Identify in SPP planning reports the expansion projects that are needed because of thermal overload. Projects needed to solve voltage issues were not considered because these power flow controllers – except the Transformer-less UPFC – are not intended to provide reactive power support.
- Evaluate whether PFCs can be used to relieve the overloads and meet the reliability requirements of the original expansion project.
- If so, evaluate for how long the original expansion project could be deferred or whether it could be fully substituted with the PFC alternative.
- Estimate potential economic benefits from differing expansion projects or from the use of alternatives solutions.

It is worth to mention that in most of the case studies we did not have enough information and data to estimate the deferral time. Indeed, it is necessary to perform detailed power flow analysis on future scenarios to determine for how long the PFC solution can defer a planned transmission investment. However, we did an analysis to illustrate what would be the minimum number of years that the original investment must be deferred in order to justify investing in an interim solution based on the use of PFCs. Besides, we found that in most of the cases the PFC solution is effective for the scenario at the horizon year. Hence, the solution could actually replace the original project. In such situations, the economic benefits can be assessed solely on the cost of PFC alternatives compared to the conventional solution proposed in the planning reports.

CASE STUDIES

Due to space limitations, we only describe in some detail two of the several cases studied, and provide a summary and main results from other cases. The final project report [2] provides a detailed and complete description of this study. It is important to mention that the cost figures presented in these cases for the different PFC solutions are for reference only and should not be considered as definite or accurate numbers.

Case 1: New 115-kV Line Needed to Solve Overload

This is the 115-kV system upgrade identified in the SPP's HPILS report [4]. Figure 1 is the one-line diagram of the portion of the system that was analyzed. The real names of the substations have been removed due to confidentiality restrictions. The dotted red line indicates the new 115-kV line proposed in SPP's report. This new line is needed because the outage of one of the lines from Substation 1 to Substation 2 results in an overload condition on the other line. The HPILS report analyzes transmission needs resulting from significant incremental load growth expectations in certain parts of SPP. Transmission reinforcement projects were developed for the 2023, 2018, and 2015 scenarios. For each of the projects in the 2023 and 2018 study years, a staging assessment was performed to determine the start date required for each of the projects based on their lead time.

A possible alternative solution to delay the construction of the new 115-kV line linking Substation 1 with Substation 3 is to install variable impedance devices (DSR or MA) to increase the impedance of the lines connecting Substation 1 and Substation 2, in order to reduce the overload by diverting power flow through other branches with available capacity. Table 2 shows the contingency analysis results with the line impedance increase needed to reduce overload in each of the three scenarios. Notice that it is necessary to increase the impedance 87% above its original value in 2023; however, much less change is needed in the other two scenarios.

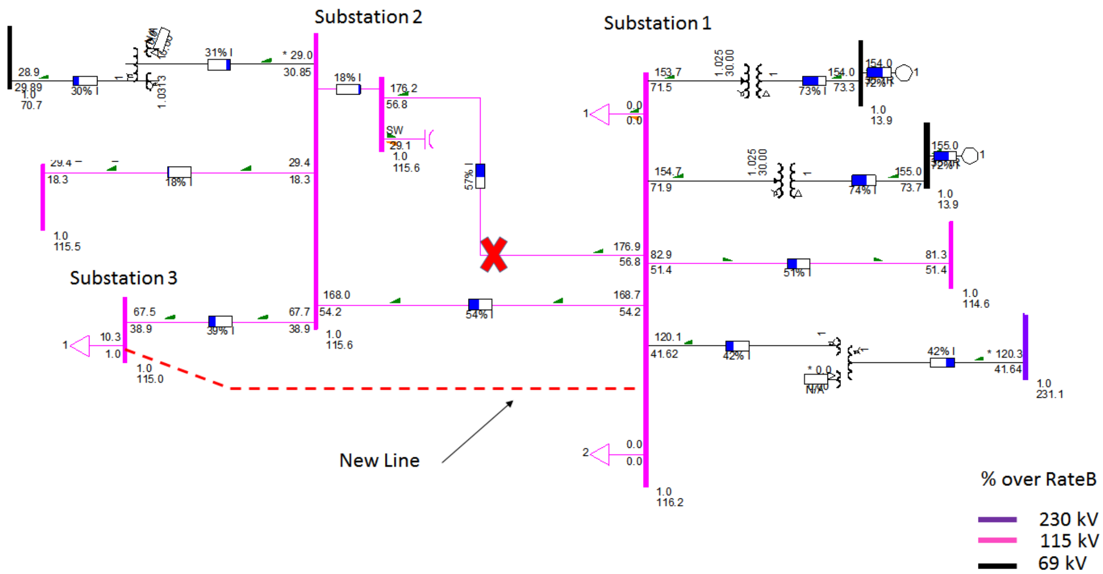

Figure 1: New 115-kV project proposed in the SPP's HPILS report

Table 2: Line impedance change to avoid overloads

Sub 1 to Sub 2 115KV Line			Post-contingency Power Flow - % of Contingency Rating		
	X final (p.u)	DX(%)	2015	2018	2023
Original line	0.01763		101%	102	115%
8% impedance increase	0.019	8%	100%	101%	113%
13% impedance increase	0.02	13%	99%	100%	112%
87% impedance increase	0.033	87%			100%

We estimated the number of DSR devices using proprietary information provided by Smart Wires, Inc. Considering the latest DSR design; only a few devices are needed to produce the changes in line impedance needed for each scenario, as follows: 6 units in 2015; 12 units in 2018; and 60 units for 2023. Clearly, the devices need to be installed in both lines because the contingency can occur in either of the them. Therefore, the number of devices required is double these amounts. The estimated cost for the solution for 2023 is approximately $1.5 million.

The MA solution is defined for the horizon year. The MA is not a modular in design as are the DSR devices. In some cases, the MA could be designed in modules to be installed over time as needed, however, it might not provide the same level of flexibility as the DSR. The maximum impedance that the MA needs to provide in the horizon year is 2.03 Ω. The cost of these solutions is about $4 million.

According to the HPILS report, the cost of the 7.7-mi 115-kV line that is proposed to solve this overload is $16.8M. As can be observed, the power router solution, with either DSRs or MA, is very competitive in this case. Such a cost is significantly higher than the typical cost of a 115-KV line. The reason for such increased cost is not described in the HPILS report. However, the PFC option can still be competitive in more typical cases, especially if the benefits from the flexibility of the solution are considered. With the DSR-based solution, the number of devices can be gradually installed over the years as needed. Should the expected conditions leading to the expected severe overload never materialize, the DSR installation can be halted, thereby avoiding economic penalties for non-optimized solutions.

Case 2: Rebuild of 138-kV Corridor to Solve Overloads

This is a project described in the report "ITP10 2015 Integrated Transmission Plan 10-Year Assessment"[5]. It consists of rebuilding approximately 77 mi (123,919 m) of a 138-kV corridor to address the overload of the corridor caused by the outage of a 345-kV line. Figure 2 shows the overloaded line.

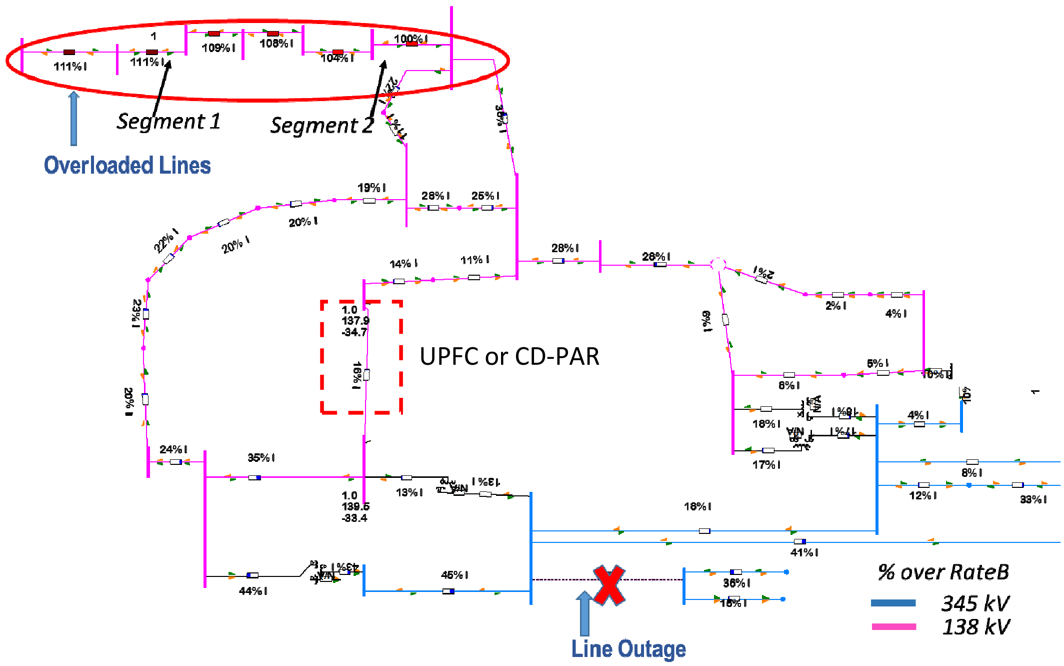

Figure 2: Overload of 115-kV line caused by 230-kV line outage

DSRs and MAs can be used to reduce the overload. In this case, it is necessary to increase by 50% the impedance of only two line segments to solve the overload of the entire corridor. The total number of DSRs required is 153, and the estimated cost is around $3.7M. For MA solution, we assumed that two units - one providing 9.17 Ω and the other unit providing 9.6 Ω - would be installed at two of substations along the line. The total cost of this solution would be around $2.4M. Transformer-less UPFC and CD-PAR solutions could be used for this case as well. In that case, the device would be installed in a different line, not the overloaded line, as indicated in Figure 2. The cost of that solution would be around $3 million.

According to the ITP10 2015 report, the cost to rebuild the entire 138-kV corridor is $60.2M. The PFC-based solution is potentially an order of magnitude less expensive than the corridor upgrade. In this case the entire corridor that consists of several line segments needs to be completely rebuilt in order to increase the capacity to avoid overload. With the PFC solution on the other hand, devices with relatively small to moderate control and rating capacity are needed to reduce the power flow that affects the entire corridor, making the solution more effective. Investment deferral analysis shows that, because the cost of the PFC solution is so small ($3M–$4M) as compared with the original project, even a short deferral time of 1 or 2 years would justify the use of PFC solutions.

Other case studies

A 115-kV line needs to be thermally upgraded with a new conductor. A 230/115-kV substation needs to be upgraded as well. The expansion is needed to solve an overload caused by a transformer outage. The cost of the conventional solution is $7.15 million. A transformer-less UPFC or CD-PAR can be installed in one of the adjacent 115 kV lines to divert power flow and avoid the overload. The cost would be approximately $2.4 million.. In this case, the PFC solution is effective for the scenario at the horizon year. Therefore, the solution could eventually replace the original project. If, on the contrary, the solution is to be considered as a temporary option to defer the construction of the original project, it might not be cost-effective, because even though it is less expensive, the deferral time would need to be of several years (more than 10 yrs) to economically justify such option.

In another case study, 26 miles of existing 115-kV line needs to be rebuilt due to overload at N-1 condition. The total cost of the project is $14.2 million. DSRs or MAs can be installed in two segments of the affected line to reduce the overload. In this case though, significant impedance increase is needed (> 100%). The cost of such solution can vary from $2.0 to $5.0 million depending on the technology considered. A solution using Transfomer-less UPFC or CD-PAR can be implemented as well. In that case, a 17.4 MVA device needs to be installed in the affected line. The cost of the solution would be around $2.0 million. The analysis of deferred transmission capacity investment shows that if the original project can be deferred for more than two years, there is a net economic benefit to implement the PFC option as an interim solution.

CONCLUSIONS

The main observation from this anlayis is that in most of the cases analyzed, the PFC solution happens to be significantly more economic than the conventional solution proposed in the corresponding expansion plan. The relatively low cost of the PFC solution suggests that they can be cost-effective alternatives to defer construction of transmission expansions.

The case studies presented have been selected to show the cases where solutions based on PFC are viable options to defer capacity-expansion projects or serve as mitigation solutions while the main strategic project is built. In some very specific cases, the PFC options can also replace transmission projects. Even though these cases show promising application of PFC for transmission reliability projects, there are many other cases where such an option is not feasible. In fact, we studied several other projects in the SPP's transmission plans and found a number of them where PFCs cannot be used as viable alternatives. PFCs do not provide additional transmission capacity to the network, but rather they allow the use of the existing capacity in a more efficient manner. Therefore, in cases where there are no alternative paths to reroute the power flow to alleviate the overload, PFCs do not provide a solution to the problem. Indeed, additional transmission capacity needs to be built in those cases.

An important observation is that DSRs could be a very effective option to flexible or adaptable transmission expansion, because of the modularity, rapidly deployable, and mobility features of this power flow control technology. Certainly, unlike conventional assets such as lines and substations that are lumped solutions in nature, DSRs can be gradually installed as they are needed, based on the evolution of system conditions. Furthermore, one far-reaching advantage of incorporating flexible assets in the planning process is the possibility to defer commitment to major conventional projects until the need for such investment is fully established. In other words, use as interim solutions until more information regarding system evolution is available, and definite solutions can be devised.

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