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CE C1 – Power system development and economics

TECHNICAL ANALYSIS OF POWER FLOW CONTROL TECHNOLOGIES AND DYNAMIC LINE RATING IN TRANSMISSION SYSTEMS

D. URBAEZ
Smart Wires Inc.
Colombia
durbaezl[1]

L. SALAZAR
Smart Wires Inc
Colombia
laura.salazaro[2]

N. GALLEGO
Smart Wires Inc.
Colombia
natalia.gallegor[2]

S. GOMEZ
Smart Wires Inc.
Colombia
santiago.gomez[3]

A. DUQUE
Smart Wires Inc.
Colombia
alejandro.duque[3]

P. VIANA
Smart Wires Inc.
Colombia
pablo.viana[3]

M. PATIÑO
Smart Wires Inc.
Colombia
mario.patino[3]

Abstract *– This paper presents an analysis of Power Flow Control in combination with Dynamic Line Rating technologies, taking a study case in which the integration of each type of technology was evaluated individually and together in a transmission system. Subsequently, with the results obtained, an economic evaluation of the implementation of each technology is made through a quantitative comparison of price for the energy generated, reduction in the restriction costs, and investment cost of each alternative. Results and analysis show good synergies between the two technologies in maximizing grid utilization.*

Keywords: Power flow control – Dynamic line rating – FACTS – M-SSSC – Dynamic compensation – Infrastructure – Operational planning – Reliability.

1 INTRODUCTION

The energy transition poses significant challenges for power systems, power flow and overload control being among the most relevant. Currently, measures to face these challenges include installing phase-shifting transformers, compensation devices (shunt or series), repowering or constructing new transmission lines; the latter entailing significant environmental, social, and economic impacts, in addition to the long lead times associated with the development of conventional infrastructure. This results in the construction of projects without exhausting the existing grid's capacity.

Considering the aforementioned, this paper presents a case study for the redirection of flows in order to optimize the use of transmission capacity in an existing electrical network. The study is based on implementing Modular Static Synchronous Series Compensation (M-SSSC), a Flexible AC Transmission System (FACTS) technology for Power Flow Control (PFC) [1], and dynamic line rating (DLR) technology for estimating thermal capacity of transmission lines in real time [2]. The paper provides a technical description and a comparative analysis of the use of each technology individually and together with respect to the system conditions on different operation scenarios. The purpose of this study is to evaluate the economic benefits resulting from freeing transmission capacity for new generation sources with the use of the assessed technologies. The analysis is made via a quantitative comparison of the additional power generation released to the system and the price per kilowatt hour (kWh) in Colombia. Likewise, an approximation is made on the investment cost for equipment acquisition in each case, which is compared afterward with the cost of building a new transmission line (taking the constructive values from the Mining-Energy Planning Unit -UPME- as reference). Finally, restriction costs for each alternative and the cost reduction in load-shedding hours are estimated and compared.

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* Calle 7D# 43A – 40, Medellín, Colombia – [1]@unal.edu.co [2]@upb.edu.co [3]@smartwires.com

2 OPERATING PRINCIPLE OF M-SSSC

The Modular Series Synchronous Static Compensator (M-SSSC) is a device that allows real-time control of power flow in a given system, by effectively increasing or decreasing the reactance of the specific circuit, thanks to the power electronics and its fast operation. The term modular refers to the ease of implementation or re-implementation by reduction or expansion of a solution based on this device. This type of solutions aims to be adaptable and reduce regret in continuously changing networks in generation and system load. The M-SSSC allows the utilization of existing networks by redirecting flows from overloaded facilities to underutilized facilities, accelerating the interconnection of renewable generation in the system. The solution offers other benefits such as saving space in the substation due to its modularity, optimizing transmission margins by releasing transmission capacity in the network, alleviating thermal overloads with short term implementation and a high level of control.

The M-SSSC considered operates by injecting a leading or lagging voltage shifted by 90 degrees (in quadrature) with respect to the line current, assuming respectively the role of a series reactor or a series compensator as illustrated in Fig. 1. In this case, such M-SSSC is capable of injecting voltage independently of the line current, thus differing from the conventional legacy solutions.

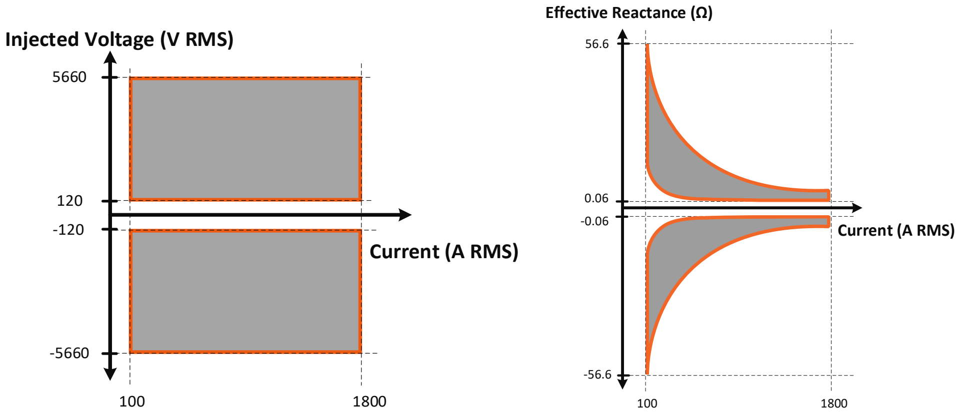

Fig. 1. M-SSSC Voltage Operating Range (left) and Reactance Operating Range (right)

In addition, the M-SSSC for this study case acts as a solid-state synchronous voltage source which injects the necessary voltage to maintain the desired reactance value in the network based on the line current magnitude estimated using built-in sensors. Among its main components, the M-SSSC includes a filter to protect the device from system transients, a bypass system that protects and provides control over the converters in the device during fault conditions, and a set of interconnected converters in charge of injecting the voltage in series with the transmission line.

3 OPERATING PRINCIPLE OF DLR

This technology consists of dynamically changing the rating of a transmission line beyond what is established in its theoretically established static characteristics (SLR). This is possible through the analysis of conductor temperature, transmission current, and meteorological variables through the deployment of high precision sensors and communication devices for real time monitoring of characteristics such as wind speed and direction, solar radiation, ambient temperature, precipitation, and others. With this information, DLR algorithms can predict the maximum ampacity of a specific line according to conductor behavior in real time. The effectiveness of said algorithm depends directly on the correct collection of data and the reliable operation of the sensors [3].

It is also possible to estimate mechanical variables of the line such as buckling, slack or tension by combining specs and historic data from the line with the sensors equipped in the DLR system [4]. Having devices that measure the real energy flowing through transmission lines at all times enables a more efficient use of the grid, deferring the construction of new lines and all that this activity entails from the technical, economic, and environmental perspectives.

Since DLR technology is based on increasing the line's transfer capacity, it is important to highlight that the nominal values of said lines are limited by standard distances that should be kept between conductors and other objects. This along with temperature limits to preserve the conductor's mechanical integrity, causes this temperature to be affected by both the electrical load and the environmental conditions of the site.

DLR technology is an effective solution to accommodate increased renewable energy production in existing systems, covering part of the role of network reinforcement required by the increase of this type of intermittent power generation [5].

4 STUDY CASE

In order to evaluate both the M-SSSC and DLR, a conceptual exercise is performed on the network shown in Fig. 2, which represents the equivalent of a portion of a real power system located in Latin America. The network originally does not present overloads in any of its elements; however, the potential for integrating renewable generation projects in substations #1 and #2 is identified, which requires expanding the system. Considering that after the integration of new generation units, some lines will be underutilized, while others will operate at their maximum capacity, a set of limitations in the operation of the electrical network start to take place.

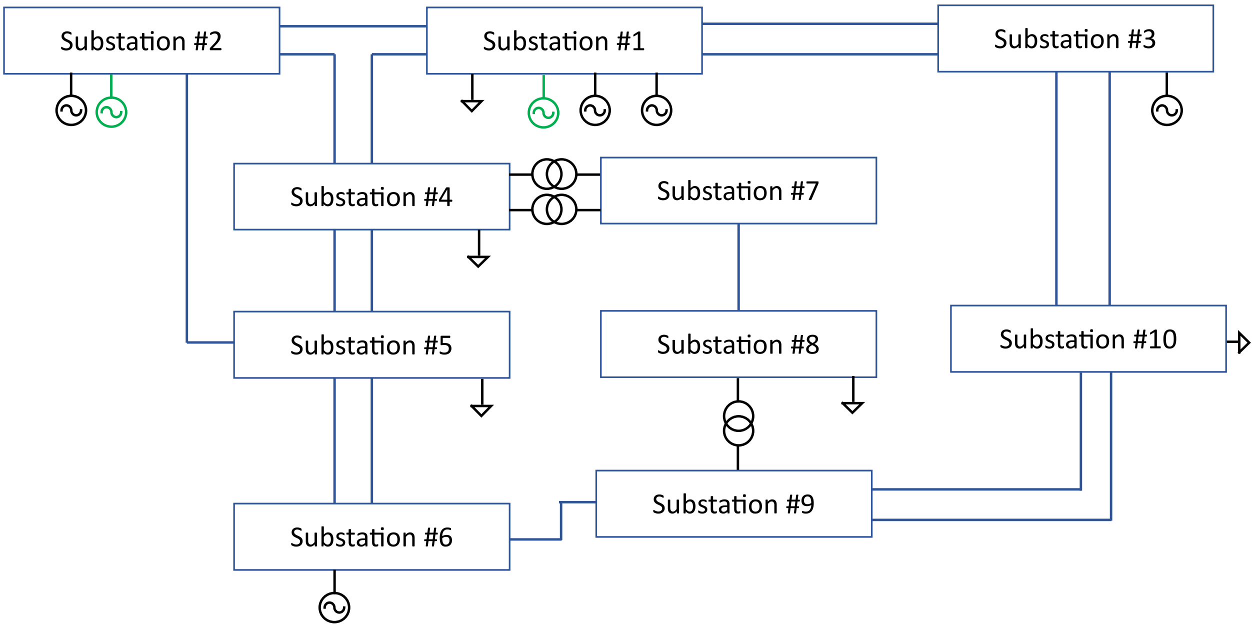

Fig. 2. Study case single-line diagram

The first step to identify potential issues was to determine the capacity of the existing network, this step consisted of connecting the new generation in the corresponding substations and making increments of 50 MW in each of the units. For this purpose, the software PowerFactory [6] was used to run several load flows and contingency analysis. For each simulation case, line loading was calculated for critical N-1 scenarios and results are summarized in Fig. 3.

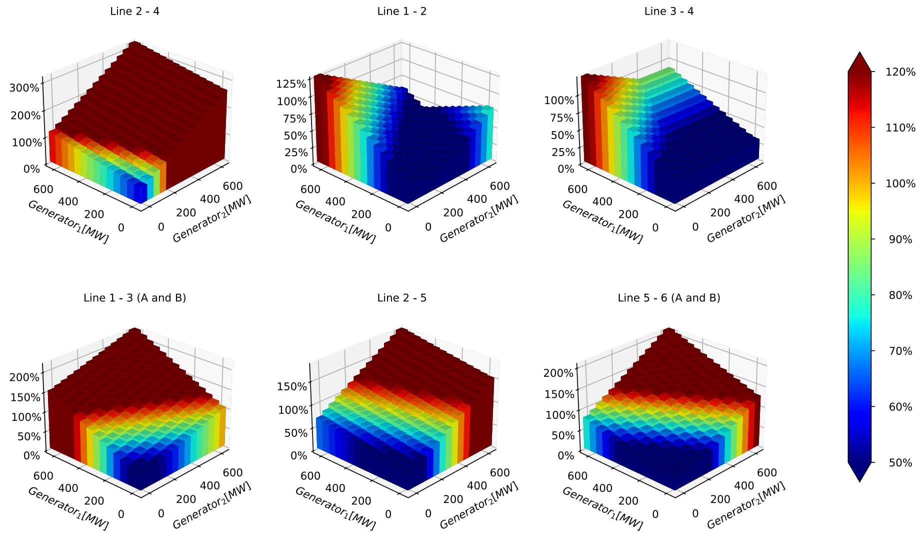

Fig. 3. Line loading under different generation scenarios for the two generation alternatives.

From the cases above presented, one can conclude that without any network upgrade, it is possible to increase the generation capacity of the system up to 350 MW. Additionally, the lines that restrict power generation can be identified from Fig. 4. These lines are 2-4A, 1-3A, and 1-3B.

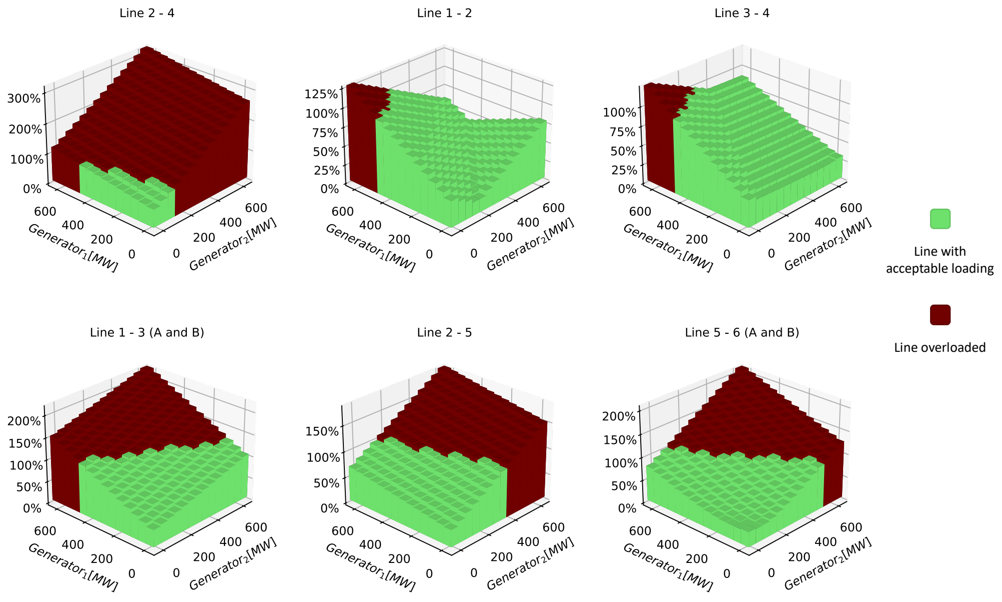

Fig. 4. Network lines loading under different generation scenarios considering DLR installed in lines 1-3A and 1-3B.

The most critical overloads take place on lines 1-3A and 1-3B, therefore DLR technologies are installed on said lines. One assumption of this study is that by installing DLR, the line capacity can be effectively increased 20% over its nominal rating [7], using only DLR it is possible to unlock 450 MW. Follow up analysis shows that it is more feasible to increase only the power of new generation in substation #1, thus, for the following scenarios, only this alternative will be considered.

Another solution to these overload scenarios is to place power flow control technologies on the critical lines that limit the operation of the network. For the use of these technologies, M-SSSC type devices [8] are evaluated. Analysis shows that installing three units per phase on selected circuits of substation #1 allows for an increase of 500 MW of additional power generation with no overloads in full network and N-1 conditions. One of the benefits of using M-SSSC is that the same device can operate in inductive (Push) or capacitive (Pull) compensation depending on the contingency presented in the grid as shown in Fig. 5.

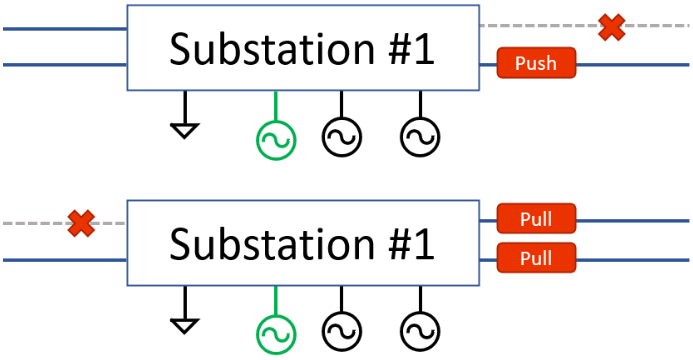

Fig. 5. Power Flow Control (PFC) devices operation under different N-1 scenarios.

After showing the individual benefits of DLR and PFC technologies in enhancing network capacity, the next step is to evaluate potential synergies when both technologies work together. To accomplish this, both solutions are installed on lines 1-3A and 1-3B. Additionally, one DLR element is installed on line 2-4. In this operation scenario, it is possible to increase the output power from generator 1 up to 600 MW.

Finally, one additional operating scenario to evaluate the synergy between PFC+DLR technologies further is studied. This scenario consists in installing four M-SSSC devices per phase in lines 1-3A and 1-3B along with DLR devices in lines 1-3A, 1-3B, 1-2, 1-4, and 2-4. This new operating scenario shown in Fig. 6 results in a total increase of 650 MW in the power produced by generator 1.

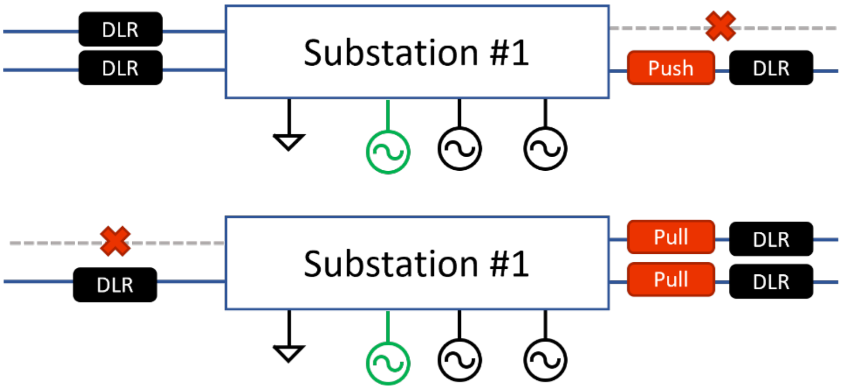

Fig. 6. Power Flow Control (PFC) and Dynamic Line Rating (DLR) devices operation under different N-1 scenarios.

5 ECONOMIC ANALYSIS

The studies carried out in the previous section led to enabling new generation in the system thanks to the implementation of PFC and DLR devices. The next step is to take these results and assess the economic impact of the power capacity released when it is integrated into the system and conduct a cost-benefit analysis of the solution.

Table I shows the demand that could be supplied annually with the new generation and the value of annual income that would result from each scenario based on the additional power that would flow with no risks through the system. For this purpose, a load factor of 45% was considered (assuming that the generation source is wind) and that the average 2022 exchange price of 1kW in Colombia was $215.78 COP [9], which is equivalent to approximately $0.046 USD at the time of writing this paper. It is important to note that to determine the electricity demand supplied in the base scenario, a capacity factor of 85% was used, corresponding to a legacy (hydraulic or thermal) generation plant.

TABLE I. ECONOMIC IMPACT OF
THE POWER CAPACITY RELEASED.

Scenario	**Increase in power generation [MW]**	**Total new generation [MW]**	**Benefited demand of Power increased [MWh/year]**	**Benefited demand of Total New Generation [MWh/year]**	**Revenue per year of Power increased [MUSD]**	**Benefit-Cost ratio**
Base Case (Existing network)	-	350	-	2,606,100	-	1.81
DLR	100	450	394,200	3,000,300	$ 18,08	1.81
PFC	150	500	591,300	3,197,400	$ 27,13	1.81
PFC+DLR Scenario #1	250	600	985,500	3,591,600	$ 45,21	1.81
PFC+DLR Scenario #2	300	650	1,182,600	3,788,700	$ 54,25	1.81

The benefit-cost ratio was also determined for each scenario, according to an estimate of the investment cost for the equipment and the profits obtained annually from the enabled power. The result in all cases is around the same value, thus, the choice of a particular scenario would depend especially on the available generation resources, and the demand to be supplied. It is important to highlight that, given the modular characteristic of the DLR and M-SSSC devices, the project can be carried out in a scalable way, according to the growth of the demand or the network needs that may arise, starting with the individual PFC or DLR solution, up to the solution with both technologies [10].

By implementing PFC and DLR in transmission networks, it is not only possible to enable the connection of new generation, but also to achieve benefits similar to those of traditional transmission projects, such as improved reliability and quality of service, which results in improved connectivity, better use of public space, economic growth and lower prices for the end user.

With the implementation of power flow control devices, these benefits can be materialized in a much shorter time compared to legacy solutions, mainly the construction of new transmission lines. In addition to this, and unlike transmission lines, PFC projects do not require the intervention of large portions of land. In fact, M-SSSC can be installed in the yard of an existing substation, thus avoiding the impact on different biotic environments, as well as the processes related to obtaining environmental permits, purchasing new land, socialization with communities, and others [10]. Table II shows the time it takes to carry out these processes in Colombia.

TABLE II. PROCESS TIME BEFORE LINE CONSTRUCTION [11]

Procedure	**Portion year**
Opportunity cost for environmental diagnostics of alternatives	0.64
Opportunity cost for environmental licensing	0.41
Opportunity cost for prior consultations	0.91
Opportunity cost for subtraction of forest reserve areas	0.40
Opportunity cost for archaeological management plans	0.24

Considering the information presented previously, in [11] the average cost of delays in the construction of transmission expansion projects for a 90 MW generation project was calculated, obtaining as a result that this cost is approximately $ 55,4 MUSD. Given that the power to be transmitted is a variable directly proportional to this cost, it is estimated that this amount can be a lot higher due to the additional amount of generation that could be released using the solutions presented in this study. As a result, the savings from avoiding this delay is even more relevant to the power system industry.

6 CONCLUSION

With the analysis performed, it was possible to determine that in an area with significant potential for new renewable generation, the existing spare capacity in the network for the integration of said plants may be limited if expansion alternatives or grid enhancing solutions are not explored. Additionally, the results revealed how PFC and DLR technologies complement each other in optimizing the use of the grid by reducing network congestion. Moreover, PFC and DLR are key elements to enable distributed generation faster and with less economic and environmental impact on generators, utilities, and end users, compared to traditional expansion solutions. Although both technologies were shown to enable additional power individually, the best results were obtained with a complementary solution.

The benefit-cost ratio was around 1.81 for each scenario, showing that the inversion is worth it. Furthermore, with the combined solution it is possible to earn more than 50 MUSD with the new renewable energy in the network.

The methodology followed in this paper can be used for future studies in other networks, in order to explore possible grid-enhancing technologies along with traditional grid expansion alternatives. In addition, the analysis of the complementarity between the technologies used in this document with other compensation devices might be evaluated.

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