Economic Benefit Comparison of D-FACTS and FACTS in Transmission Networks with Uncertainties

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***Abstract*—Distributed flexible AC transmission systems (D-FACTS) has become increasingly popular in recent years. Among all types of D-FACTS devices, variable-impedance D-FACTS is the most cost-effective. However, integration of these devices within an optimal power flow problem introduces nonlinearities that are computationally challenging. In this study, a computationally efficient stochastic optimization model is proposed to optimally allocate variable-impedance D-FACTS considering the randomness of wind power output and load variation. The optimal locations and economic benefits of D-FACTS are compared with those of conventional FACTS. The results show that D-FACTS devices are more cost-effective than conventional FACTS, considering complex operation conditions in a transmission network. The economic benefits will increase if periodical redeployment of D-FACTS is allowed.**

***Index Terms*—distributed flexible AC transmission systems (D-FACTS), FACTS, mixed integer linear programming (MILP), optimal allocation, power system economics.**

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.
$x_{k,i}^D$	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^{FACTS}	Cost of FACTS in $/kVA depending on the compensation level of a FACTS device.
C_k^F	Cost of FACTS with a desired reactance adjustment range if installed on line k ($).
C_k^{Fh}	Cost of FACTS with a desired reactance adjustment range if installed on line k converted to an hourly basis ($/h).
$f_{k,s}$	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_{DFACTS}	Maximum number of D-FACTS installed 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_{base}	MVA base of the system.
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.
$\Delta\theta_k^{max}$	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.

I. INTRODUCTION

Distributed flexible AC transmission system (D-FACTS) is a light-weight version of flexible AC transmission systems (FACTS). It is an effective technique to adjust transmission line impedances or bus voltage angles, in order to control the real power flow and reduce congestions in the transmission network. Instead of being centrally installed and requiring a large area of land, D-FACTS can be attached to the conductor of the transmission lines in a large number, and re-deployed if needed. Its flexibility has attracted interests from both industry and academia. A commercial D-FACTS brand is the Smart Wires; their devices have been successfully deployed in a number of transmission systems across the world. With the increasing application of D-FACTS, an effective method to optimally allocate them is highly desired. Meanwhile, the costs of power flow control technologies, including FACTS and D-FACTS, need to be compared in a transmission network considering complex operation conditions, in order to facilitate the economic deployment of these technologies.

D-FACTS can be categorized into two types: variable impedance devices and phase shifters. Variable impedance devices include distributed series reactor (DSR), and distributed series impedance (DSI), which is able to inject inductive or capacitive reactances into the transmission line. Phase shifters mainly refer to distributed series static compensator (DSSC), which injects a voltage in quadrature with line current [1]-[5]. Generally speaking, variable-impedance D-FACTS have a lower cost and simpler structure than phase-shifting D-FACTS [6], but optimally placing them is more challenging. When the optimal allocation problem is integrated into a DC optimal power flow (DCOPF) problem, the adjustment of impedance makes the problem nonlinear; additionally, there are usually hundreds or thousands of D-FACTS being allocated in each problem, making the problem extremely computationally complex.

In recent years, a great deal of research efforts have been put into investigating effective allocation methods and evaluating economic benefits of D-FACTS. Reference [7] proposes a D-FACTS allocation method based on graph theory; this method is able to minimize losses and maximize line capacities using FACTS, but the total generation dispatch cost from a system operator's point of view is not considered. A particle swarm optimization (PSO) based optimal allocation model for D-FACTS is proposed in [8], but uncertainties in the grid are not modeled. OPF-based methods are proposed in [9][10], but these methods are either nonlinear or only applicable for DSSC. The costs of FACTS and D-FACTS are compared in [11] using a simple one-transmission line system; however, there has been no work that evaluates the economic benefits of D-FACTS considering complex operation conditions of a meshed transmission network yet. Thus, in order to perform a systematic analysis of D-FACTS economic benefits, a computationally efficient optimal allocation method for variable-impedance D-FACTS is required.

A linear model for optimal allocation of conventional variable-impedance FACTS is also very important. Linearized variable-impedance FACTS allocation algorithms are proposed in [12]-[16]; although the formulation is not applicable for D-FACTS, similar linearization techniques can be applied. Moreover, the FACTS allocation model in [12] can be used to obtain the cost of using FACTS, setting a reference for the economic benefit comparison of D-FACTS and FACTS.

In this paper, a computationally efficient stochastic optimization model for variable-impedance D-FACTS allocation based on DCOPF is proposed; the model is linearized using the technique proposed in [12]. This model allows the adjustment ranges of the transmission lines equipped with D-FACTS to be optimized at a pre-determined resolution, such as two, five, or ten different levels, considering load and renewable generations uncertainties. Simulations were carried out on a modified RTS-96 test system to study the influence of seasonal load patterns on D-FACTS allocation; the cost and allocation of D-FACTS were compared to those of FACTS. Results showed that with the same investment, D-FACTS produced more savings than conventional FACTS, even if D-FACTS were not re-deployed periodically. If D-FACTS are allowed to be re-deployed seasonally based on the changes of load patterns, which is a viable option according to Smart Wires [17], then the savings can be even higher.

The following parts of this paper is organized as follows. The D-FACTS optimization model is presented in Section II. Simulation results are shown and discussed in Section III and conclusions are drawn in Section IV.

II. THE OPTIMAL ALLOCATION MODEL FOR D-FACTS

A two-step approach proposed in [12] is used in the D-FACTS optimization model. In this model, a base case of stochastic optimization considering all the scenarios of load and renewable generation but no power flow control technique is solved at first; the power flow direction is obtained from the results and then used in the next step – the stochastic optimization problem that allocates D-FACTS.

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

After solving the base case, 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 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.

In the D-FACTS allocation problem, the investment in D-FACTS is considered. According to [18], a reasonable cost for each D-FACTS unit is \$1000; 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 [19]-[23]:

$$C_{sh}^D = C_{single}^D \frac{I(1+I)^N}{8760\left((1+I)^N - 1\right)} \tag{15}$$

The formulation of the second step, which optimally allocates D-FACTS considering D-FACTS investment, is described by (16) – (24). The objective of this problem not only considers the generation dispatch, but also the investment in D-FACTS. A number of constraints are the same as the base case, as (17) shows. In this model, D-FACTS are allocated per a certain distance per phase, the total investment of D-FACTS on a three-phase transmission line can be expressed by (18). In (18), the scalar u is introduced to allow D-FACTS to be allocated per different distances, and the unit distance can be calculated by $1/u$. For example, if $u = 5$, D-FACTS is allocated per 0.2 mile per phase. (19) – (24) are the DC power flow constraints which considers the installation of D-FACTS; (19) and (21) apply when i D-FACTS are installed on a line and the power flow direction is positive; (20) and (22) apply when i D-FACTS are installed on a line and the power flow direction is negative; (23) and (24) apply when no D-FACTS is installed on the line. (25) makes sure that only at most one $x_{k,i}^D$ is equal to 1 for all i for each line, and (26) sets a limit for the total number of D-FACTS installed in the system. In this formulation, M is a very large number; in this problem, they have to be much larger than the absolute value of the bus voltage angle differences between the two ends of all transmission lines in the system.

$$min\left(\sum_{s=1}^{N_s} p_s\left(\sum_{g=1}^{N_g}\left(\begin{array}{c}\sum_{seg=1}^{N_{seg}} c_{g,seg}^{linear} P_{g,s}^{seg}\\ +c_g^U R_{g,s}^U + c_g^D R_{g,s}^D + c_g^{NL}\end{array}\right)\right) + C_{inv}^D\right) \tag{16}$$

{(2) – (4), (6) – (14)} (17)

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

$$(1 + i\eta_L)X_k F_{k,s} + \left(1 - x_{k,i}^D\right)M + \left(1 - f_{k,s}\right)M \geq \theta_{fr,k,s} - \theta_{to,k,s} \tag{19}$$

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

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

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

$$X_k F_{k,s} + M \sum_{i=1}^{i_{max}} x_{k,i}^D \geq \theta_{fr,k,s} - \theta_{to,k,s} \tag{23}$$

$$X_k F_{k,s} - M \sum_{i=1}^{i_{max}} x_{k,i}^D \le \theta_{fr,k,s} - \theta_{to,k,s} \quad (24)$$

$$\sum_{i=1}^{i_{max}} x_{k,i}^D \le 1 \quad (25)$$

$$\sum_{k=1}^{N_{br}} \sum_{i=1}^{i_{max}} 3ul_k i x_{k,i}^D \le N_{DFACTS} \quad (26)$$

III. Simulation Results And Discussions

A. Simulation Setup

A modified 24-bus RTS-96 test system described in [24] was used in this study. In practical power systems, load patterns change not only with time, but also location, due to reasons such as tourism [25]. Thus, besides changes made in [24], load factors were also modified to reflect seasonal patterns. In winter, the peak load at each bus was the original one increased by 1%; in summer, 400MW of load on bus 13 was shifted to bus 3 and 9 and evenly distributed among the two buses; in spring and fall, 95.95MW of load was shifted from bus 13 to bus 3, and 101MW of load was shifted from bus 13 to bus 9. The original load factors were mapped to a range of 0.55 – 1.0. Typical load scenario sets for each season and the whole year were extracted from the load profiles and used in different stochastic optimization cases; renewable generation was set as 0 so that the influence of seasonally load patterns on D-FACTS allocation can be studied exclusively.

B. Cost Comparison of FACTS and D-FACTS

In this study, 1 FACTS device with impedance adjustment range of ±20% was allocated using the model proposed in [12], but capital investment of FACTS and stochasticity was added to the model and load scenarios of one year were considered. Then the capital investment of FACTS was obtained and set as a cap for the total D-FACTS capital investment. Then D-FACTS were allocated using the proposed model; the maximum impedance adjustment range for each line is limited to ±20%. D-FACTS were allocated per 0.2 mile and 0.5 mile, respectively, under four different sets of typical load scenarios: one year, winter, spring, and summer, because they can be re-deployed seasonally. An expected dispatch cost assuming D-FACTS can be re-deployed every season was also calculated.

The total generation dispatch costs in cases when D-FACTS were allocated per 0.2 mile are shown in TABLE I, along with the dispatch cost in case of one FACTS was used. It can be seen that savings induced by using D-FACTS differed from season to season, but most of the time it was better than those of using FACTS at the same or even higher capital investment. When assuming D-FACTS cannot be re-deployed seasonally, the saving of D-FACTS was 0.12% higher than that of using FACTS; but when they were allowed to be re-deployed every season, the savings was 0.52% higher. Since the savings were within 1% - 2%, an increase of 0.52% is a good improvement. Also, in large-scale systems whose operation costs are billions of dollars a year, a 0.52% of saving increase means an increase by millions of dollars. From the computation perspective, all the cases were solved in less than 15 seconds, showing the computational efficiency of this method.

Allocating D-FACTS per 0.5 mile yielded better results; the saving in case of considering typical scenarios of a year was 1.70% and the expected saving assuming D-FACTS could be re-deployed seasonally was 2.03%. However, the solution time was 5 – 6 orders of magnitude longer than allocating them per 0.2 mile. Thus, a trade-off needs to be made between economic benefits and computational complexity.

TABLE I
Cost and Savings Comparison ($u = 5$)

Scenarios		Total Cost ($/h) Base Case	Total Cost ($/h) With FACTS/ D-FACTS	Solution Time (sec)	Savings with FACTS/ D-FACTS
FACTS	1 Year	78671	77597	1.27	1.36%
D-FACTS	1 Year	78671	77503	14.65	1.48%
	Winter	87561	85756	7.92	2.06%
	Spring	67703	66897	3.60	1.19%
	Summer	85508	83328	3.04	2.55%
	Expected	78671	77194	NA	1.88%

C. Allocation Comparison of FACTS and D-FACTS

The simulation procedure ensured that the total capital investment of D-FACTS did not exceed that of FACTS installed at its optimal location. The optimal locations and capital investments of FACTS and D-FACTS (allocated per 0.2 mile) are shown in TABLE II.

TABLE II
FACTS and D-FACTS Allocation ($u = 5$)

Scenarios		Locations (Line No.)	Quantity (per 0.2 mile per phase)	Total Quantity	Adjustment range	Investment ($/h)
FACTS	1 Year	21	NA	1	±20%	11.46
D-FACTS	1 Year	24	1	180	±10%	11.44
		26	1	510	±10%	
		28	2	540	±20%	
		30	1	150	±10%	
	Winter	22	1	900	±10%	11.20
		24	1	180	±10%	
		28	1	270	±10%	
	Spring	24	1	180	±10%	11.44
		25	1	510	±10%	
		28	2	540	±20%	
		30	1	150	±10%	
	Summer	21	1	1005	±10%	10.57
		28	1	270	±10%	

It can be seen that, with one FACTS installed at its optimal location, bus 21, 1382 D-FACTS can be allocated with the same investment. But since the actual number of D-FACTS that got allocated had to be a multiple of the length of line that they were allocated on, in many cases not all the 1382 D-FACTS were allocated, making the actual capital cost lower than that of FACTS. From the results, it can be seen that D-FACTS were optimally allocated on 2 – 4 lines with different quantities, allowing the lines to have an adjustment range of 10% or 20%, while FACTS can only be allocated for one line. The optimal locations of D-FACTS vary from season to season; about two thirds of the D-FACTS should be re-deployed every season to achieve an optimal dispatch cost. At present, no data on D-FACTS re-deployment cost is available, so this cost is not included in this study. But in real-world problems, re-deployment costs need to be compared with additional dispatch savings to make sure the re-deployment is economic.

IV. Conclusions and Future Work

This paper proposed a DCOPF-based MILP stochastic model to optimally allocate D-FACTS in transmission systems. Compared with existing D-FACTS allocation methods, the proposed method is relatively computationally efficient and able to optimize the locations of D-FACTS considering complex network conditions and uncertainties in the grid. Simulation results showed that, with similar capital investment, D-FACTS result in a lower generation dispatch cost than FACT in most cases; if D-FACTS can be re-deployed according to seasonal load patterns, the total dispatch cost can be further reduced. This study verified the economic benefit of D-FACTS, and proposed a method to maximize the economic benefit of D-FACTS in power system operations.

This study also guides interesting future work, including further improve the computational efficiency of this D-FACTS optimization model. A high-fidelity efficient model should be able to handle large-scale, industrial-size transmission networks. Furthermore, studying impact of renewable generation on D-FACTS allocation and co-optimizing D-FACTS with transmission expansion and other power flow control technologies are also important future areas of research.

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