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ALGORITHM FOR CALCULATING THE DISPATCH OF MULTIPLE POWER FLOW CONTROL DEVICES USING CURRENT SENSITIVITY FACTORS

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Abstract *– This paper presents an algorithm to determine the required series voltage injection setpoint for multiple Modular Static Synchronous Series Compensation (M-SSSC) installations. These devices are part of the Flexible AC Transmission Systems (FACTS) family, and one of its main objectives is to allow power flow control to enhance grid utilization. With the proposed algorithm, it is possible to automatically reach the required magnitude for a set of line currents, which can be associated to the line's thermal limit or to preferred operational setpoints. Additionally, the algorithm performance is tested in different power systems, identifying systemic benefits such as wide-area control, grid capacity optimization, system reliability and security, and facilitating the integration of renewable generation.*

Keywords: Power flow control – M-SSSC – Flexibility – control

1 INTRODUCTION

With the recent dynamics of growth in electricity demand and integration of new renewable generation, it has become necessary to make the power grid more flexible to guarantee a safe network operation required by these new system conditions. The typical approach to solve those necessities is to build new infrastructure that reduces the existing restrictions; however, this implies high investment costs and execution times, in addition to the socio-environmental impacts associated with the nature of this type of project [1]. Over the last decade, several alternatives have been proposed to defer or avoid the construction of new infrastructure by optimizing the use of the existing network. Flexible AC Transmission Systems (FACTS) technologies based on power electronics are a representative example of said grid enhancing technologies [2]. This paper is focused on Modular Static Synchronous Series Compensation (M-SSSC), a FACTS device that injects a series voltage at ±90° with respect to the line current, which is equivalent to a variable reactance in series with the transmission line [3]. On top of that, this work covers other Power Flow Control (PFC) technologies that could make good use of the algorithm presented.

Defining the location and the dimension of multiple PFC devices is a complex task, some of the previously proposed algorithms use DC load flows to define optimization algorithms that calculate the dispatch of multiple PFC devices [4] or to choose their optimal allocation [1]. However, due to the limitations of DC load flows, those algorithms inherited their restrictions and accuracy. There are other more complex approaches that consider other variables such as the total cost of installation, for which genetic algorithms are proposed that require a significant number of iterations [5]. Other research has been conducted regarding the dispatch of multiple PFC control devices such as those presented in [8] - [9], with the limitation that these proposals require adapting the Jacobian matrix within the Newton-Raphson method.

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This paper presents a strategy to model M-SSSC devices for steady-state operation without interfering with the matrices associated with the load flow calculation. This is an advantage since commercial power system analysis software typically does not give access to their solution engine, and therefore the Jacobian matrix. The proposed methodology is based on the calculation of a sensitivity index for line current to the injected series voltage from a M-SSSC installation. This index is used iteratively with power flow calculations to find the operating point of different M-SSSC devices that achieves a predefined target set of currents.

This work is divided into four sections. First, it presents an overview of the M-SSSC technology globally used for Power Flow Control (PFC) applications. Second section discusses the operating point calculation algorithm of each device and its respective mathematical basis. Furthermore, the pseudocode of the proposed algorithm is covered. Third section provides application examples of the algorithm on two study cases, one with a simplified network, and another with a more complex network based on the IEEE 39 bus system. Finally, fourth section studies the algorithm's effectiveness and performance by analyzing the value of the current sensitivity matrix and the convergence and robustness of the algorithm.

The detailed analysis highlights both the systemic benefits associated with the installation of M-SSSC solutions at different points of the network and their limitations related to the constructive capacity of the network where they are deployed. Systemic benefits include wide-area control through dynamic, controllable, and even automatic voltage injection, maximizing grid's utilization, reliability, and security, especially during N-1 contingencies. Other benefits include accelerated integration of renewable generation due to the fast installation of the equipment.

2 POWERFLOW CONTROL TECHNOLOGY

FACTS devices have been used historically to improve transmission capacity, reliability, and flexibility of the existing transmission system. This technology has evolved substantially due to advances in power electronics. FACTS technologies are divided into shunt-connected devices (SVC, STATCOM), series-connected devices (FSC, TCSC, SSSC), or a combination of both (UPFC). Shunt-connected devices are typically used to regulate voltage and series-connected devices are used to control power flow in meshed networks [2]. Power Flow Control Devices (PFC) or series-connected FACTS alleviate thermal overloads and optimize existing transmission capacity, reducing the need to build complex electrical infrastructure such as new transmission lines or new electrical substations.

Traditional PFC solutions have several characteristics that reduce the return on investment margins, such as a large substation footprint, complex maintenance, and custom-engineering which directly impact investment costs and construction lead times [3].

PFC solutions based on Thyristor Controlled Series Capacitors (TCSC) inject a voltage in series with the transmission line, which implies an additional capacitive series impedance that increases the active power flow through the line; pulling power from heavily loaded lines.

Moreover, PFC solutions based on the Static Synchronous Series Compensator (SSSC) use voltage source converters (VSC) to create a quasi-sinusoidal voltage waveform. This injected voltage is controlled to be quadrature with the line current. The magnitude of said voltage injection is independent of the line current and it is capable of achieving both capacitive and inductive effects, thus providing flexible power flow control. Modular SSSC (M-SSSC) has a standardized voltage agnostic design that reduces manufacturing, execution, and installation times compared to its traditional counterpart [10].

3 PFC DISPATCH ALGORITHM

The main objective of the proposed algorithm is to control a set of line currents in a meshed power grid using M-SSSC solutions. For this purpose, two sets need to be defined; the first one is the set of elements in which the current will be monitored and modified to a desired magnitude. Second set contains transmission lines with M-SSSC installations, thus, lines on which the series voltage injection is applied. Even though this work is focused on studying modifications in line current, it is worth noting that the algorithm can be extended to any type of branches, including power transformers.

Once the sets of elements for monitoring and injection have been defined, next step is to determine the target current magnitudes. These magnitudes are typically given by the line's nominal thermal capacity or by an emergency limit declared to the system operator. The target current values are defined as $I_{i\,target}$, where the sub-index i refers to transmission line i of the monitoring set. An important consideration when selecting the monitoring elements is Kirchhoff's current law: in order to ensure that PFC solutions redirect the flows effectively, there must be at least one "free" element that keeps the summation of currents in a bus to 0 A. Trying to control line currents flowing in and out a single bus will likely cause no convergence of the algorithm.

The proposed algorithm is based on calculating changes in line current due to M-SSSC's voltage injection as linear index. For this purpose, the impact of the series compensation solution must be independent from the impact of the other sources in the network. This is achieved by performing a load flow calculation without the M-SSSC injection, and then proceed to connect the M-SSSC with an arbitrary series voltage injection, it is recommended to use a voltage injection equivalent to a reactance of 0.1 p.u. Finally, the independent influence of the M-SSSC device is calculated as follows:

$$\Delta \boldsymbol{I} = \begin{bmatrix} I_{11} \\ I_{21} \\ \vdots \\ I_{N1} \end{bmatrix} - \begin{bmatrix} I_{10} \\ I_{20} \\ \vdots \\ I_{N0} \end{bmatrix} \tag{1}$$

Equation (1) can be interpreted as the influence of the M-SSSC voltage source without the contributions given by the other generators in the network, as presented in Fig 1.

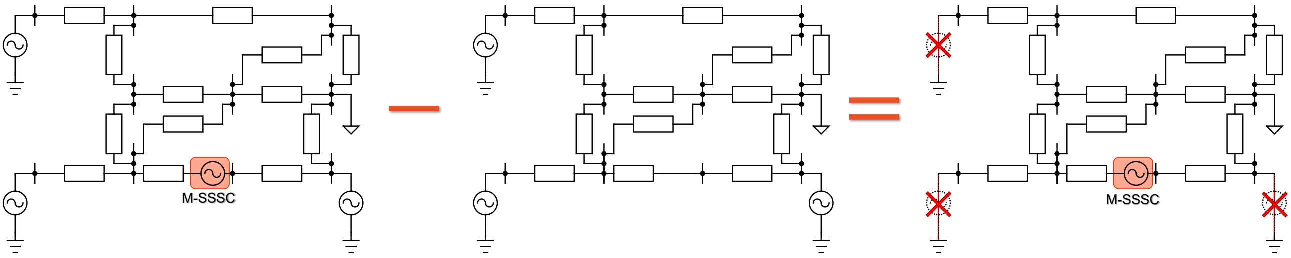

Fig. 1. Process to isolate the impact of the M-SSSC injected voltage.

The network response given by ΔI is variable with respect to the voltage injection V_{inj} given by the device, to obtain the sensitivity factor $\frac{\Delta I}{\Delta V}$ the following calculation is done:

$$\frac{\Delta \boldsymbol{I_k}}{\Delta V_k} = \begin{bmatrix} (I_{11} - I_{10})/\Delta V_k \\ (I_{21} - I_{20})/\Delta V_k \\ \vdots \\ (I_{N1} - I_{N0})/\Delta V_k \end{bmatrix} \tag{2}$$

Note that equation (2) is valid for any voltage injection applied to the network. ($\Delta V_k = V_{inj} - 0$). The sensitivity factor represents the change in current for the monitoring element caused by fixed voltage injection. To select the transmission lines on which to apply the series voltage injection, it is recommended to consider the locations with the largest magnitudes in vector $\Delta \boldsymbol{I_k}/\Delta V_k$. Further sections show that the proposed algorithm limits the selection of elements with series voltage injection to be the same as the number of elements that are monitored. Even though it is possible for a specific bus to have the highest $\Delta \boldsymbol{I_k}/\Delta V_k$ this simple rule accounts for typical space limitations in the substation.

Once the locations for the M-SSSC compensation devices have been selected, the $[\Delta \boldsymbol{I}/\Delta \boldsymbol{V}]$ matrix is created from the all vectors of $\Delta \boldsymbol{I_k}/\Delta V_k$ indexes calculated with (2).

$$\left[\frac{\Delta \boldsymbol{I}}{\Delta \boldsymbol{V}}\right] = \left[\frac{\Delta \boldsymbol{I_1}}{\Delta V_1} \middle| \frac{\Delta \boldsymbol{I_2}}{\Delta V_2} \middle| \cdots \middle| \frac{\Delta \boldsymbol{I_k}}{\Delta V_k}\right] \tag{3}$$

After calculating the sensitivity factor matrix $\left[\frac{\Delta \boldsymbol{I}}{\Delta \boldsymbol{V}}\right]$, the next step is to determine $\Delta \boldsymbol{I}_{\boldsymbol{req}}$ for each monitored element by subtracting the intial current through the monitored elements with the target current magnitudes defined previously.

$$\Delta \boldsymbol{I}_{\boldsymbol{req}} = \begin{bmatrix} I_{1\,target} - I_{10} \\ I_{2\,target} - I_{20} \\ \vdots \\ I_{N\,target} - I_{N0} \end{bmatrix} \tag{4}$$

Finally, the magnitude of the required voltage injection for each M-SSSC solution is given by equation (5).

$$\Delta \boldsymbol{V}_{\boldsymbol{inj}} = \left[\frac{\Delta \boldsymbol{I}}{\Delta \boldsymbol{V}}\right]^{-1} \Delta \boldsymbol{I}_{\boldsymbol{req}} \tag{5}$$

Note that the matrix $\left[\frac{\Delta \boldsymbol{I}}{\Delta \boldsymbol{V}}\right]$ must be invertible, so the number of elements in the injection set must be equal to the number of elements in the current monitoring set. In most of the studied cases, an error below 10% is achieved within the first iteration. However, the process can be performed iteratively following the process described below to determine the required voltage injection from all M-SSSC locations to achieve the desired current magnitudes and thus, the desired operation scenario.

Algorithm 1 Multiple M-SSSC dispatch calculation

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Calculate the initial load flow and obtain the current values in the N
monitored lines ($I_{10}, ..., I_{N0}$).
Inject an arbitrary quadrature voltage equivalent to a reactance of 0.1
p.u on the M-SSSC devices.
Extract the new current values in the N monitored lines ($I_{11}, ..., I_{N1}$).
Calculate $\Delta I$ with (1) and $\Delta I_{req}$ with (4).
while $|\Delta I| > Threshold$ do
    Calculate the current sensitivity factor for the series injected voltage
    $\frac{\Delta I}{\Delta V}$ using (2) and (3).
    Calculate the required voltage injection with (5).
    Run a new load flow with the new injected voltage values.
    Update current values in the N monitored lines. ($I_{11}, ..., I_{N1}$).
    Update $\Delta I$ using equation (1).
end while
The process is finished and the results are presented.
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4 STUDY CASES

4.1 Study case 1: Simple network

For this study case, a single generator supplying energy to a single load through three transmission lines with reactances of 1 Ω is considered. The first step is defining the set of lines to be monitored, in this case lines L1 and L2 are selected. Second step is to select facilities on which to apply the series voltage injection, for this example, the same lines are selected. It is worth noting that line L3 is set free in order to ensure the sum of currents given by Kirchhoff's laws. In other words, the magnitude of current I_F is equivalent to the sum of the currents monitored through L1 and L2 and the current supplied by the generator.

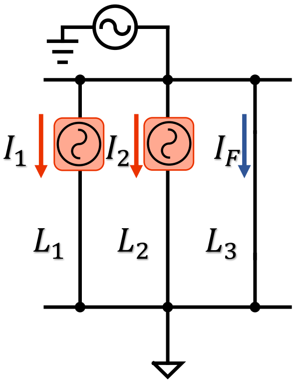

Fig. 2. Single line diagram for study case 1 – simple network

The assumed operation scenario sets the generator to supply 1000 A to the load, which implies an initial current of 333.3 A on the monitored elements. Moreover, a target current value of 200 A is set for both lines of the monitored set, due to their thermal capacity. L3 is assumed to have higher thermal capacity.

4.2 Study case 2: IEEE 39 bus system.

In this network, a N-1 contingency scenario is considered for line 06-07 with a load reduction of 30% at bus 8. Under this operating scenario, there is an overload of 117.9% on line 06-05. Additionally, multiple M-SSSC devices are installed to alliviate this condition. Transmission lines 06-11, 04-14 and 08-09 are selected for the set of elements with series voltage injection. Transmission lines 05 - 06, 04 - 14 and 08 – 09 are selected for the monitored set. Besides that, lines from other areas are included in the injection and monitoring sets to show the algorithm's effectiveness in determining wide-area operating conditions. The selected transmission lines are 28-29 and 21-22, with target current magnitudes of 0.3 kA and 0.8 kA respectively.

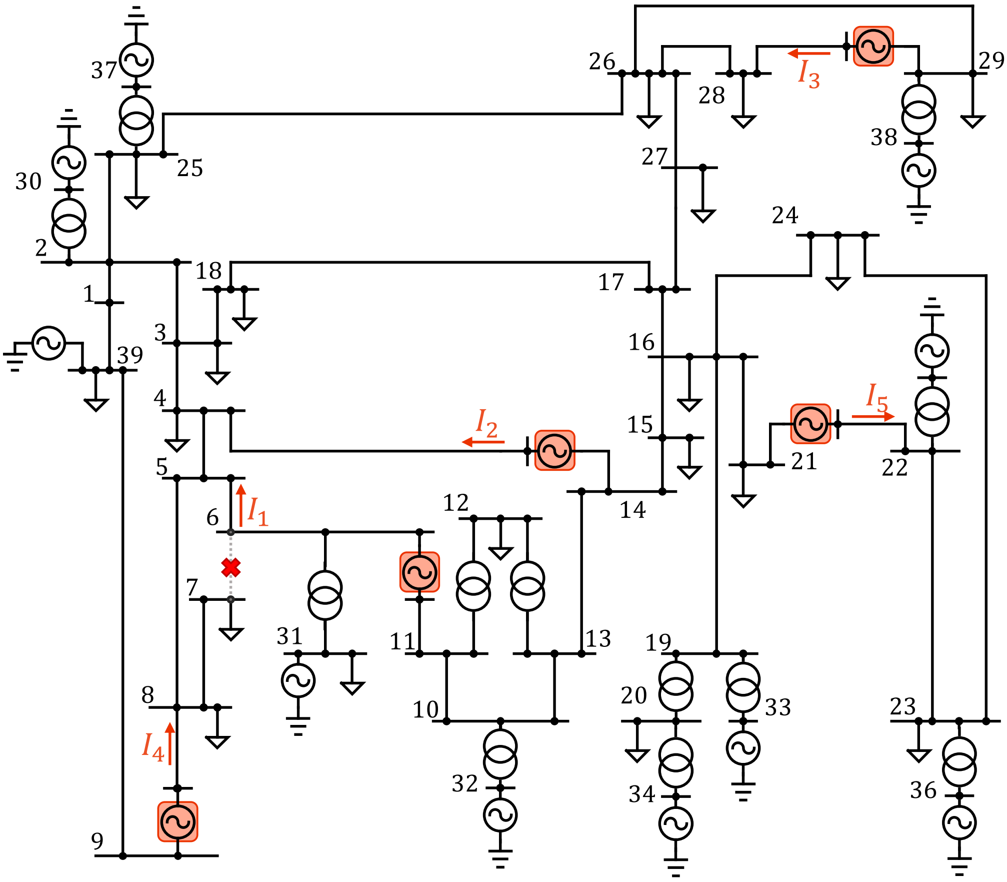

Fig. 3. Single line diagram for study case 2 – IEEE 39 bus system

5 RESULTS

5.1 Study case #1: Simple network.

The values obtained in the sensitivity factor matrix for the first iteration are shown in Table I. Voltage injection on line 1 shows that for each kV injected in series, the current decreases 0.666 kA on line 1 and increases 0.333 kA on line 2.

TABLE I. CURRENT SENSITIVITY FACTOR MATRIX
FOR AN INJECTED SERIES VOLTAGE - FIRST ITERATION [kA/kV]

Injection / **Monitor**	**Line 1**	**Line 2**
Line 1	-0.6666	0.3333
Line 2	0.3333	-0.6666

Regarding the convergence of the algorithm, Fig. 4 shows that only two iterations are necessary to achieve the setpoint magnitudes assigned to lines 1 and 2.

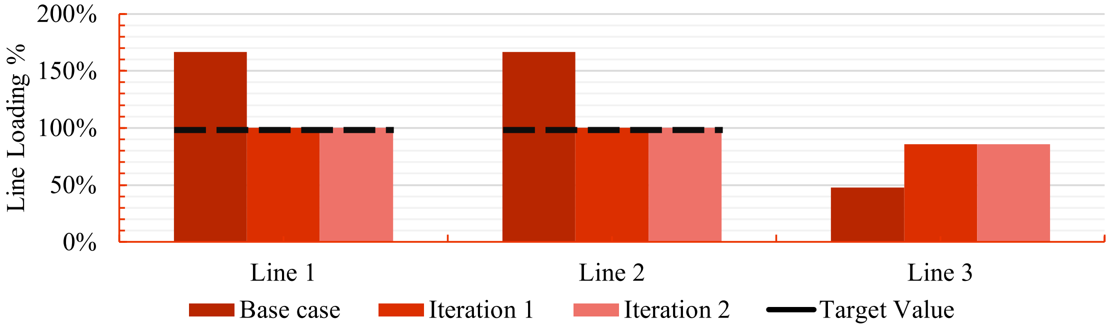

Fig. 4. Line loading results of the algorithm proposed for study case 1

Since the algorithm bases its operation on the injected voltage, it is possible to determine the required voltage injection from each M-SSSC solution. Results presented in Table II show that a 0.4 kV (0.2 ohm) inductive injection in Lines L1 and L2 is required. Said voltage injection can finally be used to dimension the PFC solution. As mentioned in section 2, positive values of voltage injection represent inductive compensation, which is consistent with the objective of this example: decreasing current through lines L1 and L2.

TABLE II. INJECTED VOLTAGE AND EQUIVALENT
REACTANCE IN THE ELEMENTS OF THE INJECTION SET

	Line L1	**Line L2**
Injected Voltage [kV]	0.4	0.4
Equivalent Reactance [Ω]	0.2	0.2

5.2 Study case 2: IEEE 39 bus.

The values obtained in the sensitivity factor matrix for the first iteration are shown in Table III, this matrix shows that injecting 1 kV in line 06 - 11 implies a reduction of current of 0.0159 kA in line 05-06, while in line 04 - 14 the current increases by 0.01326 kA. For the rest of monitored transmission lines, the change in line current due to M-SSSC injection is negligible.

TABLE III. CURRENT SENSITIVITY FACTOR MATRIX
FOR AN INJECTED SERIES VOLTAGE - FIRST ITERATION [kA/kV]

Injection **Monitor**	**Line 06 – 11**	**Line 04 - 14**	**Line 28 - 29**	**Line 08 - 09**	**Line 21 - 22**
Line 05 - 06	-0.015900	0.013764	0.000010	0.002157	0.000168
Line 04 - 14	0.013265	-0.020706	0.000003	0.000381	-0.000014
Line 28 - 29	0.000000	0.000000	-0.006722	0.000000	0.000000
Line 08 - 09	0.000698	0.000459	0.000007	-0.007512	0.000174
Line 21 - 22	0.000059	-0.000008	0.000009	0.000154	-0.010606

Fig. 5 shows that in a few iterations it is possible to reach the target current magnitudes assigned to the lines in the monitoring set, causing the power flows among the rest of the grid to be accordingly.

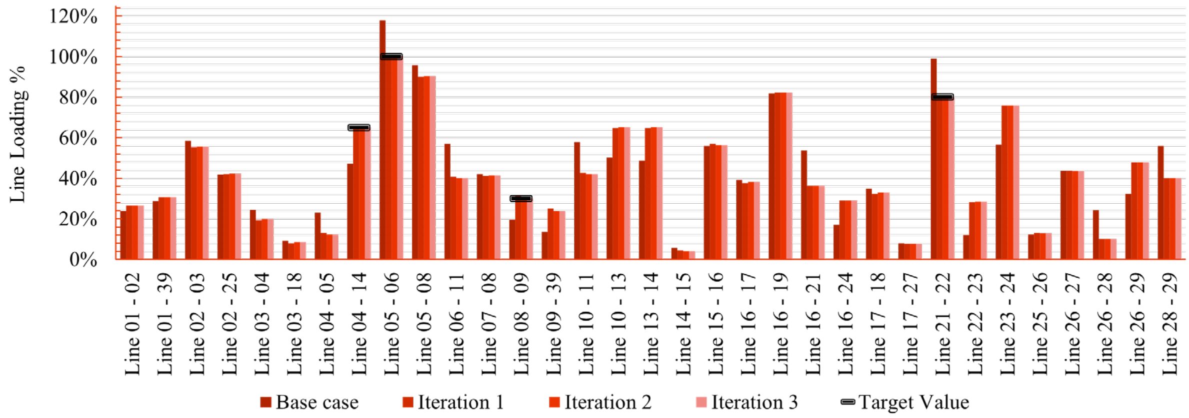

Fig. 5. Line loading results of the algorithm proposed for study case 2.

As in the previous study case, after running the algorithm, it is possible to determine the required series injection voltage to achieve the set of line current objectives. Results are presented in Table IV.

TABLE IV. INJECTED VOLTAGE AND EQUIVALENT
REACTANCE IN THE ELEMENTS OF THE INJECTION SET

	Line 06 - 11	**Line 04 - 14**	**Line 28 - 29**	**Line 08 - 09**	**Line 21 - 22**
Injected Voltage [kV]	5.612	-5.164	23.875	-12.437	17.749
Equivalent Reactance [Ω]	13.884	-7.945	59.688	-41.456	22.186

In this scenario, lines 04-14 and 08-09, contrary to the other lines, require negative voltage injection, which is effectively a capacitive compensation performed by their corresponding M-SSSC devices. These results are reasonable due to the fact that the objective line current for these specific lines was set higher than the original scenario.

6 CONCLUSION

This work presents a methodology for selecting the location of PFC devices, for instance M-SSSC or TCSC, using sensitivity factors of line current with respect to their series voltage injection. Additionally, the methodology can be also used to determine the dispatch of multiple PFC devices either in inductive or capacitive injection in order to achieve a provided set of target currents. It was shown that in a few iterations, it was possible to achieve the set of target currents. Even though this algorithm has a clear benefit in studying

PFC devices, it does not consider the specific PFC construction limits when operating at maximum or minimum capacity. Nonetheless, the algorithm is helpful to size the required deployment to achieve a desired system operating condition, and therefore alleviate the identified congestions. The algorithm bases its functionality in running AC load flows iteratively in commercial software without the need of modifying the internal code associated with the jacobian matrix.

Using PFC technologies under the methodology described in this paper may allow utilities to reduce the need of building new infrastructure such as transmission lines, substations or reconductoring. In adition, renewable generators could accelerate their connection time by avoiding system upgrades and could also benefit in reducing their curtailment by achieving maximum grid utilization.

The specific benefits of using M-SSSC were analyzed in two example cases. These devices enable effective PFC via inductive and/or capacitive compensation. The study cases showed that using these technologies unlocks power transfer capacity in the network even during contingency scenarios.

Moreover, M-SSSC solutions allow for reducing long and growing interconnection queues and reducing operational grid challenges. This type of solution follows the current trend in power systems where both renewable generation and loads are growing rapidly, increasing system needs due to changes in load profiles and restrictions caused by thermal overloads.

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