A Sensitivity-Based Method for Optimal Placement of FACTS Devices

Xinyang Rui, Omid Mirzapour, and Mostafa Ardakani
Department of Electrical and Computer Engineering, *University of Utah*, Salt Lake City, UT, USA
xinyang.rui@utah.edu, omid.mirzapour@utah.edu, mostafa.ardakani@utah.edu

***Abstract*—Flexible AC transmission system (FACTS) devices enable power flow control and enhance the transfer capability over the existing grid. Therefore, they can play a vital role in the future power grid, with high penetration of renewable energy resources. The effectiveness of FACTS deployment is highly dependent upon the placement of these devices in the transmission system. Optimizing the location of FACTS devices is a rather computationally challenging problem. This paper proposes a fast and effective method for the optimal FACTS placement problem based on sensitivities calculated using DC optimal power flow (DCOPF) shadow prices that are available from system operation data. The proposed method allows fast identification of the most effective potential FACTS deployment locations and facilitates more complicated analyses for optimal allocation. The effectiveness of the proposed method is tested with simulation studies conducted on modified RTS-96 and IEEE 300-bus test systems.**

***Index Terms*—FACTS devices, optimal power flow, power flow control, power systems operation, transmission congestion.**

I. Introduction

EFFECTIVE utilization of flexible AC transmission system (FACTS) technology highly depends on the location, especially in highly decarbonized systems where the spatial distribution of FACTS and renewable resources directly impacts carbon emission and renewable energy spillage [1]. Therefore, determining the optimal placement of FACTS devices in the transmission system is essential. FACTS allocation belongs to the family of expansion planning models that are computationally burdensome [2]. An effective approach to facilitate the optimal allocation of FACTS is to create an index list or ranking of transmission lines, providing favorable candidates for FACTS deployments. The solution space is, thus, effectively reduced after applying such methods [3], providing top candidates for more detailed analyses [4]. Depending on the purpose of FACTS deployments, the ranking of candidate locations has been developed by previous research based on various metrics or variables. For example, line outage sensitivity factors, locational marginal price (LMP) differences, and congestion rent contributions are used in previous studies [5], [6] for optimal placement of the thyristor-controlled series compensator (TCSC). Sensitivity-based methods have also been developed for FACTS devices that are based on voltage source converters (VSC), such as the static synchronous series compensator (SSSC). The sensitivities are derived in previous studies [7]–[9] for SSSC operation based on various system performances, including bus voltages, line flow changes, line loadings, power losses, and load increases.

An essential application of FACTS devices is reducing overall generation dispatch costs via power flow control. This is especially vital to facilitate the endeavors of decarbonizing the energy sector, as FACTS operations can help improve the utilization of cheaper renewable energy sources in the power grid by enhancing the transfer capability of the transmission system. However, sensitivity-based placement methods that directly link total dispatch cost to the setpoint adjustments for prominent VSC-based FACTS devices are lacking, as the methods in the existing literature mostly do not provide ranking metrics that reflect the effectiveness of FACTS operation in this important aspect. An example of such sensitivity-based methods is presented in [4], which is developed for variable-impedance FACTS that directly alter the line reactance, such as the TCSC. Devices such as the SSSC and the unified power flow controller (UPFC) are prominent VSC-based devices for power flow control with different operating principles for reactance adjustments and modeling in power system optimization problems compared to the TCSC. They provide various advantages and have been deployed for congestion alleviation purposes [10]–[12]. Examples in the industry include the UPFC PLUS [13] by Siemens and the SmartValve by Smart Wires, Inc. [14], with the latter having a modular design that allows extra operation flexibility through easier relocations. Therefore, it is essential to have a sensitivity-based allocation method for the VSC-based FACTS to enhance their utilization. A screening method based on first-order sensitivities in the optimal power flow (OPF) for UPFC placement is presented in [15]. In [16], a sensitivity-based UPFC location method for congestion management is proposed. However, the proposed methods are based on AC power flow formulation, which is more computationally demanding and not compatible with existing market operation software.

To fill such research gaps, this paper contributes to the literature by presenting a simple, fast, and effective sensitivity-based placement method for prominent VSC-based FACTS devices such as the SSSC and the UPFC. This method utilizes the DC power flow modeling of such devices and computes the sensitivity of total dispatch cost to the FACTS setpoints.

This research was supported by the National Science Foundation under grant number 2146531.

2024 56th North American Power Symposium (NAPS) | 979-8-3315-2103-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/NAPS61145.2024.10741659

The sensitivities are employed to develop ranking metrics for FACTS deployment locations, providing the basis for the proposed method. The method presented in this paper provides the following benefits and advantages:

1) The proposed method can facilitate planning for VSC-based FACTS for congestion alleviation and cost reduction purposes, leading to improved utilization of the existing grid.
2) The proposed method is based on DC power flow, a linearized model of the more complicated AC power flow models. It provides better computational efficiency and is widely used in market-clearing software tools.
3) Derivation of the sensitivities utilizes the shadow prices from the dual solution of DC optimal power flow (DCOPF), which are available from past data. They can be directly used without a need to change the operation software or strategies.
4) The DCOPF formulation based on injection shift factors (ISF), used in this paper, provides better scalability than the $b-\theta$ formulation [17].

The rest of this paper is organized as follows. The derivation of sensitivities and the proposed method are presented in Section II. Numerical studies are shown in Section III. Finally, Section IV concludes the paper.

II. Methodology

A. Sensitivities of dispatch cost to FACTS setpoint adjustment

This subsection presents the derivation of sensitivities of dispatch cost to FACTS setpoint adjustments. FACTS setpoint adjustments are regarded as perturbations to the DC power flow constraints. The impact of such perturbations can be derived using the dual variables of the DCOPF. Devices such as the SSSC and the UPFC use voltage injections to provide the function of power flow control. Therefore, the sensitivities linking cost reduction to the voltage injection can be used to evaluate the effectiveness of such devices, which provide the basis for the FACTS placement method shown later in this paper.

The ISF-based DCOPF problem in time period t is formulated as follows:

$$(\mathbf{P1}:)\ \text{minimize } PC(t) = \sum_{s=1}^{\bar{s}} \mathbf{c}_s^{\mathrm{T}} \mathbf{p}_s \tag{1}$$

s.t.

$$\sum_{s=1}^{\bar{s}} \mathbf{p}_s = \mathbf{p}, \qquad (\boldsymbol{\alpha}) \tag{2}$$

$$\mathbf{f} = \boldsymbol{\Phi}(\boldsymbol{\mathcal{G}}\mathbf{p} - v(t)\mathbf{d}), \qquad (\boldsymbol{\sigma}) \tag{3}$$

$$-\mathbf{f}^{\max} \le \mathbf{f} \le \mathbf{f}^{\max}, \qquad (\boldsymbol{\beta}_-, \boldsymbol{\beta}_+) \tag{4}$$

$$\mathbf{0} \le \mathbf{p}_s \le \mathbf{p}_s^{\max}, 1 \le s \le \bar{s}, \qquad (\boldsymbol{\gamma}_s) \tag{5}$$

$$\mathbf{p}^{\min} \le \mathbf{p}, \qquad (\boldsymbol{\delta}) \tag{6}$$

$$\mathbf{1}^{\mathrm{T}}(\boldsymbol{\mathcal{G}}\mathbf{p} - \mathbf{d}) = 0. \qquad (\lambda) \tag{7}$$

$\mathbf{P1}$ is formulated considering the load profile data because the sensitivities are calculated for multiple time periods, which will be further elaborated on later in this paper. In $\mathbf{P1}$, the objective function (1) minimizes the production cost $PC(t)$. The production of each generating unit is represented using $\bar{s}$ linearized segments, with $\mathbf{c}_s$ and $\mathbf{p}_s$ being the vectors of the linearized cost and production for segment s respectively. It is specified in (2) that the summation of productions in each segment equals the total generation of generating units $\mathbf{p}$. In (3), $\mathbf{f}$ is the vector of power flows and is calculated using the ISF matrix $\boldsymbol{\Phi}$ and nodal power injections, which consist of both generation and demand. Productions of generators are projected to nodal injections using the generator location matrix $\boldsymbol{\mathcal{G}}$, Vector $\mathbf{d}$ represents the demands at each node and is multiplied by the load profile data $v(t)$, which represents a percentage of peak load in time period t. Matrix $\boldsymbol{\mathcal{G}}$ is defined as follows:

$$\boldsymbol{\mathcal{G}}_{ng} = \begin{cases} 1 & \text{if } l(g) = n \\ 0 & \text{else} \end{cases}, \quad n \in N, g \in G, \tag{8}$$

where g and n are indices of buses and generators that belong to the set of generators G and the set of buses N. Furthermore, $l(g)$ is the function identifying the location of generator g. The thermal limits of transmission elements are enforced in (4), with $\mathbf{f}^{\max}$ denoting the line capacity. The constraints on generator output are formulated in (5) and (6). The system-wide power balance constraint is shown in (7). The vectors of dual variables are presented in parentheses following the corresponding constraints.

FACTS operations lead to perturbations to (3) and (4), which can be presented as follows:

$$\mathbf{f} = \boldsymbol{\Phi}(\boldsymbol{\mathcal{G}}\mathbf{p} - v(t)\mathbf{d} - \mathbf{A}^{\mathrm{T}}\boldsymbol{\Delta}\mathbf{f}), \tag{9}$$

$$-\mathbf{f}^{\max} \le \mathbf{f} + \boldsymbol{\Delta}\mathbf{f} \le \mathbf{f}^{\max}. \tag{10}$$

Vector $\boldsymbol{\Delta}\mathbf{f}$ represents the perturbations that can be regarded as nodal power injections following the injection pair modeling [17]. The incidence matrix $\mathbf{A}$ is defined as follows:

$$\mathbf{A}_{kn} = \begin{cases} 1 & \text{if } n = l^+(k) \\ -1 & \text{if } n = l^-(k) \\ 0 & \text{else} \end{cases}, \quad n \in N, k \in K, \tag{11}$$

where k represents indices of transmission elements that belong to the set K and functions $l^+(k)$ and $l^-(k)$ find the "from" and "to" buses of transmission element k, respectively.

The value of the dual variables of $\mathbf{P1}$ are sensitivities of the total cost to the perturbation of the constraints. Therefore, the vector of the sensitivities of the total cost to FACTS setpoint change can be formulated as follows:

$$\boldsymbol{\zeta} = \boldsymbol{\beta}_-^* - \boldsymbol{\beta}_+^* - \mathbf{A}\boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{\sigma}^*. \tag{12}$$

In this paper, * represents the optimal solution.

In addition, the following equation is formulated from the Karush–Kuhn–Tucker (KKT) conditions of $\mathbf{P1}$:

$$\frac{\partial \mathcal{L}}{\partial \mathbf{f}} = (\boldsymbol{\beta}_+^* - \boldsymbol{\beta}_-^*) + \boldsymbol{\sigma}^* = \mathbf{0}, \tag{13}$$

where $\mathcal{L}$ is the LaGrangian function. Therefore, (12) can be further derived as follows:

$$\boldsymbol{\zeta} = (\mathbf{I} - \mathbf{A}\boldsymbol{\Phi}^{\mathrm{T}})(\boldsymbol{\beta}_{-}^{*} - \boldsymbol{\beta}_{+}^{*}), \tag{14}$$

where $\mathbf{I}$ is the identity matrix. It is revealed in (14) that the sensitivity vector is derived using the flowgate marginal prices (FMP) $\boldsymbol{\beta}_{+}^{*}$ and $\boldsymbol{\beta}_{-}^{*}$. Note that $\boldsymbol{\zeta}$ is equivalent to the susceptance prices in the $b-\theta$ DCOPF shown in [18].

VSC-based FACTS devices, as previously mentioned, use voltage injections to control power flows. Therefore, the sensitivities linking total cost reduction to FACTS voltage injection are needed. Suppose FACTS devices are installed on line k, the impact of FACTS operation is presented as follows [19]:

$$\Delta f_k = \pm V_k^{\mathrm{inj,pu}} b_k, \tag{15}$$

where $V_k^{\mathrm{inj,pu}}$ is the FACTS voltage injection in the per-unit (pu) value and b_k is the line susceptance. Then, the sensitivity of the total cost to FACTS voltage injection is derived as follows:

$$-\frac{\partial PC^{*}(t)}{\partial V_k^{\mathrm{inj,a}}} = -\frac{\partial PC^{*}(t)}{\partial \Delta f_k}\frac{\partial \Delta f_k}{\partial V_k^{\mathrm{inj,pu}}}\frac{1}{V_k^{\mathrm{base}}} = \pm\frac{\zeta_k b_k}{V_k^{\mathrm{base}}}, \tag{16}$$

where $V_k^{\mathrm{inj,a}}$ is FACTS voltage injections on line k in the actual value and V_k^{base} is the base voltage level of transmission line k.

Optimal FACTS operation will lead to total cost reduction. SSSC and UPFC devices can inject voltages that can either lag or lead to the line current in phase angles, thus effectively achieving capacitive or inductive reactance adjustments. Therefore, we can use the following vector of sensitivities to determine the effectiveness of FACTS operation on each line:

$$\boldsymbol{\epsilon} = abs(\mathbf{b} \odot \boldsymbol{\zeta} \odot \hat{\mathbf{v}}), \tag{17}$$

where $\mathbf{b}$ is the vector of line susceptances, and $\hat{\mathbf{v}}$ is defined with each element shown as follows:

$$\hat{v}_k = \frac{1}{V_k^{\mathrm{base}}}. \tag{18}$$

In (17), $abs(\cdot)$ represents the operation of taking element-wise absolute values of a vector, and $\odot$ is the Hadamard product that takes the element-wise product of two vectors.

Transmission lines with a larger value of ϵ_k are more effective in reducing the total cost with voltage injections. Granted, $\boldsymbol{\epsilon}$ consists of sensitivity values that are more accurate with smaller perturbations. However, aggregating the sensitivities for different time periods involving different loading patterns can offset the potential inaccuracy.

B. Sensitivity-based FACTS placement method and verification

Based on the sensitivities presented in the previous subsection, the proposed optimal placement method consists of the following steps:

1) Obtain historical data and select typical time periods, e.g., weekly peak load hours;
2) Solve $\mathbf{P1}$ for each time period and obtain FMPs;
3) For each time period, calculate the sensitivity vector $\boldsymbol{\epsilon}$ using (17);
4) Calculate the aggregated sensitivities $\tilde{\boldsymbol{\epsilon}}$ following $\tilde{\boldsymbol{\epsilon}} = \sum_{t\in T}\boldsymbol{\epsilon}_t$, with t denoting the time period;
5) Rank transmission lines based on vector $\tilde{\boldsymbol{\epsilon}}$ and report the top candidate lines with the largest values of $\tilde{\epsilon}_k$.

The aggregation in step 4), where T represents the set of time periods, allows the method to more accurately reflect the effectiveness of FACTS for the planning horizon as (17) provides sensitivities of single-hour operations. FACTS operations can offer more cost savings when a higher congestion level occurs. Peak load hours, thus, can be selected as representative time periods to calculate the sensitivities, as the system is heavily loaded, and likely heavily congested. This approach is applied in the simulations, presented in the next section. However, it is worth noting that for systems with changing loading patterns, e.g., different spatial loading in the morning and evening, the selected snapshots should represent all the important congestion patterns.

The effectiveness of the proposed method is tested via comparison with the results of an exhaustive search based on the savings in production cost achieved with FACTS deployment at each possible location. We consider the a DCOPF problem that incorporates FACTS operation on a single line, which is represented by the following vector:

$$\boldsymbol{\Delta}\mathbf{f}(k) = \big[\underbrace{0 \;\cdots\; 0}_{k-1} \quad \Delta f_k \quad \underbrace{0 \;\cdots\; 0}_{|K|-k}\big]^{\mathrm{T}}. \tag{19}$$

The k^{th} element of $\boldsymbol{\Delta}\mathbf{f}(k)$ is the only non-zero element, which is the variable representing the FACTS nodal injection on line k. Similar to the formulation of $\mathbf{P1}$, the DCOPF considering a single FACTS deployment on line k is formulated as follows:

$$(\mathbf{P2}:)\ \text{minimize}\ PC'(t,k) = \sum_{s=1}^{\bar{s}} \mathbf{c}_s^{\mathrm{T}}\mathbf{p}_s \tag{20}$$

s.t.

$$(2), (5), (6), (7), (19),$$

$$\mathbf{f} = \boldsymbol{\Phi}(\boldsymbol{\mathcal{G}}\mathbf{p} - \mathbf{d} - \mathbf{A}^{\mathrm{T}}\boldsymbol{\Delta}\mathbf{f}(k)), \tag{21}$$

$$-\mathbf{f}^{\max} \le \mathbf{f} + \boldsymbol{\Delta}\mathbf{f}(k) \le \mathbf{f}^{\max}, \tag{22}$$

$$-V_k^{\max}|b_k| \le \Delta f(k) \le V_k^{\max}|b_k|. \tag{23}$$

Eqn. (23) presents the constraint on FACTS operation [19], with $V_k^{\max}$ being the maximum FACTS voltage injection magnitude in per unit value.

The aggregated saving from the FACTS device on line k across all time periods is, thus, calculated using the following equation:

$$AS(k) = \sum_{t\in T}(PC^{*}(t) - PC'^{*}(t,k)). \tag{24}$$

$\mathbf{P2}$ is solved with every possible k for FACTS placement to obtain the aggregated saving $AS(k)$, providing a metric based on which transmission lines are ranked. The ranking result is compared with that of the proposed method. The effectiveness of the proposed method is verified when the proposed method determines similar top candidates for FACTS placement with the exhaustive search.

III. Numerical Studies

Numerical studies are carried out on two different test systems to evaluate the effectiveness of the proposed method. Note that transformers are not considered for FACTS placement.

A. 24-bus system

Simulation studies are conducted using a modified RTS-96 system [20] (1 area) with 24 buses, 33 generating units, and 38 transmission elements. The system data is available at [21]. The sensitivities are calculated with T consisting of the 52 weekly peak load hours. Lines A7, A10, A25-2, and A22 have their thermal limits reduced to 200 MW, 105 MW, 300 MW, and 350 MW, respectively. Such modifications increase the congestion so that the system is more suitable for studying the impact of FACTS deployments by allowing FACTS operations to generate higher production cost savings.

The exhaustive search is implemented with a voltage injection at each transmission line with a maximum of 12 kV, which is determined considering the specifications of the SmartValve^{TM}, which is a modular SSSC, from Smart Wires Inc. [22]. Note that the exhaustive search is carried out with T being the set of daily peak load hours for the entire year. The transmission lines are then sorted based on the aggregated dispatch cost. Optimization problems are modeled with CVXPY [23] and solved using the CPLEX solver.

The results are presented in Table I, which show that the proposed method reports the same top 5 candidate lines as in the exhaustive search. Furthermore, the results are demonstrated with Fig. 1, in which the x-axis shows top FACTS placement candidates ranked based on the aggregated sensitivity. Fig. 1 reveals that a larger value of the aggregated sensitivity is associated with higher savings. Therefore, the results confirm the effectiveness of the sensitivity-based method.

TABLE I
Ranking of transmission lines as FACTS placement candidates in the 24-bus system

Sensitivity-based method			**Exhaustive search**		
Rank	Line no.	$\tilde{\zeta}_k$	Rank	Line no.	$AS(k)$ ($)
1	A6	5619.62	1	A6	156,139
2	A26	4958.11	2	A26	144,126
3	A24	4030.39	3	A24	125,916
4	A2	2643.90	4	A2	92,745
5	A28	2509.40	5	A28	89,059

B. 300-bus system

The proposed method is further tested using a modified IEEE 300-bus system [24]. The data is obtained from the PGlib IEEE 300-bus test case v21.07 [25]. Modifications are made to the test system to increase congestion. Transmission elements No. 61, 101, 115, 137, 190, 349, 365, and 400 have their thermal limits reduced by 50%. Additionally, the thermal

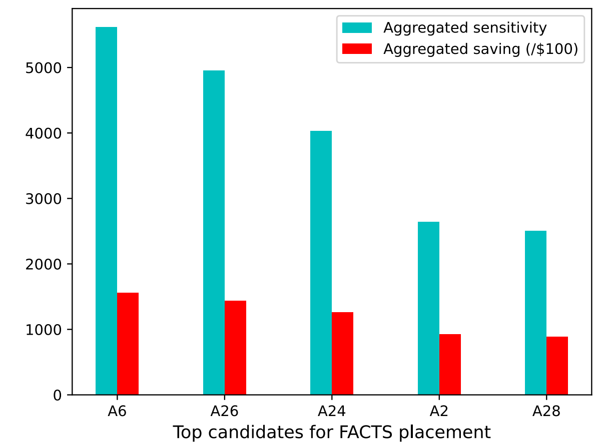

Fig. 1. Aggregated sensitivity and savings results for the 24-bus system

limit of elements No. 268 and 410 are reduced by 25% and 30%, respectively. The year-long load profile data from the RTS system is used for the 300-bus system.

Simulation results are shown in Table II and Fig. 2. The top 20 candidate locations reported by the proposed method achieve the highest savings in the verification. The results again show that the sensitivity-based method effectively provides the top candidate locations for cost reduction. There exist three mismatches between the rankings. However, it is worth noting that the exhaustive search does involve substantially more time periods than when calculating the sensitivities. Therefore, such mismatches can be expected. Moreover, the proposed method shows good performance despite only using weekly peak load hours, solidifying its effectiveness and simplicity.

C. Discussions

One of the key benefits of FACTS deployment is facilitating RES integration in the power system. The simulation studies in this paper do not involve any RES integration. However, the developed method is generic, meaning that it can be applied to different systems under various loading conditions. The sensitivities are based on total cost reduction, thus leading to better utilization of cheaper renewable generation if it is involved in the generation mix.

The sensitivity of one transmission line can be affected by FACTS operation in other locations. This means that accurately allocating multiple devices simultaneously may require further studies. However, the ranking can provide more accurate guidance for placing one FACTS device. Moreover, the proposed method still provides a simple screening procedure, effectively reducing the solutions space by identifying the most effective locations for FACTS deployment, which can serve as the basis for more complex optimal allocation methods for FACTS, especially in larger systems.

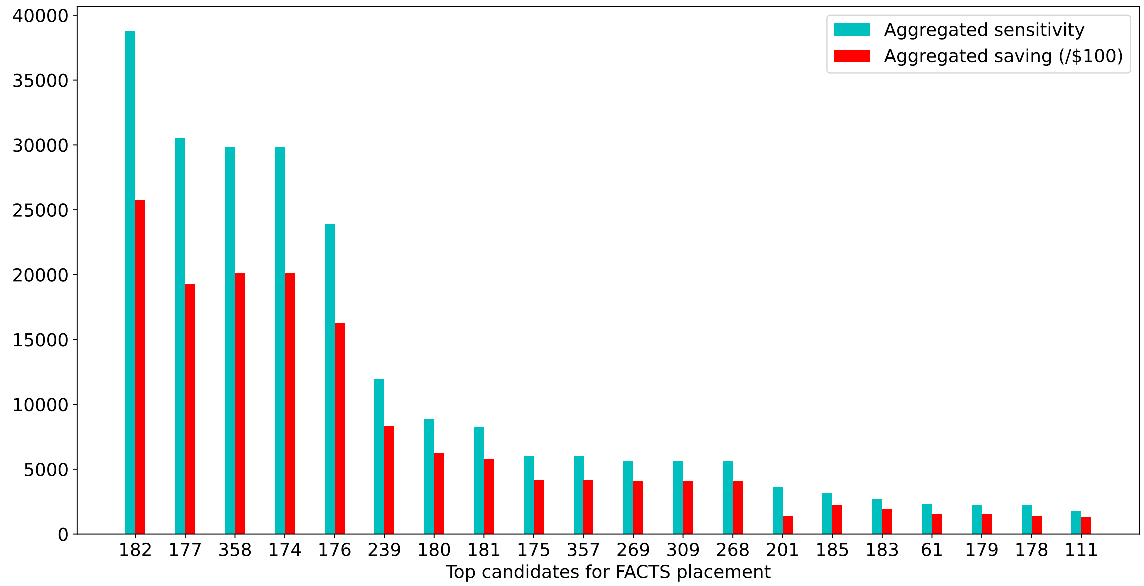

Fig. 2. Aggregated sensitivity and savings results for the 300-bus system

TABLE II
RANKING OF TOP CANDIDATE LOCATIONS FOR FACTS IN THE 300-BUS SYSTEM

Sensitivity-based method			Exhaustive search		
Rank	Line no.	$\tilde{\zeta}_k$	Rank	Line no.	$AS(k)$ ($)
1	182	38751.30	1	182	2,578,151
2	177	30527.73	2	358	2,013,399
3	358	29867.46	3	174	2,013,399
4	174	29867.46	4	177	1,930,428
5	176	23868.22	5	176	1,623,803
6	239	11955.92	6	239	831,351
7	180	8883.84	7	180	621,713
8	181	8223.58	8	181	576,331
9	175	5999.24	9	175	419,579
10	357	5999.24	10	357	419,579
11	269	5589.76	11	269	405,040
12	309	5589.76	12	309	405,040
13	268	5589.76	13	268	405,040
14	201	3652.85	14	185	224,296
15	185	3174.28	15	183	190,774
16	183	2697.32	16	179	157,448
17	61	2303.66	17	178	157,448
18	179	2224.34	18	61	152,064
19	178	2224.34	19	201	139,332
20	111	1786.25	20	111	132,553

IV. CONCLUSION

This paper presents a sensitivity-based method for the optimal placement of prominent VSC-based FACTS devices. The sensitivities are calculated using dual variables obtained from the DCOPF and used to develop ranking metrics for potential locations for FACTS deployment. The presented method is easy to implement with the usage of shadow prices and is computationally efficient due to its linear nature. It is an effective approach to facilitate the planning of FACTS devices, thus enhancing their utilization in congestion alleviation.

REFERENCES

[1] O. Mirzapour, X. Rui, and M. Sahraei-Ardakani, "Transmission impedance control impacts on carbon emissions and renewable energy curtailment," *Energy*, vol. 278, Sep. 2023, Art. no. 127741.

[2] R. A. de Araujo, S. P. Torres, J. Pissolato Filho, C. A. Castro, and D. Van Hertem, "Unified AC transmission expansion planning formulation incorporating VSC-MTDC, FACTS devices, and reactive power compensation," *Electr. Power Syst. Res.*, vol. 216, Mar. 2023, Art. no. 109017.

[3] S. Dawn, P. K. Tiwari, A. K. Goswami, and R. Panda, "An approach for system risk assessment and mitigation by optimal operation of wind farm and FACTS devices in a centralized competitive power market," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1054–1065, Jul. 2019.

[4] X. Zhang, D. Shi, Z. Wang, B. Zeng, X. Wang, K. Tomsovic, and Y. Jin, "Optimal allocation of series FACTS devices under high penetration of wind power within a market environment," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6206–6217, Nov. 2018.

[5] H. Hashemzadeh and S. H. Hosseini, "Locating series FACTS devices using line outage sensitivity factors and particle swarm optimization for congestion management," in *2009 IEEE Power Energy Soc. Gen. Meeting*. IEEE, Jul. 26–30, 2009, pp. 1–6.

[6] N. Acharya and N. Mithulananthan, "Locating series FACTS devices for congestion management in deregulated electricity markets," *Electr. Power Syst. Res.*, vol. 77, no. 3-4, pp. 352–360, Mar. 2007.

[7] X. Fang, J. H. Chow, X. Jiang, B. Fardanesh, E. Uzunovic, and A.-A. Edris, "Sensitivity methods in the dispatch and siting of FACTS controllers," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 713–720, May 2009.

[8] N. Eghtedarpour and A. R. Seifi, "Sensitivity-based method for the effective location of SSSC," *J. Power Electron.*, vol. 11, no. 1, pp. 90–96, Jan. 2011.

[9] D. Menniti and N. Sorrentino, "A new method for SSSC optimal location to improve power system available transfer capability," in *2006 IEEE PES Power Syst. Conf. Expo.* IEEE, Oct. 29–Nov. 1, 2006, pp. 938–945.

[10] European Network of Transmission System Operators for Electricity (ENTSO-E), "Static synchronous series compensator." [Online]. Available: https://www.entsoe.eu/Technopedia/techsheets/static-synchronous-series-compensator
[11] O. Mirzapour, X. Rui, and M. Sahraei-Ardakani, "Grid-enhancing technologies: Progress, challenges, and future research directions," *Electr. Power Syst. Res.*, vol. 230, May 2024, Art. no. 110304.
[12] Power Engineering International, "Managing grid stability in the changing energy landscape," Oct. 2020. [Online]. Available: https://www.powerengineeringint.com/smart-grid-td/td-infrastructure/managing-grid-stability-in-the-changing-energy-landscape/
[13] Siemens Energy, "UPFC PLUS." [Online]. Available: https://assets.siemens-energy.com/siemens/assets/api/uuid:c1fb5690-e885-4c7c-972d-a2449fded8ac/two-pager-layout-se.pdf?ste_sid=67453f9c227e7d13f675ea824b9d3cd4
[14] Smart Wires Inc., "SmartValve^{TM}." [Online]. Available: https://www.smartwires.com/smartvalve/
[15] S. An, J. Condren, and T. W. Gedra, "An ideal transformer upfc model, opf first-order sensitivities, and application to screening for optimal upfc locations," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 68–75, Feb. 2007.
[16] B. Chong, X.-P. Zhang, K. Godfrey, L. Yao, and M. Bazargan, "Optimal location of unified power flow controller for congestion management," *European Trans. on Elect. Power*, vol. 20, no. 5, pp. 600–610, Jul. 2010.
[17] M. Sahraei-Ardakani and K. W. Hedman, "Computationally efficient adjustment of FACTS set points in DC optimal power flow with shift factor structure," *IEEE Trans. Power Syst.*, vol. 32, no. 3, pp. 1733–1740, May 2017.
[18] M. Sahraei-Ardakani and S. A. Blumsack, "Transfer capability improvement through market-based operation of series FACTS devices," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3702–3714, Sep. 2016.
[19] X. Rui, M. Sahraei-Ardakani, and T. R. Nudell, "Linear modelling of series FACTS devices in power system operation models," *IET Gener., Transmiss. Distri.*, vol. 16, no. 6, pp. 1047–1063, Mar. 2022.
[20] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty *et al.*, "The IEEE reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1010–1020, Aug. 1999.
[21] Department of Electrical Engineering, University of Washington, "Power systems test case archive." [Online]. Available: http://labs.ece.uw.edu/pstca/rts/pg_tcarts.htm
[22] Smart Wires Inc., "SmartValve^{TM} 10-1800 v1.04," 2023. [Online]. Available: https://www.smartwires.com/smartvalve/
[23] S. Diamond and S. Boyd, "CVXPY: A Python-embedded modeling language for convex optimization," *J. Mach. Learn. Res.*, vol. 17, no. 83, pp. 1–5, Apr. 2016. [Online]. Available: http://jmlr.org/papers/v17/15-408.html
[24] Department of Electrical Engineering, University of Washington. Power systems test case archive. [Online]. Available: http://labs.ece.uw.edu/pstca/pf300/pg_tca300bus.htm
[25] S. Babaeinejadsarookolaee, A. Birchfield, R. D. Christie, C. Coffrin, C. DeMarco, R. Diao, M. Ferris, S. Fliscounakis, S. Greene, R. Huang *et al.*, "The power grid library for benchmarking AC optimal power flow algorithms," *arXiv preprint arXiv:1908.02788*, 2019.