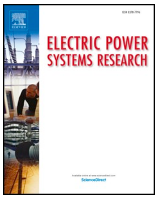
Electric Power Systems Research 168 (2019) 127–136

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Effective power flow control via distributed FACTS considering future uncertainties

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ARTICLE INFO

Keywords:
Distributed flexible ac transmission systems (D-FACTS)
DCOPF
FACTS
Optimal allocation
Smart transmission
Stochastic optimization

ABSTRACT

Flexible AC transmission systems (FACTS) are important contributors to smart transmission systems. They can offer some level of power flow control and enhance the transfer capability over the existing network. This flexibility can be utilized for congestion mitigation and renewable energy integration. Distributed FACTS (D-FACTS) is a light-weight version of FACTS, which can be redeployed conveniently. Due to its lower cost and ease of installation, D-FACTS has become an attractive power flow control technology in recent years. This paper proposes a computationally efficient stochastic allocation model for D-FACTS and studies their impact on power flows. The reduction in operation cost and renewable energy curtailment, achieved through D-FACTS, is compared with that of conventional FACTS. The results are presented under a wide range of scenarios to reflect the changing and uncertain conditions of the future. The scenarios include fluctuating fuel prices, retirement of old generators, and renewable energy generation. The results show that D-FACTS can bring larger economic savings than conventional FACTS, due to its additional flexibility and lower cost; the results also suggest that D-FACTS can better accommodate the future uncertainties.

1. Introduction

1.1. Background

Congestion widely exists in North American electric grid interconnections, even with the increasing investment in transmission systems during the past decade. In 2015, $20.1 billion was invested in various forms of transmission upgrades [1]; however, many ISOs still reported a considerable level of congestion cost in the same year. Fig. 1 shows the congestion cost for seven ISO/RTOs in the U.S., with a total cost of about $4.3 billion [2–8]. It should also be noted that transmission congestion is a leading cause of renewable energy curtailment [9].

In addition to transmission expansion, transmission congestions can also be mitigated by energy storages [10,11], electric vehicles (EV) integration [12–14], demand response[15], and power flow control technologies [16–20]. Variable-impedance series flexible ac transmission system (FACTS) offers effective power flow control; it is an important contributor to smart transmission systems [21], which ensures full utilization of the existing transmission network and supports more sustainable delivery of power.

Distributed FACTS (D-FACTS) is a light-weight version of FACTS, which has a lower cost than FACTS and can be conveniently reallocated. D-FACTS devices are built in a modular fashion and can be attached to the conductors or installed on transmission towers. In recent years, D-FACTS technologies have greatly advanced and Smart Wires, a commercial implementation of D-FACTS, has successfully completed many projects. There are mainly three types of D-FACTS, namely, distributed series static compensator (DSSC), distributed series reactor (DSR), and distributed series impedance (DSI). DSR and DSI can adjust the impedance of transmission lines, while DSSC functions similar to a phase shifter [22–25]. Unlike conventional FACTS which are installed in a centralized manner, usually a large number of D-FACTS modules need to be installed in a distributed manner to achieve a desired level of power flow control. The total cost of D-FACTS can be lower than conventional FACTS while maintaining the same or even better level of power flow control, however, the distributed characteristic of D-FACTS introduces a large number of binary variables in the D-FACTS planning problem, which makes it computationally challenging.

1.2. Literature review

A limited number of models have been proposed in the existing literature to allocate D-FACTS devices. These models have different levels of complexities and are designed for different purposes. Ref. [26] is the earliest work on D-FACTS allocation, which proposes a nonlinear DC-power-flow-based optimization model that can be used to optimally

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https://doi.org/10.1016/j.epsr.2018.11.017
Received 26 April 2018; Received in revised form 23 November 2018; Accepted 26 November 2018

Nomenclature

Indices

g	Generator
i	The number of D-FACTS installed per phase per a certain distance for a transmission line
k	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
$c_{g,seg}^{linear}$	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 ($)
C_{sh}^{D}	Cost a of single D-FACTS unit converted to an hourly figure ($/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 figure ($/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	A Large positive number
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_{base}	MVA base of the system
S^{D}	Spinning down reserve requirement g
S^{U}	Spinning up reserve requirement g
$u\frac{1}{u}$	Is unit distance per which D-FACTS are allocated for each line
X_{k}	The reactance of transmission line k
X_{k}^{max}	The maximum reactance of transmission line k if D-FACTS are installed on this line
X_{k}^{min}	The minimum reactance of transmission line k if D-FACTS are installed on this line
η_{C}	The maximum adjustment percentage of the line's reactance in the capacitive mode that a single D-FACTS module (1 device/phase/mile) can achieve
η_{L}	The maximum adjustment percentage of the line's reactance in the inductive mode that a single D-FACTS module (1 device/phase/mile) 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

Acronyms

AC	Alternating current
DC	Direct current
DCOPF	Direct current optimal power flow
D-FACTS	Distributed flexible AC transmission system
DSI	Distributed series impedance
DSR	Distributed series reactor
DSSC	Distributed series static compensator
EV	Electric vehicle
FACTS	Flexible AC transmission system
ISO	Independent system operator
MILP	Mixed-integer linear program
PSO	Particle swarm optimization
RTO	Regional transmission organization
RTS	Reliability test system
TCSC	Thyristor controlled series compensator
U.S.	United States

allocate D-FACTS devices. In Ref. [26], D-FACTS locations are optimized similar to conventional FACTS, where the reactance adjustment range for transmission lines are pre-determined and cannot be adjusted. However, a key advantage of modular D-FACTS devices is their ability to offer a great deal of flexibility in the reactance adjustment range. In Ref. [27], a D-FACTS optimal allocation model based on particle swarm optimization (PSO) is proposed. The model can be used to reduce the loading of overloaded lines with D-FACTS devices. In terms of complexity, the model proposed in Ref. [27] does not consider the change in generation and load, or any type of uncertainties caused by renewable generation. Ref. [28] proposes a D-FACTS allocation method based on the graph theory, with the objective of minimizing losses. The model is designed to optimally allocate specific types of D-FACTS devices, which provide voltage support. The model cannot be used for D-FACTS devices which offer active power flow control. An optimal allocation algorithm for DSSC, based on DC optimal power flow (DCOPF) is proposed in Ref. [29]; however, this model is not applicable to variable-impedance D-FACTS allocation, such as DSR and DSI. Modeling of DSR and DSI devices, which are cheaper and have a better market prospect than DSSC, is more complicated. Their ability to adjust the impedance of transmission lines can be modeled through a variable impedance, which introduces nonlinearities in DCOPF. Currently, there is no well-developed model for planning variable-impedance D-FACTS as a power flow control technology in order to improve network transfer capability, mitigate transmission congestion, reduce generation dispatch cost, and ultimately make electricity more economical for electricity consumers. Moreover, the existing D-FACTS allocation methods come short in properly addressing the computational challenges of the problem, while considering the future uncertainties.

1.3. Contributions

This paper aims to fill this gap by proposing a linear, computationally efficient model for optimal allocation of variable-impedance D-FACTS, such as DSR and DSI, for the purpose of improving network transfer capability. The capabilities of the proposed model are compared with other existing D-FACTS allocation models in Table 1. The objective of the model is minimization of the operation cost over the lifetime of the D-FACTS devices. The model considers the uncertainties of power system operating conditions and allows for different levels of D-FACTS investment. To show the effectiveness of the model in terms of optimal D-FACTS allocation, simulations were carried out on a modified RTS-96 test system. The results show that substantial cost savings and reduced renewable energy curtailment can be achieved by optimally allocating D-FACTS in the system. In order to further confirm the superiority of D-FACTS in terms of power flow control, operation cost savings and reduced renewable energy curtailment resulted from D-FACTS were compared with those of conventional FACTS. The results show that, with the same level of investment, D-FACTS is able to produce larger savings than conventional FACTS. If D-FACTS is allowed to be redeployed, which is feasible according to Smart Wires [30], based on the change of load patterns, fuel prices, and renewable energy production, the savings become even larger. Thus, owing to its flexibility in reallocation, D-FACTS seems to be able to support a more robust power flow control plan for an uncertain future.

1.4. Organization of the paper

The rest of this paper is organized as follows. The D-FACTS optimization model is presented in Section 2. The simulation setup is described in Section 3. The economic benefit comparison of D-FACTS and conventional FACTS is presented in Section 4, and the impact of investment levels and transmission line reactance adjustment ranges on the savings resulted from D-FACTS is analyzed in Section 5. The optimal locations of D-FACTS and conventional FACTS are analyzed in Section 6. The computational complexity of the proposed D-FACTS allocation algorithm is discussed in Section 7. The effectiveness of the proposed algorithm and the advantages of D-FACTS over FACTS are verified through simulations under a large number of scenario realizations in two operation conditions in Section 8 and conclusions are drawn in Section 9.

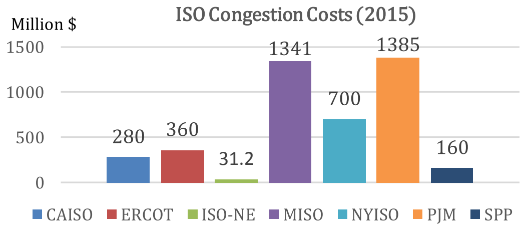

Fig. 1. Congestion cost reported by seven ISO/RTOs in 2015.

2. D-FACTS optimization model

2.1. Motivation

Previously, a FACTS optimization model has been proposed in Ref. [17]. The model optimally allocates a given number of FACTS devices with a pre-determined adjustment range, and only one FACTS device can be allocated to each transmission line at most. The model applies solely to conventional and centralized FACTS devices, because they usually have high compensation levels and are installed at substations, and at most one device can be used per line. However, the model cannot fully take advantage of the flexibility of D-FACTS devices, which are distributed and modular. Each D-FACTS has a low compensation level (usually 2–2.5% if one module is installed per phase per mile), and a large number of devices are needed on a line to reach a desired reactance adjustment range. The flexibility of D-FACTS lies in the fact that different number of D-FACTS can be allocated to different lines, resulting in a reactance adjustment range that is optimal for each transmission line without wasting any adjustment capability and investment. Thus, for a D-FACTS optimization model, the location, set point, and reactance adjustment range should be co-optimized. Moreover, the large number of D-FACTS modules that need to be optimized results in a large number of binary integer variables in the optimization problem, which can significantly add to the computational burden of the model. This issue needs to be properly handled, so that the computational complexity remains manageable. This study aims to tackle these challenges by proposing a computationally efficient D-FACTS optimization model, which fully captures the flexibility of D-FACTS devices. Consequently, with the proposed model, the power flow control capability of D-FACTS devices can be maximumly utilized to mitigate transmission congestion and improve the social welfare.

2.2. Formulation

The proposed D-FACTS allocation model is a DCOPF-based stochastic mixed-integer linear program (MILP). We use a linearized model of the power flows because of the following reasons: (1) DCOPF is widely adopted for energy and reserve market optimization in North American electricity markets [31–40]; (2) this work focuses on active power flow, and congestion management with respect to active power, which can be accurately represented by DC power flow equations; (3) DCOPF can be solved relatively quickly and provide accurate solutions for active power flows, while ACOPF requires at least one order of magnitude faster solvers than the existing solvers in the electric power industry [41]; (4) the pricing mechanism for a nonlinear market needs to be agreed upon by the stakeholder before ACOPF can be adopted. The model optimally allocates the quantity of D-FACTS devices per a given distance, such as 0.25, 0.5 or 1 mile, per phase, considering a number of scenarios with different levels of load and renewable generation. The quantity of D-FACTS modules allocated on each line is indicated by a vector of binary variables; if the element with an index i in a vector has the value of 1, it means i D-FACTS modules are allocated per the given distance per phase on this line. The set points of D-FACTS under different scenarios are optimized simultaneously with the allocation; D-FACTS devices, allocated on the same transmission line, share the same set point. With the communication and control system integrated with each D-FACTS unit, the set points of D-FACTS devices can

Table 1
Comparison of existing models and the proposed model.

References	Existing models	The proposed model
[26]	Optimally allocates variable-impedance D-FACTS with pre-determined transmission line reactance adjustment range; no uncertainty is considered.	Optimally allocates variable-impedance D-FACTS and optimizes the transmission line reactance adjustment range, while considering uncertainties.
[27]	D-FACTS are used to reduce transmission line overloading; no uncertainty is considered.	D-FACTS are used to increase transmission network transfer capability so that generation dispatch cost can be reduced, while considering uncertainties.
[28]	The model is designed for optimally allocating FACTS devices that provide voltage support, and cannot be used for devices offering active power flow control.	The model is design for optimally allocating D-FACTS devices that adjust the reactance of the transmission lines and provide active power flow control.
[29]	The model is designed for phase-shifter-type D-FACTS devices and cannot be used for variable-impedance D-FACTS.	The model is designed for variable-impedance D-FACTS devices.

be adjusted depending on the scenario to achieve an optimal power flow.

In this model, since the reactances of the lines need to be adjusted, applicable DC power flow constraints depend on the directions of power flows [17]:

$$\text{If}\quad \theta_{fr,k,s}-\theta_{to,k,s}\geq 0,\ (\theta_{fr,k,s}-\theta_{to,k,s})/X_k^{max}\leq F_{k,s}\leq(\theta_{fr,k,s}-\theta_{to,k,s})/X_k^{min} \tag{1}$$

$$\text{If}\quad \theta_{fr,k,s}-\theta_{to,k,s}\leq 0,\ (\theta_{fr,k,s}-\theta_{to,k,s})/X_k^{min}\leq F_{k,s}\leq(\theta_{fr,k,s}-\theta_{to,k,s})/X_k^{max} \tag{2}$$

The directions of power flows can be modeled with binary integer variables in the optimization problem; however, these binary integers will significantly increase the computational burden and make the problem computationally intractable. In order to improve computational efficiency, first, a base-case optimization considering all the scenarios with no D-FACTS, is solved. Then, the power flow direction on each transmission line under each scenario, $f_{k,s}$, is obtained from the results and used in the next step of the allocation problem. Although optimality is not guaranteed with this method, extensive analysis shows that it almost always finds the optimal solution [17].

$$min\left(\sum_{s=1}^{N_S} p_s\left(\sum_{g=1}^{N_g}\left(\sum_{seg=1}^{N_{seg}} c_{g,seg}^{linear}P_{g,s}^{seg}+c_g^U R_{g,s}^U+c_g^D R_{g,s}^D+c_g^{NL}\right)+\sum_{r}^{N_r} c_r P_{r,s}^C\right)\right) \tag{3}$$

$$P_{g,s}=\sum_{seg=1}^{N_{seg}} P_{g,s}^{seg} \tag{4}$$

$$P_g^{min}\leq P_{g,s}\leq P_g^{max} \tag{5}$$

$$-F_k^{max}\leq F_{k,s}\leq F_k^{max} \tag{6}$$

$$(\theta_{fr,k,s}-\theta_{to,k,s})/X_k=F_{k,s} \tag{7}$$

$$\sum_{k\in\sigma^+(n)} F_{k,s}-\sum_{k\in\sigma^-(n)} F_{k,s}+\sum_{g\in g(n)} P_{g,s}+\sum_{r\in r(n)} (P_{r,s}-P_{r,s}^C)=L_{n,s} \tag{8}$$

$$\sum_{g=1}^{N_g} R_{g,s}^U\geq S^U \tag{9}$$

$$\sum_{g=1}^{N_g} R_{g,s}^D\geq S^D \tag{10}$$

$$R_{g,s}^U\leq P_g^{max}-P_{g,s} \tag{11}$$

$$R_{g,s}^D\leq P_{g,s}-P_g^{min} \tag{12}$$

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

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

$$\Delta\theta_k^{min}\leq\theta_{fr,k,s}-\theta_{to,k,s}\leq\Delta\theta_k^{max} \tag{15}$$

$$\theta_{1,s}=0 \tag{16}$$

The formulation for the first step is described with Eqs. (3)–(16). The objective of this problem, as shown in Eq. (3), is to minimize the total operation cost, including generation dispatch cost, spinning reserve cost, no load cost and renewable energy curtailment cost, considering all the scenarios and their probabilities. Eqs. (4) and (5) are the generation constraints; Eq. (6) is the transmission capacity constraint. The capacity of short lines (0–50 miles) is set to their thermal limit; for medium lines (50–156 miles), the capacity is determined by the voltage drop limit; for the case of long lines (more than 156 miles), the capacity is limited by the angular stability limit [42]. Eq. (7) is the DC power flow equation; Eq. (8) is the nodal power balance constraint; Eqs. (9)–(14) are the spinning reserve constraints; Eqs. (15) and (16) are the bus voltage angle constraints.

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 the second step, a 2-dimensional binary integer, $x_{k,i}^D$, is introduced to indicate the number of D-FACTS allocated to each line. The index i indicates the number of D-FACTS modules that are allocated on line k; the maximum number of D-FACTS that can be allowed on each line, i_{max}, should be predetermined. When $x_{k,i}^D=1$, there will be i D-FACTS devices allocated to 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, no D-FACTS is allocated to line k. The binary integers and adjustment of reactances introduce nonlinearities to the DCOPF-based problem; the nonlinear formulation of DC power flow constraints in the problem is shown in Eqs. (17)–(23). In these equations, $(1+i\eta_L)X_k$ and $(1-i\eta_C)X_k$ are equivalent to X_k^{max} and X_k^{min}, respectively. Eqs. (17) and (18) apply when i D-FACTS are installed on a line and the power flow direction is positive; Eqs. (19) and (20) apply when i D-FACTS are installed on a line and the power flow direction is negative; Eqs. (21) and (22) apply when no D-FACTS is installed on the line. Eq. (23) ensures that at most one $x_{k,i}^D$ is equal to 1 for each line. In these constraints, i is a known integer constant, which varies from 1 to i_{max}. $f_{k,s}$ is a binary integer constant and its values is obtained in the first step, as described above.

$$x_{k,i}^D f_{k,s}(1+i\eta_L)X_k F_{k,s}\geq x_{k,i}^D f_{k,s}(\theta_{fr,k,s}-\theta_{to,k,s}) \tag{17}$$

$$x_{k,i}^D f_{k,s}(1-i\eta_C)X_k F_{k,s}\leq x_{k,i}^D f_{k,s}(\theta_{fr,k,s}-\theta_{to,k,s}) \tag{18}$$

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

$$x_{k,i}^D(1-f_{k,s})(1-i\eta_C)X_k F_{k,s}\geq x_{k,i}^D(1-f_{k,s})(\theta_{fr,k,s}-\theta_{to,k,s}) \tag{20}$$

$$\left(1-\sum_{i=1}^{i_{max}} x_{k,i}^D\right)X_k F_{k,s}\geq\left(1-\sum_{i=1}^{i_{max}} x_{k,i}^D\right)(\theta_{fr,k,s}-\theta_{to,k,s}) \tag{21}$$

$$\left(1-\sum_{i=1}^{i_{max}} x_{k,i}^D\right)X_k F_{k,s}\leq\left(1-\sum_{i=1}^{i_{max}} x_{k,i}^D\right)(\theta_{fr,k,s}-\theta_{to,k,s}) \tag{22}$$

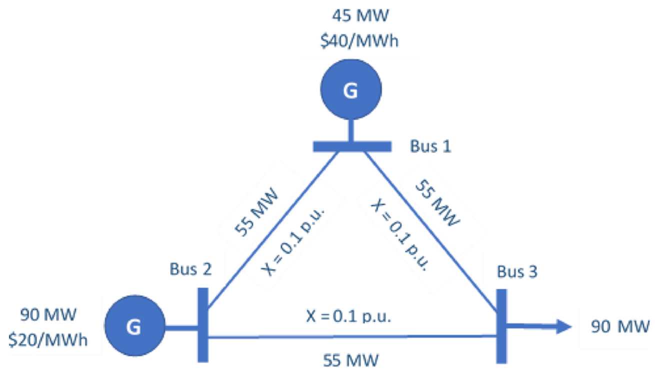

Fig. 2. The congested 3-bus test system.

$$\sum_{i=1}^{i_{max}} x_{k,i}^{D} \le 1 \tag{23}$$

In this study, the nonlinearities caused by the multiplication of variables $x_{k,i}^{D}$ and $F_{k,s}$ are linearized using the big-M technique to improve computational efficiency. Eqs. (24)–(29) are the linearized DC power flow constraints, corresponding to Eqs. (17)–(22), respectively. In these equations, M is a very large positive number; it has to be larger than the absolute value of the voltage angle differences between the two ends of all transmission lines in the system.

$$(1 + i\eta_{L})X_{k}F_{k,s} + (1 - x_{k,i}^{D})M + (1 - f_{k,s})M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{24}$$

$$(1 - i\eta_{C})X_{k}F_{k,s} - (1 - x_{k,i}^{D})M - (1 - f_{k,s})M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{25}$$

$$(1 + i\eta_{L})X_{k}F_{k,s} - (1 - x_{k,i}^{D})M - f_{k,s}M \le \theta_{fr,k,s} - \theta_{to,k,s} \tag{26}$$

$$(1 - i\eta_{C})X_{k}F_{k,s} + (1 - x_{k,i}^{D})M + f_{k,s}M \ge \theta_{fr,k,s} - \theta_{to,k,s} \tag{27}$$

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

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

In the D-FACTS allocation problem, the investment cost for D-FACTS is considered. Since this optimization problem is based on an hourly DCOPF problem, the cost for each D-FACTS unit is converted to an hourly figure [42–46], in order to facilitate analysis.

$$C_{sh}^{D} = C_{single}^{D}\frac{I(1 + I)^{N}}{8760((1 + I)^{N} - 1)} \tag{30}$$

The complete linear formulation for the second step, which optimally allocates D-FACTS considering D-FACTS investment cost, is presented in Eqs. (31)–(35). The objective not only considers the generation dispatch, but also D-FACTS investment costs. A number of constraints are the same as the base case, as shown in Eq. (32); Eq. (33) includes the DC power flow constraints considering the installation of D-FACTS presented above. In this model, D-FACTS devices are allocated per a certain distance per phase and the total investment of D-FACTS on a three-phase transmission line is expressed by Eq. (34). In Eq. (34), the scalar u is introduced to allow D-FACTS to be allocated per a distance of $1/u$ mile. For example, if $u = 4$, D-FACTS is allocated per 0.25 mile per phase. At last, Eq. (35) sets a limit for total D-FACTS investment.

$$min\left(\sum_{s=1}^{N_{S}} p_{s}\left(\sum_{g=1}^{N_{g}}\left(\sum_{seg=1}^{N_{seg}} c_{g,seg}^{linear}P_{g,s}^{seg} + c_{g}^{U}R_{g,s}^{U} + c_{g}^{D}R_{g,s}^{D} + c_{g}^{NL}\right) + \sum_{r=1}^{N_{r}} c_{r}P_{r,s}^{C}\right) + C_{inv}^{D}\right) \tag{31}$$

$$\{(4) - (6), (8) - (16)\} \tag{32}$$

$$\{(23) - (29)\} \tag{33}$$

$$C_{inv}^{D} = \sum_{k=1}^{N_{br}}\sum_{i=1}^{i_{max}} 3ul_{k}iC_{sh}^{D}x_{k,i}^{D} \tag{34}$$

$$C_{inv}^{D} \le C_{inv}^{max} \tag{35}$$

2.3. Analytical example

The objective of the proposed model is to optimally allocate D-FACTS devices in order to mitigate transmission congestion in a system, considering an investment limit. In order to demonstrate the goal and performance of the proposed method, the model is implemented on a congested 3-bus test system, shown in Fig. 2. In this test system, bus 1 has a 45-MW generator with the cost of $40/MW h. Bus 2 has a 90-MW generator with the cost of $20/MWh. Bus 3 has a load of 90 MW. There are three transmission line connecting the three buses, each of which with a capacity of 55 MW and a reactance of 0.1 p.u. The length of each line is assumed to be 1 mile.

In this test system, the generator at bus 2 has a capacity of 90 MW, and is cheaper than the generator at bus 1. If transmission constraints could be ignored, this generator would supply the entirety of the 90-MW load with a generation dispatch cost of $1800/h. However, such solution would result in a power flow of 60 MW on the line connecting buses 2 and 3, which exceeds the 55-MW capacity of the line. In order to avoid this flow violation, the more expensive generator at bus 1 has to be committed. Without violating any transmission constraint, the most economical solution is 75 MW generated by the generator at bus 2, and 15 MW generated by the generator at bus 1. The total dispatch cost for this case would be $2100/h, where transmission congestion causes a $300/h increase in generation dispatch cost.

D-FACTS devices, as a tool for active power flow control, can effectively mitigate transmission congestion and reduce generation dispatch cost, increasing the social welfare for the system. The D-FACTS modules can result in a ± 2.5% reactance adjustment range if 1 module is allocated per phase per mile. Using the proposed D-FACTS allocation algorithm, D-FACTS modules are allocated per phase per mile, and a maximum reactance adjustment range of ± 30% is allowed for each line. To eliminate the congestion on the line, connecting bus 2 to bus 3, while generating more power at bus 2, the reactance of this line should be increased. The results show that the best solution is to allocate 11 D-FACTS modules per phase per mile on the line connecting buses 2 and 3, resulting in a ± 27.5% reactance adjustment range. With D-FACTS modules allocated this way, the reactance of the line between buses 2 and 3 can be increased to 0.1273 p.u. Under this condition, the generator at bus 2 is able to supply the entire system demand of 90 MW, with 55 MW flowing directly from bus 2–3, and 35 MW flowing from bus 2 to bus 1 and then to bus 3. Note that the power flow on the two parallel paths (2 → 3 and 2 → 1 → 3) is inversely proportional to the reactance of the paths: $55/35 = 0.2/0.1273$. This reactance adjustment eliminates transmission congestion and reduces the generation dispatch cost to $1800/h.

Detailed simulation results on an RTS-96 test system are presented in Section 3.

3. Simulation setup

In this study, the model proposed in Section 2 is adopted to study the cost effectiveness of D-FACTS under increasing investment in power flow control devices. Uncertainties that are modeled include generator fuel price, retirement of old generators, and integration of renewable energy. Additionally, the cost effectiveness of variable-impedance series FACTS, i.e., TCSC, was obtained for the same test system and scenarios, using a modified version of the model proposed in Ref. [17]. Capital cost of FACTS and stochasticity was added to the model described in

Ref. [17] to make the results comparable with those of D-FACTS. The simulation test system was chosen and uncertainties were generated to provide a sound comparison of the economic benefits of FACTS and D-FACTS under future uncertainties. Furthermore, the configurations of FACTS and D-FACTS were chosen according to practical conditions.

3.1. Test system

A modified 24-bus RTS-96 test system was used in this study. Further modifications were made based on the system described in Ref. [47], including increasing the peak load at each bus by 5% and reducing the peak load at Bus 3 and 9–90 MW and 86.2 MW, respectively. The original load factors were mapped to a range of 0.55–1.0. Appropriate capacity limits were chosen for each line depending on its length. In the studied test system, 90% of the lines are short lines, and their thermal limits were used as their capacity. 10% of the lines are medium lines, for which voltage drop limits were used as the capacity, in order to ensure the voltage drops caused by active power losses do not cause stability issues.

3.2. Changes in fuel prices

The lifespan of a FACTS device can be 10–30 years; fuel prices can change drastically during this lifespan, affecting generation dispatch and transmission congestion patterns. During the past 10 years, the prices for both coal and oil showed some fluctuation, especially oil, whose highest price was almost 5 times as much as its lowest price [52,53]. The RTS-96 test system includes four types of generators: coal-fired, oil-fired, nuclear, and hydroelectric. In order to study the influence of fuel price changes on the cost performance of FACTS and D-FACTS, simulations were conducted with two sets of fuel prices. The first set adopts the original prices used in the test system; in the second set of fuel prices, the price of oil was reduced to 20% of its original value and the price of coal was increased by 33%.

3.3. Retirement of old generators and increased penetration of renewable energy

During the lifespan of FACTS/D-FACTS, the power system is very likely to go through retirement of old generators and increased penetration of renewable energy. The changes of power plant locations and the uncertainties, caused by renewable generation, influence congestions patterns in a network. The economic benefits of FACTS or D-FACTS can be influenced accordingly. This paper considers such changes in the analysis of FACTS/D-FACTS cost effectiveness. To do so, the 400 MW power plant at bus 21 was retired; at the same time, two 400 MW wind farms were added to bus 19 and 20, respectively. The wind speed data at the height of 100 m in Taylor County, Texas, in 2012, was used in this study [54]. 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 Ref. [55]. 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, as some system operators offer compensations for curtailed wind power.

3.4. D-FACTS and FACTS configurations

It is assumed in this study that each D-FACTS module is designed to be able to adjust the line's reactance by ± 2.5% per phase per mile [24], and the maximum reactance adjustment range for a three-phase transmission line using D-FACTS is ± 20% [56]. D-FACTS results in this paper were obtained when D-FACTS were allocated per 0.25 mile per phase. Conventional variable-impedance series FACTS devices with a reactance adjustment range of ± 20% were used for comparison.

The costs for D-FACTS and FACTS can be determined based on industry data and previous academic studies, involving FACTS/D-FACTS costs. According to Ref. [57], the cost for D-FACTS is $100/kVA; the D-FACTS compensation level in kVA depends on the parameters of the transmission line on which the D-FACTS device is installed. In order to make the D-FACTS module reusable for all the lines in the system, the compensation level that satisfies the most demanding line was adopted. For the RTS-96 system, the largest compensation level, needed to offer such a reactance adjustment range, is a 30kVA/module. Thus, a cost of $3000/module for D-FACTS was adopted in this study. The commonly used FACTS cost evaluation method, discussed in Refs. [47–51], was adopted to calculate FACTS costs in this study. Assuming a discount rate of 6% and a lifespan of 30 years for both FACTS and D-FACTS [58], investment cost for D-FACTS or FACTS can be converted into an hourly figure according to Eq. (30), and a maximum investment limit can be applied to the optimization model using Eq. (35).

4. Saving comparison of D-FACTS and FACTS

In order to evaluate the economic benefits of D-FACTS and compare with those of conventional FACTS, simulations were carried out under four conditions: (1) original fuel prices with no renewable energy added and no generator retired; (2) original fuel prices with two wind farms added and one generator retired as described in Section 3.3; (3) fuel prices changed as described in Section 3.2, no renewable energy added and no generator retired; (4) fuel prices changed, wind farms added and a generator retired as described in Sections 3.2 and 3.3, respectively. Under each condition, simulations were carried out under 7 different FACTS/D-FACTS investment limits, from $5/h to $35/h with an increment of $5/h.

Both FACTS and D-FACTS can reduce congestions in the network as well as the expected dispatch cost. The expected dispatch cost in each simulation case was obtained from the objective function of the FACTS or D-FACTS optimization model, and compared with that of the base case, in which a stochastic optimal power flow (OPF) was solved for the same test system under the same condition without using FACTS or D-FACTS. The savings in expected dispatch costs, resulting from employment of FACTS or D-FACTS, were calculated as a percentage of the base case dispatch cost, and presented in Fig. 3. It can be seen that the D-FACTS savings were higher than those of conventional FACTS in all simulation cases; in 15 out of 28 cases, the savings from D-FACTS were more than twice as much as those of FACTS. This can be expected from the cheaper cost of D-FACTS ($100/kVA) compared to that of conventional FACTS ($120–150/kVA), as well as the flexibility of installing different number of D-FACTS on different lines to better utilize the power flow control resources.

Under conditions (2) and (4), wind energy was integrated into the system, and the effects of FACTS and D-FACTS on wind curtailment were studied. Expected wind curtailment was calculated considering all scenarios in each condition, both in the base cases and cases with FACTS or D-FACTS. The reductions in wind curtailment, resulting from FACTS or D-FACTS, were calculated as a percentage of wind curtailment in the base cases, and are presented in Fig. 4. Since the objective of the optimization problems were to minimize dispatch costs rather than wind curtailment, employment of FACTS or D-FACTS does not reduce wind curtailment in all cases. However, it can be seen from Fig. 4 that wind curtailment was reduced in most cases when FACTS or D-FACTS were used, and D-FACTS reduced wind curtailment more than FACTS with the same limit on investment in most cases.

5. Sensitivity of benefits to the adjustment range

In Refs. [17] and [18], the savings resulting from conventional

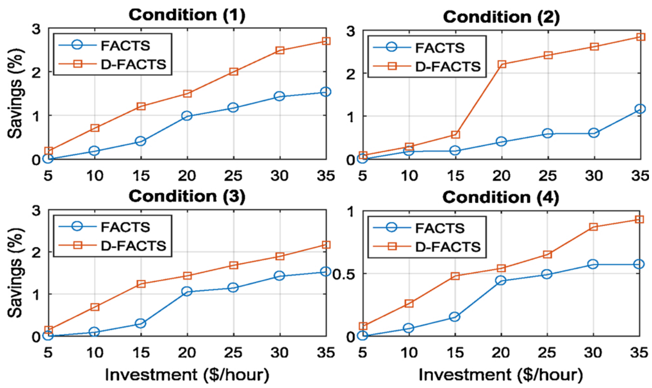

Fig. 3. Expected dispatch cost savings using FACTS or D-FACTS.

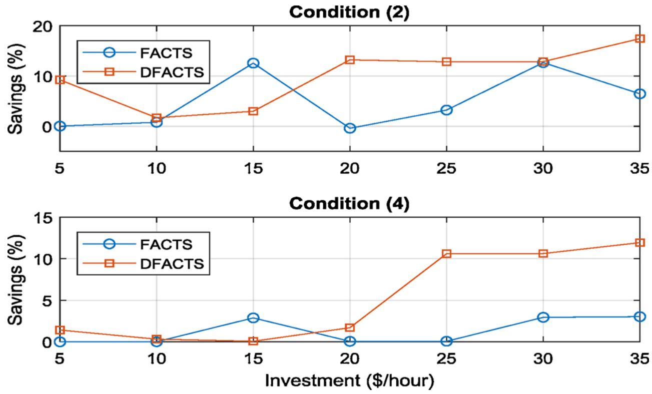

Fig. 4. Wind curtailment cost savings under different fuel prices.

FACTS with different reactance adjustment ranges were compared. Results showed that, for a given number of FACTS devices allocated in the system, with a larger adjustment range, larger savings in generation dispatch cost would be expected. However, in these two previous studies, the investment cost of FACTS was not included in the analysis. In a planning problem, there is a budget limit, and it is essential to consider this budget in search of a solution that brings the largest economic benefits.

In this section, the impact of reactance adjustment range on generation dispatch cost savings is studied in combination with the investment budget. As stated in Section 2.2, the investment has to be converted into an hourly figure and included in the objective function of the optimization problem. In this study, three investment levels are studied: $20/h, $35/h, and $50/h. At each investment level, five maximum reactance adjustment ranges are considered: ± 10%, ± 20%, ± 30%, ± 40%, ± 50%. D-FACTS optimal allocation solutions are found in the 15 cases under condition (1) described in Section 4, and the generation dispatch cost savings are presented in Fig. 5. The results show that, at a low investment level, such as $20/h, the generation dispatch cost savings are constrained by investment, and the increase of savings is not obvious with the increase in reactance adjustment range. With that exception, the savings generally increase with the increase of reactance adjustment range at the same investment level. However, increasing investment can result in a sharper increase in savings than increasing reactance adjustment range. This is due to the fact that increasing investment allows D-FACTS devices to be allocated on more lines, even though the adjustment range for each line is small. Thus, if the reactance adjustment range has to be confined within a certain level, increasing D-FACTS investment can significantly increase generation dispatch cost savings. However, with a given budget, it is reasonable to consider a larger reactance adjustment range as long as the system stability margins are respected to achieve better generation dispatch savings.

6. Optimal locations of FACTS and D-FACTS

Optimal locations of FACTS and D-FACTS under the four conditions with different limits on investments were obtained from the optimization results. The optimal locations of FACTS are shown in Table 2. Under each condition, it can be seen that, with the increase in investment, the optimal location of FACTS often changed to a completely different line rather than keeping the existing devices and adding additional FACTS to other lines. However, in practice, it is next to impossible to move FACTS to another location, and, thus, FACTS cannot be redeployed once it is installed. This may lead to suboptimal FACTS allocation and inefficient investment in cases when new FACTS are being planned in systems with existing FACTS devices. However, for D-FACTS, which can be conveniently redeployed, this issue can be resolved by moving the existing D-FACTS units to new optimal locations, in order to maximize the economic benefits.

The optimal locations of D-FACTS are shown in Tables 3 and 4, each covering two conditions. In the two tables, (a) refers to the lines on which D-FACTS were allocated, (b) refers to the number D-FACTS allocated per phase per 0.25 mile, and (c) refers to the total number of D-FACTS allocated on each line. It can be seen that, in many cases, additional D-FACTS were allocated on the same line or other lines while not moving the existing devices. This occurs, because with the flexibility in choosing the number of D-FACTS installed on each line, a small number of D-FACTS can be allocated inexpensively on lines that are effective in power flow control but require a large compensation level and high cost for a full-size conventional FACTS.

With changes in operation conditions, such as changes in fuel prices, retirement of old generators and integration of renewable generation, congestion patterns in the network change and the economic benefits of FACTS or D-FACTS that have already been installed in the system may be negatively affected. This is verified by the reduced savings of using FACTS and D-FACTS with fixed locations when the operation conditions change. In this study, condition (1) was taken as the initial condition, under which the optimal locations of FACTS and D-FACTS were obtained with an investment limit of $35/h Then, the solution was used under conditions (2)–(4), and the percentages of operation cost savings were obtained. The results are shown in Table 5; it can be seen that, with changes of operation conditions, the savings reduced in most cases when the locations of FACTS or D-FACTS were fixed as they were under the initial condition. For D-FACTS, it is possible to consider redeploying the modules to fully exploit their flexibility and achieve higher economic savings, but conventional FACTS do not offer this flexibility.

7. Computational complexity

The proposed model is an MILP and its solution time is significantly influenced by the number of binary integer variables. In the FACTS

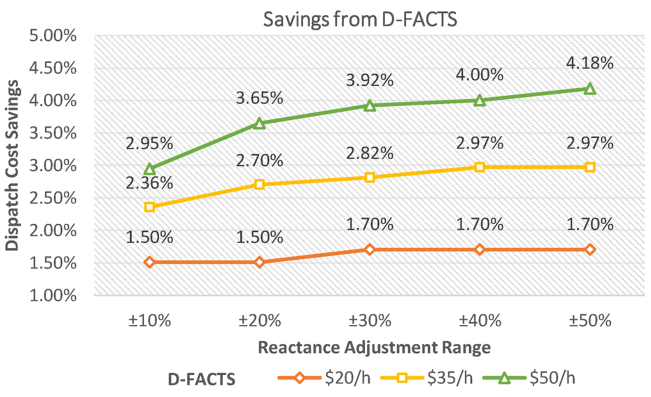

Fig. 5. Comparison of savings for D-FACTS devices with different line reactance adjustment ranges.

Table 2
Optimal locations for FACTS.

Investment ($/hour)	Condition (1)	Condition (2)	Condition (3)	Condition (4)
5	10	10	None	None
10	6	6	30	30
15	24	29	24	29
20	28	28	28	1,28
25	6,28	19	28,30	28,30
30	24,28	28,29	24,28	28,29
35	24,28,30	23	24,28,30	10,28,29

Table 3
Optimal locations for D-FACTS under original fuel prices.

Investment ($/hour)	Condition (1)			Condition (2)		
	(a)	(b)	(c)	(a)	(b)	(c)
5	24	1	144	29	1	192
10	24	1	144	19	1	348
	28	1	216			
15	24	1	144	23	1	492
	28	2	432			
20	22	1	720	22	1	720
25	22	1	720	22	1	720
	28	1	216	28	1	216
30	22	1	720	22	1	720
	28	2	432	28	2	432
35	22	1	720	22	1	720
	24	1	144	23	1	492
	28	2	432	29	1	192

Table 4
Optimal locations for D-FACTS under changed fuel prices.

Investment ($/hour)	Condition (3)			Condition (4)		
	(a)	(b)	(c)	(a)	(b)	(c)
5	24	1	144	29	1	192
10	24	1	144	1	1	36
	28	1	216	28	1	216
				30	1	120
15	24	1	144	28	2	432
	28	2	432	30	1	120
20	24	2	288	19	1	348
	28	2	432	28	2	432
25	24	1	144	22	1	720
	25	1	408	28	1	216
	28	2	432			
30	24	2	288	22	1	720
	26	1	408	28	2	432
	28	2	432			
35	24	1	144	22	1	720
	26	2	816	28	2	432
	28	2	432	29	1	192

Table 5
Savings comparison when FACTS/D-FACTS locations are fixed.

Dispatch cost savings (investment limit: $35/h)		Condition (2)	Condition (3)	Condition (4)
FACTS	Optimally allocated	1.16%	1.52%	0.57%
	Locations fixed	0.54%	1.52%	0.45%
D-FACTS	Optimally allocated	2.85%	2.17%	0.93%
	Locations fixed	2.66%	1.23%	0.83%

optimization model, the number of binary integer variables is the same as the number of candidate branches for FACTS installation in the system (N_{br}); in the D-FACTS optimization model, the number of binary integer variables is $8N_{br}/u$, given an adjustment range of ± 2.5%/phase/mile for each D-FACTS module, the total allowable reactance adjustment of ± 20% for each line, and allocation of D-FACTS per a distance of $1/u$ mile. In order to choose a reasonable value for u, we tested allocating D-FACTS per 0.25 mile and 0.5 mile, respectively. The expected operation cost obtained from the latter was slightly lower than that of the former, but the solution time was significantly longer. Thus, allocating D-FACTS per 0.25 mile offers a reasonable trade-off between cost performance and computational burden in this system.

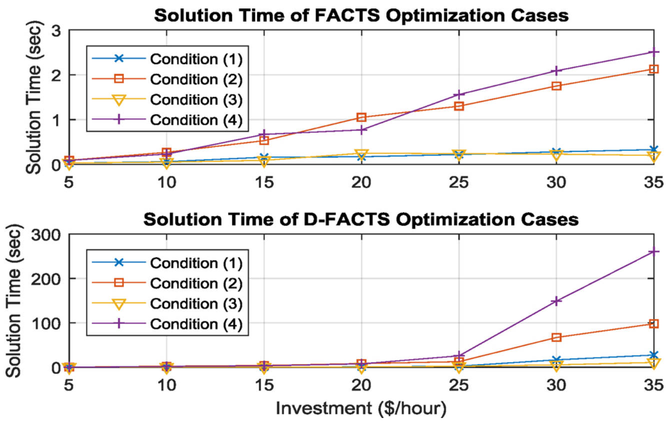

Fig. 6. Solution time for FACTS and D-FACTS optimization cases.

The solution time of optimizing FACTS and D-FACTS under different conditions with different investment constraints is shown in Fig. 6. It can be seen that the solution time varies depending on the underlying conditions and the investment allowed. FACTS optimization cases could be solved fast, within 3 s, when the investment does not exceed $35/h. For D-FACTS, below the investment of $25/h, all the cases could be solved within 1 min; hence, the algorithm is still relatively computationally efficient.

8. Verification of allocation effectiveness

In order to verify the effectiveness of the allocation algorithm and scenario selection method, simulations were carried out under 8760 scenario realizations for operation conditions (1) and (2), with optimal D-FACTS and FACTS locations obtained from the algorithm. For condition (1), 8760 load realizations were obtained from the load factors discussed in Section 3.1; for condition (2), 8760 wind power output realizations were obtained from the wind data discussed in Section 3.3 and combined with the 8760 load realizations on a one-to-one basis to create 8760 realizations with different levels of wind power output and power demand. Then, simulations for the base cases, cases with FACTS and cases with D-FACTS were carried out with each of the realizations under each operation condition. Afterward, average hourly dispatch costs under each condition for each type of cases were calculated from simulation results obtained under different scenario realizations. In cases that involved FACTS or D-FACTS, their optimal locations with an investment limit of $35/h, which were presented in Section 6, were used in the simulations. The averages of operation costs are compared with their expected values obtained from the objective function in Table 6; the values matched well as the errors were between −0.40% to 0.57%. This verifies the effectiveness of scenario selection in the stochastic optimization model.

The economic benefits of employing FACTS and D-FACTS under changing operation conditions can be further verified by these simulations. Since conventional FACTS usually cannot be redeployed, while D-FACTS can, simulations under each scenario realization were carried out under condition (1) and (2) with FACTS locations fixed as optimal locations for condition (1) and D-FACTS located at their optimal locations for each condition. Dispatch cost savings from FACTS and D-

Table 6

Comparison of the objective value and realization average cost.

Cost ($/h)	Condition (1)			Condition (2)		
	Expected	Realization average	Error	Expected	Realization average	Error
Base case	79501	79217	−0.36%	80327	80725	0.49%
With FACTS	78288	77979	−0.40%	79895	80335	0.55%
With D-FACTS	77353	77055	−0.39%	78034	78484	0.57%

Table 7

Annual cost comparison from verification simulations.

	FACTS		D-FACTS	
	Percentage of savings	Savings ($/year)	Percentage of savings	Savings ($/year)
Condition (1)	1.56%	1.08E + 07	2.73%	1.89E + 07
Condition (2)	0.48%	0.34E + 07	2.78%	1.96E + 07

FACTS under both conditions were obtained, and the actual dollars saved during the studied period were calculated. The results are shown in Table 7. It can be seen that, when the operation condition changes from (1) to (2), the advantage of D-FACTS becomes obvious; the annual savings obtained from FACTS were reduced by $7.4 million while those of D-FACTS were able to maintain a high level. With the change of operation conditions, the difference between annual savings achieved via FACTS and D-FACTS reached up to $16.2 million.

The differences between savings achieved from FACTS and D-FACTS are different depending on how the operation conditions change. In some cases, a change of operation condition does not significantly affect the economic benefits of FACTS or D-FACTS. However, in today's fast-changing grid, changes that affect their economic benefits are likely to occur and the flexibility offered by D-FACTS redeployment becomes an obvious advantage. The increase in savings, induced from D-FACTS redeployment, is also condition-dependent. Currently, there is no report on the cost of redeploying D-FACTS. However, the costs and benefits of redeployment cost should be compared, when redeployment is considered.

9. Conclusions

This paper developed a computationally efficient stochastic D-FACTS allocation model, which optimally assigns D-FACTS devices, per phase and per a certain distance, to transmission lines. It mitigates transmission congestion and reduces generation dispatch cost, resulting in a better social welfare in the electricity market. The model considers uncertainties caused by fluctuating load and renewable energy production in the system. The proposed algorithm was used to allocate D-FACTS with different investment limits under four different operation conditions. The optimal locations of D-FACTS and their effectiveness in power flow control were compared with those of conventional FACTS, and the computational complexity of the proposed optimization model was analyzed. The effectiveness of the proposed D-FACTS allocation algorithm and the economic advantages of D-FACTS over conventional FACTS were verified through simulations under a large number of scenario realizations in two operation conditions. Results show that D-FACTS yields larger savings than conventional FACTS in general, due to its flexibility and lower cost. Moreover, D-FACTS becomes especially more attractive when redeployment is required, due to the changing conditions of the grid.

Acknowledgement

This work was supported by NSF grant OAC-1756006. The support and resources from the Center for High Performance Computing at the University of Utah are also gratefully acknowledged.

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