Analyzing Mutual Influences of Conventional and Distributed FACTS via Stochastic Co-optimization

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***Abstract*—Distributed flexible AC transmission systems (D-FACTS) is an attractive power flow control technology, featuring low cost and flexibility for re-deployment. Optimal allocation of D-FACTS and the mutual influence between existing FACTS and newly planned D-FACTS are challenging but important issues that need to be addressed. This paper proposes a co-optimization model of FACTS and D-FACTS based on stochastic optimization, considering the uncertainties caused by fluctuating load and renewable energy generation. Using this model, the location and set points of FACTS and D-FACTS can be co-optimized; in a system with existing FACTS, the locations of FACTS can be pre-determined and the locations of D-FACTS can be optimized. The study shows that existing FACTS affects the optimal locations of D-FACTS and adding D-FACTS into the system affects the optimal set points of existing FACTS. Thus, it is essential to co-optimize the two technologies to maximize their economic benefits.**

Keywords—distributed flexible AC transmission systems (D-FACTS), flexible AC transmission systems (FACTS), optimal allocation, power system economics, stochastic optimization

I. NOMENCLATURE

Indices

k	Transmission line.
g	Generator.
i	The number of D-FACTS installed per phase per a certain distance for a transmission line.
n	Node.
r	Renewable generator.
s	Scenario.
seg	Segment of linearized generator cost function.

Sets

$\sigma^+(n)$	Transmission lines with their "to" bus connected to node n.
$\sigma^-(n)$	Transmission lines with their "from" bus connected to node n.
$g(n)$	Generators connected to node n.
$r(n)$	Renewable generator connected to node n.

Variables

C_{inv}	Total investment in FACTS ($).
C_{inv}^D	Total investment in D-FACTS ($).
$F_{k,s}$	Real power flow through transmission line k in scenarios s.
$P_{g,s}$	Real power generation of generator g in scenarios s.
$P_{g,s}^{seg}$	Real power generation of generator g in scenarios s in segment seg.
$P_{r,s}$	Renewable generation produced by renewable generator r in scenario s.
$P_{r,s}^C$	Curtailed renewable generation from renewable generator r in scenario s.
$R_{g,s}^D$	Spinning down reserve available through generator g in scenario s.
$R_{g,s}^U$	Spinning up reserve available through generator g in scenario s.
x_k	Binary integer indicating FACTS installed on transmission line k or not (1: installed; 0: not installed).
$x_{k,i}^D$	Binary integer indicating D-FACTS installed on transmission line k or not; when its value is 1, it means i D-FACTS are installed on line k.
$\theta_{b,s}$	Voltage angle at bus b in scenarios s.
$\theta_{fr,k,s}$	Voltage angle at the "from" node of line k in scenarios s.
$\theta_{to,k,s}$	Voltage angle at the "to" node of line k in scenarios s.

Parameters

c_g^{NL}	No load cost of generator g.
$c_{g,seg}^{linear}$	Linear cost of generator g in segment seg.
c_g^D	Down reserve cost of generator g.
c_g^U	Up reserve cost of generator g.
C_{single}^D	Cost a of single D-FACTS unit ($).
C_{sh}^D	Cost a of single D-FACTS unit converted to an hourly basis ($/h).
C_k^{Fh}	Cost of FACTS with a desired reactance adjustment range if installed on line k converted to an hourly basis ($/h).
C_{inv}^{max}	Maximum investment allowed for D-FACTS.
$f_{k,s}$	Binary integer indicating direction of power flow through line k in scenario s.
F_k^{max}	Thermal capacity/voltage drop limit of transmission line k.
i_{max}	Maximum number of D-FACTS that can be allocated per a certain distance per phase.
I	Interest rate/discount rate.
l_k	Length of transmission line k.
$L_{n,s}$	Load at bus n in scenario s.
M	Large positive numbers.
N	Lifespan of D-FACTS.
N_{br}	Number of branches in a system.
N_g	Total number of generators
N_r	Total number of renewable generators.
N_s	Number of scenarios.
N_{seg}	Number of segments for the linearized generator cost function.

p_s Probability of scenario s.
P_g^{max} Upper generation limit of generator g.
P_g^{min} Lower generation limit of generator g.
S_s^D Spinning down reserve requirement g in scenario s.
S_s^U Spinning up reserve requirement g in scenario s.
u $\frac{1}{u}$ is unit distance per which D-FACTS are allocated for each line.
X_k The reactance of transmission line k.
η_C The maximum adjustment percentage of the line's reactance in the capacitive mode that a single module of D-FACTS can achieve.
η_L The maximum adjustment percentage of the line's reactance in the inductive mode that a single module of D-FACTS can achieve.
μ Maximum adjustment percentage of the line's reactance in either inductive or capacitive mode that a FACTS device can achieve.
$\Delta\theta_k^{max}$ Maximum value of bus voltage angle difference to maintain stability for line k.
$\Delta\theta_k^{min}$ Minimum value of bus voltage angle difference to maintain stability for line k.

II. INTRODUCTION

In recent years, distributed flexible AC transmission systems (D-FACTS) have become an increasingly popular power flow control technique, with the successful deployment of its commercial version, Smart Wires, in many transmission systems [1]. D-FACTS is a light-weight version of conventional flexible AC transmission systems (FACTS), which can be attached to transmission line conductors or towers in a relatively large quantity to achieve a desired power flow control capability [2]. Compared with conventional FACTS, D-FACTS has a lower cost [3] and can be re-deployed conveniently if needed [4]. There generally three types of D-FACTS, namely, distributed series static compensator (DSSC), distributed series reactor (DSR), and distributed series impedance (DSI). DSSC works similarly to a phase shifter, while DSI and DSR can be considered as a series variable-impedance device, similar to thyristor-controlled series compensators (TCSC) [5]-[8]. In order to achieve the best power flow control performance, these devices need to be optimally allocated with appropriate set points in a transmission system.

Currently, the most popular optimization models for power flow control technologies, such as FACTS, are mixed-integer linear programs (MILP) based on DC optimal power flow (DCOPF) [9]-[12]. These models match with industry practices, which minimizes the total generation dispatch cost as a fair system operator, and can be conveniently added with uncertainties. They are linear and relatively computationally efficient with a small number of integer variables. Compared with DSSC, DSI and DSR are lower in cost and have a better commercial prospect, however, optimally allocating them is a challenging task. On one hand, compared with DSSC, since DSI and DSR involve direct adjustment of transmission line impedances, they introduce nonlinearities to optimization models based on DCOPF. On the other hand, since D-FACTS are usually deployed in large quantities, and different quantities of D-FACTS need to be allocated on different lines, this dramatically increases the integer variables needed in the optimization problem. Both factors make the variable-impedance D-FACTS optimization problem computationally complex. Until now, a number of approaches have been proposed to optimally allocate D-FACTS. A DC power flow based optimization model is developed in [13], however, the proposed optimization model is nonlinear and relatively computationally intensive. A particle swarm optimization (PSO) based optimal allocation model for D-FACTS is proposed in [14], but uncertainties are not considered in this model. Reference [15] proposes a D-FACTS allocation method based on graph theory, but the objective is not minimizing generation dispatch cost, which is what a system operator usually does to maximize social welfare. An optimal allocation algorithm for D-FACTS based on DCOPF is proposed in [16], however, this method is only applicable for DSSC. Thus, a computationally efficient model is still highly desired in order to maximize the economic benefits of series variable-impedance D-FACTS.

Another issue that arises from the increasing popularity of D-FACTS is its co-optimization with other power flow control technologies, such as TCSC. Currently, there are a number of TCSCs installed around the world; as a widely accepted technology, it can be expected that TCSC will still be a competing technology with D-FACTS in the coming years. In the future, it is likely that D-FACTS will be deployed in a system with existing TCSCs. The mutual influence and co-optimization of the two technologies need to be studied in order to maximize the economic benefits that both technologies can offer. A credible co-optimization model of the two technologies is needed to initiate this study, however, currently, there is still no such model yet.

This paper aims at filling this gap by proposing a computationally efficient co-optimization model of FACTS and D-FACTS considering uncertainties in the network, and study the mutual influence of the two technologies when D-FACTS are allocated in a system with existing FACTS, such as the influence of FACTS on the optimal locations of D-FACTS, and the influence of D-FACTS on optimal FACTS set points. Simulations were carried out on a modified RTS-96 test system; uncertainties of renewable generation and load fluctuation were both considered. Results do not only prove that D-FACTS is a more economic option than FACTS, but also show the mutual influences between the two technologies need to be considered in order to maximize the economic benefits when allocating D-FACTS in a system with existing FACTS.

The following part of the paper is organized as follows. Section III describes the co-optimization model of FACTS and D-FACTS in detail, and Section IV presents the setup of simulations. Mutual influences of FACTS and D-FACTS in the planning phase are discussed in Section V, their mutual influences in the operation phase are analyzed in Section VI, and a conclusion is drawn in Section VII.

III. CO-OPTIMIZATION MODEL FORMULATION

The co-optimization model of FACTS and D-FACTS adopts a two-step approach [9]. In the first step, a base case of stochastic optimization considering all the scenarios without power flow control technique is solved and the power flow direction is obtained; in the second step, the stochastic optimization problem that allocates FACTS and D-FACTS is solved using the power flow direction obtained in the first step.

The formulation of the first step is described with (1) – (14). The objective of this problem, as shown in (1), is to minimize total dispatch cost, including generation dispatch cost, spinning reserve cost, no load cost and renewable energy curtailment cost, considering all the scenarios and their probabilities. (2) and (3) are the generation constraints, (4) is the transmission constraints, (5) is the DC power flow equation, (6) is the power balance constraint, (7) – (10), (13) and (14) are the spinning reserve constraints, and (11) and (12) are the bus voltage angle constraints.

$$min\left(\sum_{s=1}^{N_s} p_s\left(\sum_{g=1}^{N_g}\left(\begin{array}{c}\sum_{seg=1}^{N_{seg}} c_{g,seg}^{linear} P_{g,s}^{seg}\\ +c_g^U R_{g,s}^U + c_g^D R_{g,s}^D + c_g^{NL}\end{array}\right) + \sum_{r}^{N_r} c_r P_{r,s}^C\right)\right) \tag{1}$$

$$P_{g,s} = \sum_{seg=1}^{N_{seg}} P_{g,s}^{seg} \tag{2}$$

$$P_g^{min} \le P_{g,s} \le P_g^{max} \tag{3}$$

$$-F_k^{max} \le F_{k,s} \le F_k^{max} \tag{4}$$

$$b_k\left(\theta_{fr,k,s} - \theta_{to,k,s}\right) = F_{k,s} \tag{5}$$

$$\sum_{k\in\sigma^+(n)} F_{k,s} - \sum_{k\in\sigma^-(n)} F_{k,s} + \sum_{g\in g(n)} P_{g,s} + \sum_{r\in r(n)}\left(P_{r,s} - P_{r,s}^C\right) = L_{n,s} \tag{6}$$

$$\sum_{g=1}^{N_g} R_{g,s}^U \ge S_s^U \tag{7}$$

$$\sum_{g=1}^{N_g} R_{g,s}^D \ge S_s^D \tag{8}$$

$$R_{g,s}^U \le P_g^{max} - P_{g,s} \tag{9}$$

$$R_{g,s}^D \le P_{g,s} - P_g^{min} \tag{10}$$

$$\Delta\theta_k^{min} \le \theta_{fr,k,s} - \theta_{to,k,s} \le \Delta\theta_k^{max} \tag{11}$$

$$\theta_{1,s} = 0 \tag{12}$$

$$R_{g,s}^D \ge 0 \tag{13}$$

$$R_{g,s}^D \ge 0 \tag{14}$$

After the base case is solved, the direction of power flow on each transmission line in each scenario can be obtained and used in the second step of optimization. In this step, a 1-dimensional binary integer is used to indicate the installation of conventional FACTS, and a 2-dimensional binary integer, $x_{k,i}^D$, is introduced to indicate the number of D-FACTS allocated on each line. When $x_{k,i}^D = 1$, it means there are i D-FACTS allocated on line k; as the value of the index i varies for each value of index k, only one $x_{k,i}^D$ can be 1. If no $x_{k,i}^D$ is 1 for all i for a line k, it means no D-FACTS is allocated on line k. The second step is formulated as following:

$$min\left(\begin{array}{c}\sum_{s=1}^{N_s} p_s\left(\sum_{g=1}^{N_g}\left(\begin{array}{c}\sum_{seg=1}^{N_{seg}} c_{g,seg}^{linear} P_{g,s}^{seg}\\ +c_g^U R_{g,s}^U + c_g^D R_{g,s}^D + c_g^{NL}\end{array}\right) + \sum_{r=1}^{N_r} c_r P_{r,s}^C\right)\\ +C_{inv}^D + C_{inv}\end{array}\right) \tag{15}$$

$$\{(2) – (4), (6) – (14), (18), (25), (26)\} \tag{16}$$

$$C_{inv} = \sum_{k=1}^{N_{br}} C_k^{Fh} x_k \tag{17}$$

$$C_{inv}^D = \sum_{k=1}^{N_{br}} \sum_{i=1}^{i_{max}} 3ul_k i C_{sh}^D x_{k,i}^D \tag{18}$$

$$C_{inv} + C_{inv}^D \le C_{inv}^{max} \tag{19}$$

$$(1 + i\eta_L)X_k F_{k,s} + \left(1 - x_{k,i}^D\right)M + \left(1 - f_{k,s}\right)M + x_k M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{20}$$

$$(1 + i\eta_L)X_k F_{k,s} - \left(1 - x_{k,i}^D\right)M - f_{k,s}M - x_k M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{21}$$

$$(1 - i\eta_C)X_k F_{k,s} - \left(1 - x_{k,i}^D\right)M - \left(1 - f_{k,s}\right)M - x_k M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{22}$$

$$(1 - i\eta_C)X_k F_{k,s} + \left(1 - x_{k,i}^D\right)M + f_{k,s}M + x_k M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{23}$$

$$(1 + \mu)X_k F_{k,s} + (1 - x_k)M + M\sum_{i=1}^{i_{max}} x_{k,i}^D + \left(1 - f_{k,s}\right)M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{24}$$

$$(1 - \mu)X_k F_{k,s} - (1 - x_k)M - M\sum_{i=1}^{i_{max}} x_{k,i}^D - \left(1 - f_{k,s}\right)M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{25}$$

$$(1 - \mu)X_k F_{k,s} + (1 - x_k)M + M\sum_{i=1}^{i_{max}} x_{k,i}^D + f_{k,s}M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{26}$$

$$(1 + \mu)X_k F_{k,s} - (1 - x_k)M - M\sum_{i=1}^{i_{max}} x_{k,i}^D - f_{k,s}M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{27}$$

$$X_k F_{k,s} + M_1\sum_{i=1}^{i_{max}} x_{k,i}^D + M_2 x_k \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{28}$$

$$X_k F_{k,s} - M_1\sum_{i=1}^{i_{max}} x_{k,i}^D - M_2 x_k \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{29}$$

$$x_k + \sum_{i=1}^{i_{max}} x_{k,i}^D \le 1 \tag{30}$$

In this formulation, (15) is the objective, which minimizes the total cost, including generation dispatch of all scenarios considering their probabilities, and the investment in FACTS and D-FACTS. The generation constraints, transmission constraints, power balance constraints, spinning reserve constraints, and bus voltage angle constraints are the same as the base case; the investments in D-FACTS and D-FACTS are constrained by (17), (18) and (19). The hourly figure of FACTS investment, C_k^{Fh}, can be calculated according to [17]. According to [18], a reasonable cost for each D-FACTS unit is \$100/kVA; the kVA rating needed for D-FACTS modules depends on their impedance injection level and the parameters of the transmission lines on which they are installed. In order to ensure the D-FACTS modules are reusable for all transmission lines in a system, the kVA rating of the module needs to satisfy the most demanding line in the system. In the test system used in this system, the largest kVA rating needed is 30kVA, thus a cost of \$3000/module is used for D-FACTS in this study. Since this optimization problem is based on an hourly DCOPF problem, the cost for each D-FACTS unit needs to be converted to an hourly basis [12], [19]-[22]:

$$C_{sh}^{D} = C_{single}^{D}\frac{I(1+I)^{n}}{8760((1+I)^{n}-1)} \quad (31)$$

(20) – (29) are the DC power flow constraints which considers the installation of FACTS and D-FACTS; when D-FACTS are installed on a line and the power flow direction is positive, (20) and (22) apply; when D-FACTS are installed and the power flow direction is negative, (21) and (23) apply. When FACTS is installed on a line and the power flow direction is positive, (24) and (25) apply; when FACTS is installed and the power flow direction is negative, (26) and (27) apply. When no FACTS or D-FACTS is installed on a line, (28) and (29) apply. D-FACTS and FACTS cannot be installed on the same line considering there needs to be a fair limit for reactance adjustment range, and this is enforced by (30).

IV. Simulation Setup

A. Test System Configurations

The simulations were carried out on a modified 24-bus RTS-96 test system in this study. Further modifications were made based on the system described in [18], including increasing the peak load at each bus by 5% and reducing the peak load at Bus 3 and 9 to 90MW and 86.2MW, respectively. The original load factors were mapped to a range of 0.55 – 1.0. In order to add uncertainties to the system, the 400MW power plant at bus 21 was retired and two 400MW wind farms were added to bus 19 and 20, respectively. The wind speed data at the height of 100 meters of Taylor County, Texas, in 2012, were used in this study [23], and wind power output factors, which are ratios of actual wind power outputs to the rated power output, were calculated according to the method used in [24]. Four representative wind power output factor scenarios and their probabilities were obtained, namely, the output factors of 0, 0.2, 0.6, and 1. Furthermore, four representative load scenarios and their probabilities were also obtained, namely, load factors of 0.65, 0.75, 0.85, and 0.95. Sixteen scenarios were obtained through a cross product of the wind output and load scenarios. Wind power was allowed to be curtailed in the optimization model at a cost of $30/MW, since some system operators offer compensations for curtailed wind power.

B. FACTS and D-FACTS Configurations

In this study, it is assumed that each D-FACTS module is designed to be able to adjust the line impedance by ±2.5% per phase per mile [7], and the maximum impedance adjustment range for a three-phase transmission line using D-FACTS is ±20% [25]. This model allows D-FACTS to be allocated per phase per a certain distance, and this distance does not have to be 1 mile. Results regarding D-FACTS in this paper were obtained when D-FACTS were allocated per 0.25 mile per phase. Conventional variable-impedance series FACTS devices with an impedance adjustment range of ±20% were used for co-optimization.

V. Mutual Influences in the Planning Phase

A. Co-optimization of FACTS and D-FACTS

In order to compare the cost of FACTS and D-FACTS, their locations were co-optimized using the model proposed in Section III. Three investment limits for FACTS and D-FACTS were applied, namely, $10/hour, $20/hour and $30/hour, and the allocation results for each case are shown in TABLE I. Results show that, if FACTS locations are co-optimized with D-FACTS, then only D-FACTS will be adopted in the system. This verifies the lower cost of D-FACTS than conventional FACTS.

TABLE I. FACTS and D-FACTS Allocation in Co-optimization

Maximum Investment ($/hour)	FACTS locations	D-FACTS locations	D-FACTS Number per phase per 0.2 mile	Total Number of D-FACTS
10	N/A	19	1	348
20	N/A	22	1	720
30	N/A	22	1	720
		28	2	432

B. D-FACTS Allocation without Co-optimizing with FACTS

This subsection studies the allocation of D-FACTS in a system with existing conventional FACTS when D-FACTS allocation was not co-optimized with FACTS. Using the FACTS allocation model proposed in [9], a number of conventional FACTS can be allocated. In the test system used in this study, the optimal locations of FACTS when 1, 2, or 3 of them were allocated are shown in TABLE II.

TABLE II. Optimal Locations of conventional FACTS

Number of FACTS	1	2	3
Optimal locations (Line number)	22	22,23	19,22,23

TABLE III. D-FACTS Allocation without Co-optimizing with FACTS

Line Candidates Excluded	Maximum Investment ($/hour)	D-FACTS locations	D-FACTS Number per phase per 0.25 mile	Total Number of D-FACTS
22	10	28	1	216
		36	1	180
	20	23	1	492
		28	1	216
	30	23	2	984
		28	1	216
22,23	10	19	1	348
	20	19	1	348
		28	2	432
	30	19	2	696
		28	2	432
19,22,23	10	28	1	216
		30	1	120
	20	28	2	432
		29	1	192
		30	1	120
	30	21	1	804
		28	1	216
		37	1	180

In order to show the D-FACTS allocation results without co-optimizing with FACTS, three conditions have to be satisfied in the optimization problem: (1) it is assumed that there is no existing FACTS in the system (although there actually are); (2) no new conventional FACTS can be allocated in the system; (3) the lines with existing FACTS are excluded from D-FACTS allocation candidates so that the impedance adjustment ranges for these lines do not exceed the desired limit. (1) can be met by eliminating constraints (24)-(27) and not allowing reactance adjustment for the lines with FACTS, (2) can be met by setting the upper and lower bounds of x_k for all lines to be 0, and (3) can be met by setting the upper and lower bounds of $x_{k,i}^{D}$ for lines with FACTS to be 0. The optimal locations of D-FACTS obtained under these conditions are shown in TABLE III.

Compared with results in TABLE I, the optimal locations of D-FACTS changed with different lines excluded from D-FACTS allocation candidates. It is also worth noting that the optimal locations of D-FACTS often move to different lines with the increase of investment, and this can be conveniently solved by re-deploying existing D-FACTS in the system.

C. D-FACTS Allocation Co-optimized with FACTS

In this part, the allocation of D-FACTS was co-optimized with existing FACTS in the system. This can be achieved by setting the upper and lower bounds of x_k according to whether there is FACTS installed on this line; if there is, then both the upper and lower bounds were set to 1, otherwise both were set to 0. The allocation results obtained under this condition are shown in TABLE IV. Compared with results in TABLE III, it can be seen that the optimal locations of D-FACTS are different in 6 out of 9 cases. Thus, it can be seen that excluding lines with FACTS from allocation candidates is different from co-optimizing with existing FACTS; the flexibility offered by existing FACTS may change the optimal location of newly planned D-FACTS, and this point should be considered when allocating D-FACTS in a system with existing FACTS to maximize economic benefits.

TABLE IV. D-FACTS ALLOCATION CO-OPTIMIZED WITH FACTS

FACTS locations	Maximum Investment ($/hour)	D-FACTS locations	D-FACTS Number per phase per 0.25 mile	Total Number of D-FACTS
22	10	19	1	348
	20	23	1	492
		28	1	216
	30	19	1	348
		21	1	804
22,23	10	19	1	348
	20	19	1	348
		28	2	432
	30	19	1	348
		21	1	804
19,22,23	10	24	1	144
		28	1	216
	20	24	1	144
		28	2	432
		29	1	192
	30	21	1	804
		24	1	144
		28	1	216

VI. MUTUAL INFLUENCES IN THE OPERATION PHASE

The proposed model can be used for not only planning purposes, but also evaluating the expected dispatch cost, wind curtailment cost, and FACTS/D-FACTS set points optimization in the operation phase. Section V-B and Section V-C discussed two ways of allocating D-FACTS in a system with existing FACTS; one is not co-optimizing with FACTS and the other is co-optimizing with FACTS. After the locations of both FACTS and D-FACTS are obtained, the locations of FACTS and D-FACTS can be pre-determined in the proposed model by setting both the upper and lower bounds of x_k and $x_{k,i}^D$ to values that equal to the allocation solution, in order to solve for the expected dispatch cost and wind curtailment cost considering all load and renewable generation scenarios and evaluate the economic benefits of each allocation solution.

In this study, allocations of FACTS shown in TABLE II were used; with each FACTS allocation, simulations were carried out with two sets of D-FACTS allocations, one is optimized with FACTS (shown in TABLE IV) and the other is not (shown in TABLE III). Each set of D-FACTS allocations include allocations at three different investment levels, from $10/hour to $30/hour. Expect dispatch cost savings and expected wind curtailment savings of using these FACTS and D-FACTS compared to the base case without using any power flow control technologies were calculated for each case and presented in TABLE V. On average, the expected dispatch cost savings were 0.1% higher and expected wind curtailment savings were 1% higher in the case with co-optimized FACTS and D-FACTS. Although the figures were small, it can mean millions of dollars for a large system. This verifies that D-FACTS should be co-optimized with FACTS to maximize the economic benefits.

TABLE V. EXPECTED DISPATCH AND WIND CURTAILMENT SAVINGS

FACTS locations	Maxi-mum invest-ment ($/h)	D-FACTS not co-optimized with FACTS		D-FACTS co-optimized with FACTS	
		Expected dispatch cost savings	Expected wind curtail-ment savings	Expected dispatch cost savings	Expected wind curtail-ment savings
22	10	4.07%	23.17%	4.01%	21.63%
	20	4.57%	24.42%	4.57%	24.42%
	30	4.73%	24.93%	5.20%	27.92%
22,23	10	5.31%	30.21%	5.31%	30.21%
	20	5.78%	29.84%	5.78%	29.84%
	30	5.97%	31.53%	6.16%	32.07%
19,22,23	10	5.91%	31.00%	5.94%	34.21%
	20	6.24%	32.83%	6.26%	35.79%
	30	6.55%	33.74%	6.60%	33.79%

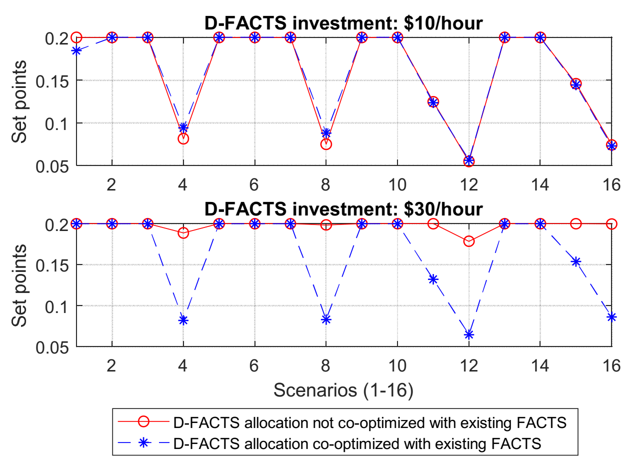

Fig. 1. FACTS set point comparison when D-FACTS locations were co-optimized and not co-optimized with existing FACTS in the system

The optimal set points of existing FACTS in the system can also be affected by different D-FACTS allocation plans. When the FACTS was at Line 22 and the investment limits were $10/hour and $30/hour, the D-FACTS allocation solutions were different when co-optimized and not co-optimized with FACTS. The optimal set points of the FACTS on Line 22 were obtained under the 16 scenarios discussed in Section IV-A with co-optimized and not-co-optimized D-FACTS allocation, and the results are compared in Fig. 1. It can be seen that the set points of FACTS under each scenario can be different with different D-FACTS allocation plans, and this is especially obvious when the D-FACTS investment is \$30/hour. Thus, in order to achieve the best cost performance of FACTS, it is essential to adjust FACTS set points according to newly allocated D-FACTS in the operation phase.

VII. Conclusion

This paper proposed a linear, computationally efficient co-optimization model of FACTS and D-FACTS based on DCOPF. The model can be used to simultaneously allocate FACTS and D-FACTS or optimize one technology based on existing devices in the system in the planning stage; it can also be employed to analyze the economic benefits of FACTS and D-FACTS or optimizing their set points in the operation phase. Mutual influences between FACTS and D-FACTS in both planning and operation phases were studied based on the co-optimization model. The Results show that D-FACTS is a cheaper option than conventional FACTS in general; D-FACTS allocation can be affected by the existing FACTS in the system, and the optimal set points of FACTS can be influenced by different D-FACTS allocation plans. When D-FACTS are being planned in a system with existing FACTS devices, it is essential to co-optimize the two technologies so that the economic benefits of the two can be maximized.

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