Techno-Economic Contribution of FACTS Devices to the Operation of Power Systems With High Level of Wind Power Integration

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***Abstract*—The wind power integration in power networks impacts the operation of power systems economically and technically. The sites where wind power can be economically generated are determined by environmental conditions, so transmission congestion in the network may arise during certain periods. The issue of transmission congestion can become more acute if the network load is assumed to be rapidly growing at different sites during different times. This paper proposes novel, comprehensive methodology for realistic assessment of techno-economic merits of placement of thyristor-controlled series capacitors (TCSCs) and static VAr compensators (SVCs) in a transmission network to facilitate wind power integration. Economic considerations take into account the cost of generated active and reactive power, the cost of wind power integrationm and the cost of allocated FACTS devices for a range of operating conditions for several probabilistically modeled load growth profiles and over the lifetime of FACTS devices. The identification of congested areas and assessment of the financial benefits are carried out using optimal power flow-based algorithms. The placement of the TCSCs and SVCs is performed using novel genetic algorithms-based optimization with the net present value calculation integrated into the objective function.**

***Index Terms*—FACTS devices, genetic algorithms (GAs), Kalman filter, optimal power flow, spot prices, wind power.**

I. Introduction

THE capacity of the installed wind power is continually growing in today's power systems. An increasing number of countries around the world are taking significant steps towards accelerating integration of wind power. The current rate of growth in the installation of wind farms could lead wind power to account for half of the total power production capacity in some countries in the foreseeable future.

Though environmental benefits clearly arise from such large-scale wind integration, new technical challenges are created for transmission system operators. Maintaining a balance between demand and production in the grid is handled with relative ease while the level of wind power penetration is small. In such cases, the wind power is generally treated as a negative load, as it reduces the overall demand; thus, the impact on system operation is small. The approach to power system operation however, needs to be reevaluated when faced with large wind power penetration due to uncertainties associated with wind power generation (it cannot be scheduled with the same certainty as conventional power plants and it is not really dispatchable).

Large-scale wind power integration could negatively impact system stability. Some studies, such as [1] and [2], have shown reduction in damping under a high level of wind power penetration. In addition, locations of wind farms (WFs) are usually far from load centers as opposed to conventional power plants. This could easily lead to long-distance power transmission and line congestion which may significantly influence the generation profile and power flows and cause considerable impact on small disturbance stability.

The transmission-line congestion and the reduction in system damping can be alleviated by the use of FACTS devices (if present in the system). Past research conducted on conventional systems (without renewable energy sources) explored the benefits of installing FACTS devices for various purposes. The aims sought varied, sometimes improving system security, loadability, or transfer capability [3]–[6] while other times the focus was shifted to the economical aspects of installing FACTS devices [7]–[11]. When it comes to modern, and future, power systems where WFs are an integral part of the network, the number of studies devoted to the technical and economical aspects of installing FACTS devices drops dramatically.

This paper presents a long-term techno-economic study of allocating TCSCs and SVCs (jointly referred to as FACTS devices in this paper) in a system with high levels of wind power penetration. The load in the chosen network is assumed to be rapidly growing resulting in the load profile change every five years during the 20-year span. The uncertainties in wind power production combined with the changing load profile may cause the transmission line congestions—among others—to change from one profile to another and sometimes from one operating point to another within the same profile. This would cause problems on many levels; for one, the placement of TCSCs and SVCs to relieve the network congestion is difficult since the location of the congested lines keep changing as the network load grows over the years. On another level, tuning the FACTS devices to accommodate the uncertainties in wind power production in addition to the very large number of possible system operating points would prove to be challenging. Nonetheless, in the sections to follow, solutions are presented to the challenges faced

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and justifications for investment decisions are made in order to offer a comprehensive technical and economical view on the benefits of installing FACTS devices and integrating wind farms in a power system network.

The main contribution of this paper is in providing a comprehensive methodology for realistic assessment of techno-economic merits of deployment of FACTS devices to facilitate wind power integration in power networks. The methodology considers the management of load growth, congestion shifting in the network, and realistic wind power generation over the lifespan of FACTS devices. It optimally places FACTS devices in the network considering cost of generated active and reactive power of conventional generators, the cost of wind power integration, and the cost of allocated FACTS devices.

II. Investment Analysis

FACTS devices, though undoubtedly beneficial to system operation, are getting deployed at a reasonably slow pace due to their high capital and annual maintenance costs. Therefore, the final decision must be carefully drafted before committing to a purchase. There are multiple financial analysis tools which can be employed to help assess an investment decision. Payback Year (PBY), Net Present Value (NPV), Life Cycle Cost (LCC), and Internal Rate of Return (IRR) are some of the tools used in the financial analysis process [12]. NPV has been the most widely used method in the past and is chosen for the economic calculations in this study.

NPV is a powerful yet a robust financial analysis tool which can be defined as the initial investment value subtracted from the total present value of a time series of cash flows starting at the first year. Mathematically, NPV can be represented as

$$\mathrm{NPV} = \sum_{T=1}^{T} \frac{S_v - M_T}{(1+r)^T} - C_{\mathrm{inv}} \tag{1}$$

where S_v is the saving incurred over the year (in this case due to the installation of FACTS device), C_{inv} is the initial investment cost, M_T is the maintenance cost required each year during the lifetime T of the installed FACTS device, and r is the discount rate. [For more detailed assessment of investment decision, annual operation costs, variable maintenance costs, and disposal costs of the device at the end of the service life can be included in (1).]

In this study, the maintenance cost is assumed to be 5% of the FACTS device price, the discount rate is chosen to be 10%, and FACTS lifetime is set to be 20 years. These are some typical values used in similar studies in the past (e.g., [8], [12]).

III. Test Power System

The test network used in this study is the IEEE 57-Bus Test System. The network consists of 57 buses, seven generators, and 17 transformers. The generators are located at buses 1, 2, 3, 6, 8, 9, and 12. The system description can be found in [13] while the data used for the analysis is included in MATPOWER, which can be downloaded from [14]. The synchronous generators were modeled using the sixth-order model [15]. Each generator is equipped with an automatic voltage regulator (AVR) and a power system stabilizer (PSS).

The integrated WFs consisted of variable speed wind turbines with doubly fed induction generators (DFIGs) and back-to-back voltage source converters. DFIGs, rotor speed control, pitch angle control, and voltage control are modeled as described in [16].

A. WF Integration

Two WFs were introduced to the system and connected at buses 17 and 31. The total size of the integrated WFs is 50% of the total capacity of the system. The WF connected at bus 31 accounts for 20% of the total capacity of the system and the WF connected at bus 31 accounts for 30% of the total capacity of the system. Each WF site has a different wind speed data during the proposed lifetime. Since the power generation of the WFs depends on wind speed, the wind speed could become an essential parameter in a long-term economic study aimed at assessing the benefits of wind integration. To account for this dependency, two measures were taken into account *during the financial analysis* in this study. First, it was assumed that the WFs are operating at their capacity factor (CF). This means that the power generation of each WF during the year depends on its CF (two CFs annually since each of the two sites has its own wind data) which is more realistic than assuming optimal wind speeds at all times. The second measure limits variability in power production at each considered operating point. The maximum power production at each WF site is set at the respective CF value and it can only decrease depending on the site's wind data. The decision to decrease the output at any particular operating point is done systematically. The hourly wind data for both WF sites is available throughout the twenty year span. For an operating point, e.g., which has an uptime of 876h during the year, the average of a randomly chosen 876 hourly-power outputs from the available 20-year data (each from its own respective site), is compared to its respective CF value. The value of this "random average" if less than the CF value would replace it; otherwise the "random average" is discarded.

By following this approach the financial analysis becomes more realistic since it avoids the use of optimal WF power production during the 20-year period. Furthermore, it highlights the potential benefits of WF integration even when it operates below the average of the actual capability.

In order to assure better overall system stability, the Generator Ranking Index (GRI) [16] was initially utilized to identify the most influential generators in the system and subsequently de-load them to facilitate integration of the WFs. The GRI aids in the decision making regarding retiring or de-loading of conventional generators to make way for renewable energy sources.

B. System Load

The load growth in the network is assumed to be rapid and that substantial change occurs every five years. Three systematic steps were employed in the determination of the location and the amount of load growth. First was the identification of all viable locations for the growth to occur. The second step combines the locations into four groups which will be known, collectively, as a "family" while each individual group will be called a "location set." The last step determines the loading level (loading factor "LF") of each "family." Multiple location combinations

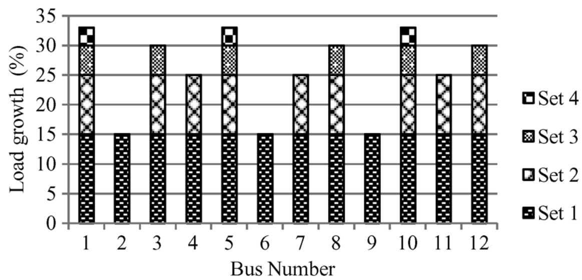

Fig. 1. Load growth concept.

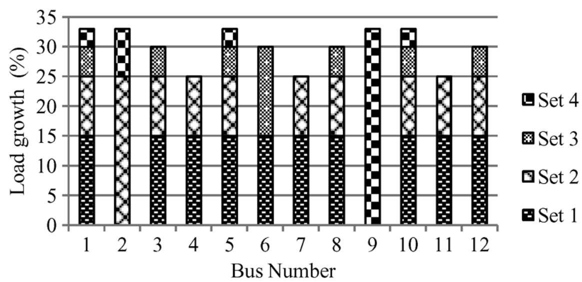

Fig. 2. Actual load growth concept.

and loading levels were assessed; ultimately choosing the family of the location sets which reflected the most significant congestion shifting and location diversity. Under the assumed life span of 20 years, four load growth instances are expected, each of which is assigned a location set from the chosen family.

To further simplify this notion, consider a hypothetical power system with loads located in buses 1–12. The load growth could be sliced in any which way; nonetheless, following the systematic steps outlined above, assume the best outcome is presented in Fig. 1. Location set 1, in this example, is a super set comprising all of the load buses. Location set 2, on the other hand, is composed of buses 1, 3, 4, 5, 7, 8, 10, 11, and 12; location sets 3 and 4 can be found from the figure by matching patterns to bus numbers. Now, suppose sets 1–4 are assigned respectively to each subsequent quinquennium.

During the first quinquennium—based on the figure—the demand increases 15% across all buses (location set 1). In the second quinquennium, location set 2 experiences 10% load growth, taking the previous quinquennium as the starting point. Similarly, the last two quinquenniums incur 5% and 3% demand growth, respectively, using the preceding quinquennium as the base.

However, location set 1 does not necessarily have to encompass the entire "loadable set" and demand growth is not conditioned to always lean on the immediately preceding quinquennium (i.e., load growth could skip one, two, or three quinquenniums). This type of location selection freedom adds to the complexity of the problem, increases the combinatorial sets, as well as mimics "real life cases". The illustration of the concept is presented in Fig. 2.

To put this complexity into perspective, the 12-bus system has a total of 4095 $\left(\sum_{n=1}^{12} C_k^{12}\right)$ possible load growth scenarios from which each quinquennium has a pick (this excludes the universal no growth state as is apparent from starting value of k in the summation). Therefore, four quinquenniums have a total of over 11 trillion possible combinations $\binom{4095}{4}$. Each one of those "over 11 trillion combinations" constitutes a "family." Unfortunately, the four location sets in each family must be permutated in order to find the best loading levels which maximize the utilization of the available generation capacity. This leads to an additional 24 permutations per available family. This step is very important in deciding which location set (within a family) gets assigned which quinquennium; and it also goes into the very heart of achieving the desired congestion shifting.

It should be noted, though, that the power system physical limits, security measures, and the pursued aim should reduce drastically the total number of possible combinations.

IV. Modeling Of FACTS Devices

The Power Injection Model (PIM) [17], [18] of FACTS devices is employed in this paper for the steady-state analysis part. In this model, the FACTS device is described as an element that injects a certain amount of active and reactive power to a node, thus qualifying the FACTS device for a PQ element representation. The advantage of PIM lies in its nondestructive nature to the symmetrical characteristic of the admittance matrix which allows efficient and convenient integration of FACTS devices into existing power system analytical tools.

A. TCSC Model

A suitable TCSC model for the simulation of steady-state operation is a static reactance. The reactance x_{TCSC} is controllable and directly used in the power flow equations as a control variable. The real and reactive power injections due to a series capacitor (TCSC) are represented in this study by P^F and Q^F, respectively, and can be calculated at buses i and j by the following equations [19]:

$$P_i^F = V_i^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij}\cos(\delta_{ij}) + \Delta B_{ij}\sin(\delta_{ij})\right) \quad (2)$$

$$P_j^F = -V_j^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij}\cos(\delta_{ij}) - \Delta B_{ij}\sin(\delta_{ij})\right) \quad (3)$$

$$Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j \left(\Delta G_{ij}\sin(\delta_{ij}) - \Delta B_{ij}\cos(\delta_{ij})\right) \quad (4)$$

$$Q_j^F = -V_j^2 \Delta B_{ij} + V_i V_j \left(\Delta G_{ij}\sin(\delta_{ij}) + \Delta B_{ij}\cos(\delta_{ij})\right) \quad (5)$$

where

$$\Delta G_{ij} = \frac{x_{TCSC} r_{ij}(x_{TCSC} - 2x_{ij})}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + (x_{ij} - x_{TCSC})^2\right)} \quad (6)$$

$$\Delta B_{ij} = \frac{x_{TCSC}\left(r_{ij}^2 - x_{ij}^2 + x_{TCSC} - x_{ij}\right)}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + (x_{ij} - x_{TCSC})^2\right)} \quad (7)$$

and

- r_{ij} resistance of the line between buses i and j;
- x_{ij} reactance of the line between buses i and j;
- δ_{ij} voltage angle between buses i and j;
- V_i voltage at bus i;
- V_j voltage at bus j.

The maximum compensation allowed for the TCSC in this study is 80% of reactance of the uncompensated line at which the TCSC is located.

TABLE I
COST FUNCTION COEFFICIENTS

G_{Num}	Bus	C_0	C_1	C_2
1	1	0	20	0.0775795
2	2	0	40	0.01
3	3	0	20	0.25
4	6	0	40	0.01
5	8	0	20	0.0222222
6	9	0	40	0.01
7	12	0	20	0.0322581

B. SVC Modeling

Unlike a TCSC, the SVC is shunt device and its reactance is configured as a shunt. The SVC susceptance $(B_{\rm SVC})$ is controllable and directly used in the power flow equations as a control variable. At the connection bus, the SVC's reactive power $(Q^{\rm SVC})$ can be calculated as follows:

$$Q_i^{\rm SVC} = -V_i^2 B_{\rm SVC}. \tag{8}$$

The SVC, in this study, was permitted a maximum absorption of 80 MVAr in an inductive mode while its maximum generation is 80 MVAr in a capacitive mode.

V. COST FUNCTION OF GENERATORS AND FACTS DEVICES

The cost of real power output of a conventional generator (C_p) is represented by a second order polynomial function and given by

$$C_p = c_0 + c_1 P + c_2 P^2 \qquad (\$/{\rm h}) \tag{9}$$

where P is the generator's real power output in MW.

The adopted values for the coefficients (taken from MATPOWER toolbox) are detailed in the Table I, where the first column represent the generator number, the second column shows the bus at which the generator is connected, and the rest of the columns represent the coefficient values accordingly.

A power system may incur additional costs when integrating wind power. The cost is dependent on the wind power-generating capacity. For only small amounts of wind generation to meet the load, the variations in wind output can be absorbed by the system's existing buffer capacity. However, when a large part of the system's total generating capacity is constituted by wind, such as in this case, the system must incur additional costs to provide reliable backup for the wind turbines [20]. In this study, \$5.70 per megawatt-hour was established as the wind integration cost which is the same rate used by Bonneville Power Administration in 2009. It is apparent that \$5.70/h for every MW drawn from a WF is still cheaper than the cheapest conventional generator in the system, thus causing the system to consume all it can from the WFs which eliminates them from the power production minimization process. Though multiple methods can be applied to account for the backup cost, the one applied in this study is in line with the followed convention of the paper; a backup cost function [$B_c = 5.70 P_w$ (\$/h)] is created at each WF (where the real power drawn in MW is assigned P_w).

The cost function of reactive power delivered by a generator (C_Q) is given by

$$C_Q = m_0 + m_1 Q \qquad (\$/{\rm h}) \tag{10}$$

as provided in [21], where Q is the generator's reactive power output in MVAr, $m_0 = 0.1C_0$, and $m_1 = 0.01C_1$.

The FACTS devices cost function can be formulated to capture the operation and installation cost though other benefits bestowed on the network from such a device, be it enhancement of the network reliability, improvement of the system dynamics, blackout prevention enrichment, or decongestion of the transmittable power which are very complex to quantify economically and effectively in a single study [22].

In this study, $C_{\rm SVC}$ and $C_{\rm TCSC}$ represent the cost functions associated with SVC and TCSC, respectively, as given in [9]

$$C_{\rm SVC} = 0.0003S^2 - 0.3051S + 127.38 \quad (\$/{\rm kVAr}) \tag{11}$$
$$C_{\rm TCSC} = 0.0015S^2 - 0.713S + 153.75 \quad (\$/{\rm kVAr}). \tag{12}$$

S in the above equations represents the operating range of the FACTS devices in MVAr.

VI. OPF FORMULATION

OPF is a tool which has many uses: sometimes it is used to calculate generation dispatch and load schedules, while in other instances it prices energy (local marginal price or nodal price) that is, of course, in addition to other uses. OPF is based on the market supply and demand. In general, the objective is minimizing the generation cost (if the loads are inelastic) while satisfying the operational and security related constraints. Mathematically, it can be formulated as

$$\min \sum_{m}^{Ng} (C_{p_m} + C_{Q_m}) \tag{13}$$

subject to

- power balance equations (equality constraints)

$$P_j(\theta, V) - P_{gj} + P_{dj} = 0 \qquad j = 1, \ldots, N_b \tag{14}$$
$$Q_j(\theta, V) - Q_{gj} + Q_{dj} = 0 \qquad j = 1, \ldots, N_b \tag{15}$$

- operational constraint

$$P_{gj}^{\min} \le P_{gj} \le P_{gj}^{\max} \qquad j = 1, \ldots, N_g$$
$$Q_{gj}^{\min} \le Q_{gj} \le Q_{gj}^{max} \qquad j = 1, \ldots, N_g$$
$$\left|V_j^{\min}\right| \le |V_j| \le \left|V_j^{\max}\right| \qquad j = 1, \ldots, N_b$$
$$|S_j(\theta, V)| \le S_j^{\max} \qquad j = 1, \ldots, N_T$$

where

N_b	number of buses;
N_g	number of generator buses;
N_T	number of transmission lines;
P_d	real power demand;

P_g generator's real power output;
Q_g generator's reactive power output;
$S_j^{\max}$ thermal limit;
$G_{jm}+iB_{jm}$ jmth element of the Y-bus matrix

$$P_j(\theta,V) \quad \sum_m^{N_b}|V_j||V_m|(G_{jm}\cos\theta_{jm}+B_{jm}\sin\theta_{jm})$$
$$Q_j(\theta,V) \quad \sum_m^{N_b}|V_j||V_m|(G_{jm}\sin\theta_{jm}-B_{jm}\cos\theta_{jm}).$$

The Lagrange function (L) of the objective function presented in (13) including its constraints is formed as

$$\begin{aligned}L=&\sum_n^{N_g}(C_{p_m}+C_{Q_m})+\sum_{j=1}^{N_b}\lambda_{P_j}\left(P_j(\theta,V)-P_{gj}+P_{dj}\right)\\&+\sum_{j=1}^{N_b}\lambda_{Q_j}(Q_j(\theta,V)-Q_{gj}+Q_{dj})+\sum_{j=1}^{N_T}\mu_{L_j}\left(|S_j|-S_j^{max}\right)\\&+\sum_{j=1}^{N_g}\mu_{P_{gj}}^{max}\left(P_{gj}-P_{gj}^{max}\right)+\sum_{j=1}^{N_g}\mu_{P_{gj}}^{min}\left(P_{gj}^{min}-P_{gj}\right)\\&+\sum_{j=1}^{N_g}\mu_{Q_{gj}}^{max}\left(Q_{gj}-Q_{gj}^{max}\right)+\sum_{j=1}^{N_g}\mu_{Q_{gj}}^{min}\left(Q_{gj}^{min}-Q_{gj}\right)\\&+\sum_{j=1}^{N_b}\mu_{V_j}^{max}\left(V_j-V_j^{max}\right)+\sum_{j=1}^{N_b}\mu_{V_j}^{min}\left(V_j^{min}-V_j\right)\end{aligned}\quad(16)$$

where the Lagrange multipliers associated with the power balance equations are λ_P and λ_Q while μ_L, μ_{pg}, μ_{Q_g}, and μ_V are the Lagrange multipliers—regardless of the superscript designation—associated with the operational constraints, that is line flow limits, generator real and reactive power limits, and bus voltage limits, respectively. The OPF solution provides the dispatch results along with the value of each multiplier. The software package used in this study was developed by the authors; however, packages such as MATPOWER, MINOS, and PowerWorld (with the OPF add-ins) can be used to replicate the results (required modifications in OPF formulation for the system with FACTS devices are detailed in the Appendix.).

Each Lagrange multiplier holds a specific economic significance. This study focuses on λ_p since it provides the spot price, known also as the local marginal price (LMP) or nodal price. LMP decomposes into three components, namely a congestion component, a marginal energy component and a marginal loss component [23].

The examination of these components reveals that the spot price at each bus is location specific and varies due to the congestion and loss components since the marginal energy component is the same for all buses. Therefore, the power price at a bus would increase if it so happens that an injection, or for that matter an extraction, of power in the same location increases the total system loss. By the same token, an increase in the nodal price at a bus is bound to occur should an injection/extraction of power at that location increase the flow across the congested lines. It should also be noted that the prices of power at all buses will be affected when any limit becomes binding.

TABLE II
OPERATING CONDITIONS AND THEIR CUMULATIVE PERCENTAGES

Operating Condition	1	2	3	4	5	6	7	8	9	10	11
Annual [%]	1	9	20	30	40	50	60	70	80	90	100

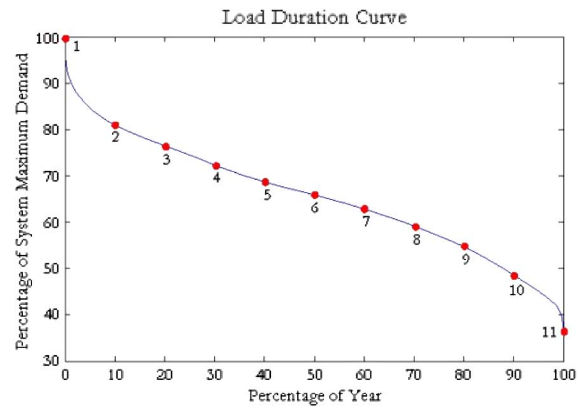

Fig. 3. Annual load duration curve with indicated operating points.

Combining the knowledge of the LMP dependence on the loss and congestion components along with the fact that a meshed system loss component is generally small raises the conclusion that the LMP difference between two buses provides direct information regarding the congestion level of that line. Even though it is tempting to pick the line with the highest LMP difference (most congested line) for the allocation of series FACTS devices, it is not always the best location [24].

VII. LOCATION IDENTIFICATION PROCEDURE

The system experiences load growth every quinquennium, which requires the load duration curve (LDC) to be updated accordingly, resulting in four LDCs during the twenty-year span. Eleven operating conditions were selected in each of the LDCs to reflect different loading conditions and ensure robustness of the solution. Thus, the total amount of forty four different operating conditions is considered in this study. In each LDC, the operating conditions will start at 100% of the system maximum demand coming down to the minimum one as shown in Table II and indicated in Fig. 3.

As aforementioned, it is not always best to allocate series FACTS devices to the highest congested lines (highest LMP difference). Therefore, a search in the close vicinity of those lines should capture a better alternative (if present) to where power can be diverted in case of FACTS device installation.

To find the best location pool where FACTS can be placed in the test system, the following steps are conducted.

1) For each operating condition run the OPF and calculate the LMP for all the buses.
2) Calculate the absolute value of the LMP difference for all the lines and arrange them in a descending order.
3) Record the ten highest LMP differences noting their line number.

(*Note*: Multiple tests that have been carried out revealed that the ten highest LMP differences cover excellently the congested

TABLE III
LINE NUMBERS WITH HIGHEST LMP DIFFERENCES

55	45	74	50	38	34	42
27	16	46	36	35	43	44

area and its surroundings in the test system. Using a higher number than 10 will add areas that are far from the affected region; thus defying the purpose of concentrating on the region of interest only. If for some reason, which had not been the case in the analysis conducted in this study but might arise in larger power systems, the ten highest LMP differences fail to identify regions of interest, the number of LMP differences taken under consideration can be easily increased without requiring any change in the proposed approach).

The resulting unrevised pool of locations should contain 440 lines which should include a lot of repeated line numbers. Filtering the repeats out, yields 14 unique lines (see Table III).

This final pool of line numbers (shown in Table III) covers the congestion area which will be encountered throughout the 20 years. Therefore, the line numbers become a congestion lookup table.

VIII. FACTS DEVICE ALLOCATION PROCEDURE

The placement of the chosen FACTS devices in the network is aimed at alleviating the congestion and maximizing the profit gained by the allocation. The use of OPF helps generate profit by reducing the generation cost (while at the same time obeying the limits imposed by the physical network, i.e., the thermal limits of the lines and the voltage limits of the buses) which introduces savings that will be compounded over the lifetime of the devices [24]. However, the allocation decision cannot be based solely on the "savings" achieved by the reduction in generation cost; simply because the initial investment cost, maintenance cost, and discount rate will reduce, and in some instances annihilate, the "savings" causing the return on investment to be very unattractive. Hence, the NPV was applied as the objective function since it incorporates all mentioned components in its assessment.

The allocation assignment was performed as follows.

1) A total of six FACTS devices, i.e., three TCSCs and three SVCs, are initially made available for placement.
2) GAs originally discussed in [25] are modified, i.e., made more computationally efficient, and applied for the optimal placement of the FACTS devices. Each device has two extra variables that need determination, rating and location. TCSCs are allowed a rating from -0.8 to 0.2 of the line reactance while SVCs allowed ratings were between -80 to 80 MVAr. The placement location is restricted to those of Table III.
3) Use the NPV as the objective function where profits (savings) are to be maximized over the lifetime of the devices. This was accomplished by apply the NPV as follows.
   Let

$$S_v = \sum_{i=1}^{OC} (C_i - \acute{C}_i) t_i \qquad \$ \tag{17}$$

TABLE IV
FACTS DEVICES ALLOCATION

Type	*Location*	*Compensation [%]*	*NPV[$M]*
TCSC	Bus 32 – Bus 34 Bus 24 – Bus 25	80.00 57.27	49.45

$$M_T = \begin{cases} 0, & T = 1 \\ k, & T > 1 \end{cases} \qquad \$ \tag{18}$$

$$F_T = \frac{S_v - M_T}{(1+r)^T}. \qquad \$ \tag{19}$$

Then

$$Obj = \max \left(\left(\sum_{T_1} F_{T_1} + \sum_{T_2} F_{T_2} + \sum_{T_3} F_{T_3} + \sum_{T_4} F_{T_4} \right) - C_{FACTS} \right) \tag{20}$$

where

S_v	savings over the year;
C_i	cost of active and reactive power before FACTS installation;
$\acute{C}_i$	cost of active and reactive power after FACTS installation;
C_{FACTS}	investment cost;
M_T	maintenance cost;
k	constant;
t_i	hours of operation during the year;
OC	operating condition;
T	life expectancy of FACTS devices.

The reason for splitting the summation is the load growth which occurs in discrete steps every five years forcing the S_v value to change. Thus, each of the summations represents a load profile segment in the 20-year span (each with its own unique F_T value).

IX. FINANCIAL ANALYSIS OF THE ALLOCATION

Following the outlined procedure yielded a placement of two FACTS devices—of the same type—which incurred maximum NPV at end of the 20-year span. The total savings achieved over those 20 years is $49.45 million. Table IV lists the location, type, and compensation of the allocated FACTS devices along with the system total savings during the life span.

The financial analysis can be extended to not only the overall outcome of the proposed investment (as in Table IV), but also to saving or losses incurred during each operating condition and the annual impact they exert during the respective quinquennium they fall within. Noting that a year has 8760 h and using Table II and Fig. 3, a summary of the loading factors of each selected operating point and corresponding annual operating hours is listed in Table V.

TABLE V
LOADING FACTORS

Operating Condition Number	*LDC₁*	*LDC₂*	*LDC₃*	*LDC₄*	*Yearly Operating Hours*
1	1.3436	1.8052	2.4254	3.2587	87.6
2	1.0893	1.4635	1.9663	2.6419	788.4
3	1.0281	1.3813	1.8559	2.4935	876.0
4	0.9724	1.3065	1.7554	2.3586	876.0
5	0.9237	1.2410	1.6674	2.2402	876.0
6	0.8852	1.1894	1.5980	2.1471	876.0
7	0.8442	1.1343	1.5239	2.0475	876.0
8	0.7947	1.0677	1.4346	1.9275	876.0
9	0.7345	0.9869	1.3260	1.7815	876.0
10	0.6524	0.8766	1.1778	1.5824	876.0
11	0.4837	0.6499	0.8731	1.1731	876.0

TABLE VI
SAVINGS PER LOADING FACTOR

Operating Condition Number	S'_{v1} *[\$/h]*	S'_{v2} *[\$/h]*	S'_{v3} *[\$/h]*	S'_{v4} *[\$/h]*	*Yearly Operating Hours*
1	671.94	1336.04	1397.57	1198.17	87.6
2	615.02	841.56	1353.45	1089.04	788.4
3	606.28	690.58	1341.57	1067.38	876.0
4	596.73	655.37	1330.55	1394.65	876.0
5	584.46	639.20	1320.66	1382.43	876.0
6	566.99	628.59	1312.75	1372.65	876.0
7	539.48	620.98	1304.16	1362.11	876.0
8	497.46	612.11	760.69	1349.28	876.0
9	446.14	599.59	663.58	1333.44	876.0
10	381.05	561.60	626.73	1310.95	876.0
11	263.21	379.10	559.43	626.10	876.0

TABLE VII
ANNUAL SAVINGS PER QUINQUENNIUM

	S_{v1}	S_{v2}	S_{v3}	S_{v4}
Annual Saving [\$M]	4.47	5.50	9.27	10.77

Each loading factor lasts a limited number of hours based on the LDC (see Table II). It can be easily seen that, except for the first and second loading factors, which last 1% and 9% of the time, respectively (i.e., 87.6 and 788.4 h), the rest operate with equal intervals of 876 h (i.e., 10% of the time). Now, if we let S'_v be the difference between the generation cost without TCSCs and with TCSCs installed, we can calculate the savings per hour per operating point as shown in Table VI.

A fast glance at Table VI affirms that the allocation did not exhibit any negative impact, financially speaking, on any of the operating points. One can also observe that the network maximum loading does not always couple itself with maximum profit. Even though the first three quinquenniums are to the contrary, the fourth has its maximum profit occurring at operating point 4. The phenomenon is related to how the load growth in the last quinquennium affects the congested area. If the added load diverts the power away from the congestion, it lowers the savings incurred.

The total annual savings in each quinquennium is found by multiplying each operating point's saving with its respective operating hours and then summing along each column [basically apply (17)]. Table VII shows the annual savings in millions of dollars and as expected they appear in ascending order. In each of the first five years, the acquired savings due to the installation of the TCSCs is \$4.47 M. This figure increases \$1.03 M during following five years (i.e., years 6 to 10) to constitute an annual savings of \$5.50 M. The years 11 to 15 see a yearly profit of \$9.27 M while the last five years of hypothetical lifetime of TCSCs provide the highest annual profits at \$10.77 M.

X. CONCLUSION

The paper presented a novel, comprehensive methodology for realistic assessment of techno-economic merits of deployment of FACTS devices to facilitate wind power integration in power networks.

The methodology is based on optimal placement of thyristor-controlled series capacitors and static VAr compensators in the network with significant wind power penetration based on their ability to alleviate transmission line congestion, their economical benefits, and life expectancy.

GA-based optimization is used to determine the type, ratings, and location of devices in the network for the purpose of maximizing the NPV of the investment. The deployment of the NPV as the objective function eased the inclusion of multiple, probabilistically modeled, loading profiles, each with its own loading factors, and a large number of operating conditions selected from the load duration curve.

The case study demonstrated that the optimally placed FACTS devices could significantly contribute both, economically and technically, to power systems with large penetration of wind generation. The economical aspect is seen through the reduction in generation cost of conventional generators in the system while the technical aspect is demonstrated through alleviation of congestion in the network and increase in power transfer.

Additional technical benefits from FACTS deployment observed in this study (though not discussed in the paper) include enhanced system stability and improved damping of system oscillations (after installation of suitable damping controllers).

APPENDIX

A. *Modifications in OPF Formulation for the System With FACTS Devices*

The OPF formulation experiences a slight modification in the presence of FACTS devices. To demonstrate this, assume that an SVC is located at bus i while a TCSC is located in the line between buses i and j. Then the power balance equations at nodes i and j will be

$$\begin{aligned} P_m(\theta,V)-P_{gm}+P_{dm}+P_m^F&=0, && m=i,j\\ Q_k(\theta,V)-Q_{gk}+Q_{dk}+Q_k^F+Q_k^{SVC}&=0, && k=i\\ Q_h(\theta,V)-Q_{gh}+Q_{dh}+Q_h^F&=0, && h=j \end{aligned}$$

while the following will be added to the operational constraints:

$$x_{\mathrm{TCSC}}^{\min}\le x_{\mathrm{TCSC}}\le x_{\mathrm{TCSC}}^{\max}$$
$$B_{\mathrm{SVC}}^{\min}\le B_{\mathrm{SVC}}\le B_{\mathrm{SVC}}^{\max}.$$

Lastly, the following terms gets added to the Lagrange function:

$$\mu_{B_{\mathrm{SVC}}}^{\max}\left(B_{\mathrm{SVC}}-B_{\mathrm{SVC}}^{\max}\right)+\mu_{B_{\mathrm{SVC}}}^{\min}\left(B_{\mathrm{SVC}}^{\min}-B_{\mathrm{SVC}}\right)$$
$$+\mu_{x_{\mathrm{TCSC}}}^{\max}\left(x_{\mathrm{TCSC}}-x_{\mathrm{TCSC}}^{\max}\right)+\mu_{x_{\mathrm{TCSC}}}^{\min}\left(x_{\mathrm{TCSC}}^{\min}-x_{\mathrm{TCSC}}\right).$$

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