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Influence of thyristor-controlled series capacitor on wheeling cost incorporating the impact of real and reactive power losses

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Abstract: Electric power transmission and transmission pricing are the key issues in the deregulated electric power industry. Factors like fast power demand growth, competition, service outage, and scarce natural resources make transmission systems operate close to their thermal limits. However, new transmission systems cannot be built in due to economic, environmental, and political reasons. For better utilization of existing power system capacities, the power electronic technology-based power system equipment called flexible alternating current transmission system (FACTS) devices like thyristor-controlled series compensators (TCSCs) can be effectively used for operating the transmission grid economically, rapidly, dynamically, and efficiently with increased flexibility and efficiency under different loading conditions. TCSCs, being costly devices, may adversely affect some deregulated power market participants. This paper proposes a unit commitment algorithm for the minimization of power losses and determination of optimal location for TCSC placement. The impact of the TCSC in conjunction with the application of the proposed algorithm on the generation cost and wheeling cost is analyzed using a power flow-based line-by-line rolled-in transmission pricing scheme. The comparison between the annual generation costs and annual wheeling costs with and without the TCSC is carried out under different load conditions in the IEEE 30-bus system. Results and simulations validate the economy of the suitable TCSC's optimal presence over its absence.

Key words: Deregulation, wheeling, power tracing, unit commitment, thyristor-controlled series compensator

1. Introduction

In the 1980s, there was a worldwide push of monopolistic utilities like railroads, airlines, telephone services, gas industries, and banks from a vertically integrated environment to open-market or deregulated or restructured systems. These rapid fluctuations in the trade environment around the world unbundled the vertically integrated electric power utilities services in order to change their way of operation and business during the 1990s. The reasons for this alteration in developing countries have been to support investments in improving generation and transmission capacities to meet the drastically increasing load demand as well as to maintain continuous supply at low cost. In developed countries, the chief objective has been to provide electricity at lower prices, offer consumers more choice in purchasing electricity, and provide better service by maintaining an improved and efficient system [1]. Power industry deregulation involves the reorganization of rules and cost-effective encouragements that federal and state rulings set up to manage the electric power industry. With deregulation,

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the vertically integrated electric utilities were segregated into three portions, namely the independent power producer of electricity, who owns plants to generate power and sell it on the open market; the transmission and distribution service provider, who provides the generated power to the electricity buyers and owns meters for billing purpose; and the retail electric provider, who buys power from the power producers and sells it to the end users. Entry of private power-generating companies in the deregulated power environment necessitates the usage of third-party-owned transmission and distribution networks for the delivery of generated power to customers [2]. The usage of transmission and/or distribution facilities of a system for power transfer from a seller to a buyer is called wheeling. Wheeling causes physical and economic effects on transmission networks. It affects the line losses, dispatch of generators, transmission line flow constraints, other power system security issues, and recovery of embedded capital costs. The wheeling company plays an important role in the evaluation of wheeling cost to be paid by the seller of electrical energy for each unit of consumption, for its service, for meeting extra losses, and for utilization of its assets and facilities. Usually based on a few factors like power plant capital cost and plant load factor, the seller and buyer agree on the rate of purchase of electrical energy.

Yang and Hug-Glanzmann [3] projected a double-stage regression-based control method to establish the optimal setting of a thyristor-controlled series compensator (TCSC) for the optimal utilization of the existing transmission network in the presence of renewable energy resources. Ziaee and Choobineh [4] proposed a novel decomposition method to determine the optimal location and size of TCSCs to reduce the congestion and generation cost in a power network. Sahraei-Ardakani and Blumsack [5] proposed a sensitivity-based technique to calculate the marginal market value to put forward efficient FACTS device impedance adjustments to provide the right financial incentives to the FACTS devices' owners to optimally operate their assets in competitive power markets. Mahapatra et al. [6] proposed an enhanced gravitational search algorithm to set the optimal location of the TCSC and a firefly algorithm to fix the cost and size of the TCSC to improve the voltage stability. Tiwari and Sood [7] proposed an investment cost recovery-based efficient and reliable optimization approach to fix the optimal location and rating of TCSCs in a double-auction power market to maximize social welfare and minimize device investment cost. Acharya and Mithulananthan [8] explored the influence of TCSCs on congestion and spot price at peak and low loading conditions in deregulated electricity markets. Shrestha and Wang [9] explored the effects of OPF on the operation of a spot price power market in the presence of a TCSC. Ghamgeen et al. [10] compared the performances of the differential evolution technique and a genetic algorithm to select the optimal location and optimal parameter setting of TCSCs to minimize the network active power loss. Besharat and Taher [11] proposed a method to determine the optimal location of TCSCs based on real power performance index to reduce the network reactive power loss to relieve the transmission corridors from congestion. From this literature review, it can be concluded that the optimal placement and/or optimal rating of TCSCs are/is considered in most of the articles for the best possible operation of the power system network present. The objective behind the optimal allocation of TCSCs is found to be either the power system's technical performance improvement like network loss reduction, transmission corridors' relief from congestion, voltage stability improvement, etc., or financial benefit for different power system owners like power producers through the shrinkage of generation cost, FACTS device owners through the reduction of device investment cost and device installation cost, etc. In this paper, the optimal placement of a suitable TCSC is proposed to verify the effectiveness of power system technical performance improvement and to benefit mostly the power producers by relieving them from both wheeling cost and generation cost simultaneously.

This paper proposes a modified power flow tracing methodology incorporating the computation of the contribution of each generating unit of the bus system towards the loads and line flows. The proposed method computes the wheeling cost under the condition of apparent power flow in the power system. The location and rating of the TCSC for minimization of different network losses for wheeling cost shrinkage and an optimal unit commitment algorithm for further reduction are proposed. A case study is conducted in the IEEE 30-bus system to demonstrate the efficacy of the proposed algorithm.

2. Transmission pricing schemes

In the regulated electric environment, wheeling dealings have charged for a minor percentage of total transmission system capability usage. The electric power industry restructuring focused on the electricity price in all power-market activities. In the transmission activity of the restructured electric power system operation, the pricing policy is such as to recover all or part of the transmission system costs like capital investment, running, and reinforcement costs and hence transmission pricing has been the objective behind every deregulated power market activity and the important phase involved is the determination of wheeling cost, which determines the economic feasibility to both the wheeling utility and wheeling customers. An effective transmission pricing mechanism ensures fairness, transparency, and predictability and also recovers the investments, meets operational and maintenance costs, and gains some profit. In addition, it encourages network users for efficient usage and network owners for investment, and it promotes nondiscriminatory behavior. No wheeling cost computation scheme suits all market structures and so each country or each streamlining model has preferred a unique scheme depending on its network characteristics. Except for a transmission pricing methodology based on a bidding process, all transmission pricing schemes are cost-based with the goal to allocate and/or assign all or part of the sum of different transmission costs to various wheeling customers on various bases [12].

Transmission pricing schemes are classified into incremental transmission pricing schemes of short-run type and long-run type, each capable of determining either incremental cost or marginal cost of transmission transaction, and embedded transmission pricing schemes comprising the postage stamp methodology, contract path methodology, boundary flow methodology, and line-by-line methodology of distance basis and power flow basis. The difference between transmission prices and transmission costs becomes very difficult and confusing particularly in the case of incremental transmission pricing methodologies. The importance of transmission cost illustrates how these are evaluated and translated to transmission prices.

The power flow-based line-by-line methodology is analyzed in this paper.

3. Power flow-based 'line-by-line' rolled-in transmission pricing scheme

In rolled-in transmission pricing schemes, the sum of the cost incurred for building the infrastructure and operational and maintenance costs along with future investment is distributed among various network users according to the degree of network usage.

The line-by-line method is the principal flow-based pricing scheme projected for full recovery of stable transmission expenses based on real handling of the transmission network. It calculates the wheeling cost connected with each wheeling transaction, taking into account the amount of transacted power as well as the distance travelled by the same, and allocates it in direct relation to the MW km of transactions where MW corresponds to either line rating or line loading [13]. Thus, it is an intuitively logical and conceptually impartial wheeling cost computation methodology. The simple and clear calculation of transmission charges by this approach raises the degree of transparency of transmission charges. Since this method assigns wheeling cost based on maximum usage of a transmission line by a transaction, it emulates the system reinforcement planning process based on local considerations rather than on the coincident peak condition for the overall system. As such, this method identifies the transmission paths for a power transaction and hence power flow calculations. Therefore, this method may overcome the limitations of the postage stamp approach and contract path approach.

Different types of MW km methodology include net difference-based, vector difference-based, and positive difference-based line-by-line methodologies. The positive difference-based methodology involving the absolute values of difference of base case power flows and transaction case power flows under the condition of transaction case power flow greater in magnitude than base case power flow is considered in this paper to determine the wheeling cost.

The power flow-based line-by-line rolled-in transmission pricing scheme maintains no priority order in the case of multiple wheeling transactions, provides correct economic signals irrespective of entities' distance involved in the wheeling process, emulates the actual system operating conditions, and encourages the economic usage of the transmission network capacity by giving a higher cost signal to transactions with several delivery points. However, this methodology recovers transmission network embedded capital costs partially, but fails to signal the future investment cost.

4. Bialek's power flow tracing methodology

Either a single entity or multiple entities could do wheeling. The latter case leads to the need for power flow tracing techniques, which, by notional decomposition of line flows and losses, provide information regarding the transmission network usage share by various generating units for either a specific load or a certain line flow to fix the wheeling cost in order to recover fixed transmission costs, decomposition of power flows on a line into its constituent generators and loads, loss energy delivered by generators, and line losses due to different loads [14]. The prerequisite for tracing of power flow is an effective power flow solution. Assuming nodal inflows are shared proportionately among nodal outflows, Bialek's power flow tracing methodology determines each generating unit's contribution depending on the estimation of topological distribution factors. It considers the inward and outward flows in each line and generation with the load at each bus. This sharing attitude is concentrated on Kirchhoff's current law and is topological in nature. The topological distribution factors are positive and hence cancel the counter-flow issue. Bialek's technique practices either an upstream-looking algorithm to allocate wheeling charge to individual generating units and losses to loads or downstream-looking algorithm to allocate wheeling charge to distinct loads and losses to generating units. Bialek's technique involving the determination of generator-wise contribution towards each load and each line flow is as follows.

For a transmission network with 'm' branches and 'n' nodes, 'B' represents an $(m \times n)$-sized incidence matrix with each element value equal to unity during active power flow from 'm' bus to 'n' bus, negative unity during active power flow from 'n' bus to 'm' bus, and zero during no active power flow between 'm' and 'n' buses. Defining 'F' as an $(m \times 1)$-sized vector of branch active power flows and representing 'B_d' and 'B_u' as two $(m \times n)$-sized matrices, both derived from 'B', with 'B_d' and 'B_u' consisting of 1s and −1s respectively, with the value of other elements in both matrices equal to zero, Eq. (1) can be used to set an $(n \times n)$-sized matrix with its (i, j) element representing active power flow from bus i to bus j.

$$F_d = -B_d^T.\mathrm{diag}\,(F)\,B_u \tag{1}$$

Defining I and P as $(n \times 1)$-sized vectors of nodal active power flows and ones respectively, Eq. (2) can be used to hold an $(n \times n)$-sized nonsingular matrix.

$$A_u = I + B_u^T.\mathrm{diag}\,(F)\,B_d.\mathrm{diag}(P^{-1}) \tag{2}$$

Defining P_G and P_D as (n × 1)-sized vectors of nodal active power generations and nodal active power demands, respectively, Eq. (3) can be used to fix the kth generating unit's contribution of real power to the ith bus's real power load and Eq. (4) to fix the same unit's contribution to the jth line's real line power flow.

$$P_{G_{ki}} = \frac{P_{D_i}.P_{G_k}.[A_u^{-1}]_{ik}}{P_i} \tag{3}$$

$$P_{G_{kj}} = \frac{F_{D_j}.P_{G_k}.[A_u^{-1}]_{ik}}{P_i} \tag{4}$$

This scheme can handle either DC or AC power flows and hence can be practiced even to fix the generating units' contributions of reactive power demands and reactive line power flows using Eqs. (5) and (6).

$$Q_{G_{ki}} = \frac{Q_{D_i}.Q_{G_k}.[A_u^{-1}]_{ik}}{Q_i} \tag{5}$$

$$Q_{G_{kj}} = \frac{F_{D_j}.Q_{G_k}.[A_u^{-1}]_{ik}}{Q_i} \tag{6}$$

A long transmission line has more weightage than a shorter one during the transmission of the same amount of power, but transmission lines with different materials, thermal ratings, and costs will have different weightages for the same length. Moreover, the cost of FACTS devices facilitated for power flow control in modern power systems cannot be easily retained by considering the lengths of transmission facilities alone. Inclusion of approximations in such cases leads to sacrifice of the accuracy of power flow-based line-by-line methodology. This can be avoided by multiplying the MW flow in each line by its length and a predetermined weighting factor reflecting the average revenue requirement per unit capacity per hour of each line for each transaction. The sum of products pertaining to all network lines leads to Eq. (7).

$$(MW.km)_g = \sum_l (P_{g,l}.L_l.W_l) \tag{7}$$

Here g = generator no., l = transmission facility no., $P_{g,l}$ = real power flow in transmission facility l due to generator g in MW, L_l = length of transmission facility l in km, and W_l = weighting factor of transmission facility l in rupees per hour.

The above process is repeated for every wheeling transaction by considering the power generation and power demand associated with that transaction.

Since wheeling cost determination by the line-by-line methodology takes into account the actual loading conditions of the transmission network, both active and reactive power loadings of the network during a transaction are considered in applying this methodology in this paper and the embedded cost of transmission is allocated accordingly. This transforms Eq. (7) to Eq. (8) as follows:

$$(MVA.km)_g = \sum_l (S_{g,l}.L_l.W_l) \tag{8}$$

Here, $S_{g,l}$ = apparent power flow in transmission line l due to generator g in MVA.

Eq. (8) is adopted to determine the wheeling cost of multiple utility wheeling transactions, assuming all generating units are privately owned and W_l = 1.

Figure 1 shows the flow chart for the MVA km scheme for wheeling cost determination. It necessitates the power flow solution of the bus system, then the determination of the contribution of each generating unit towards individual line flows and finally the resolution of generator-wise wheeling costs.

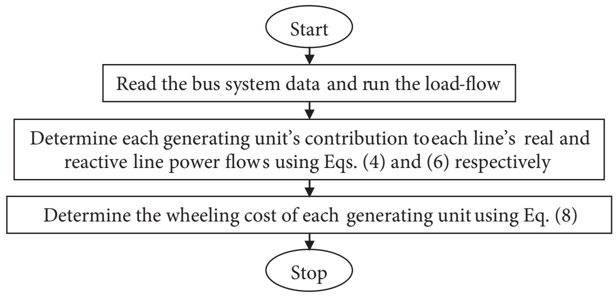

Figure 1. Flow chart for wheeling cost determination by MVA km methodology.

5. Custom power devices

While transmitting bulk power from the sources to the load centers, the transmission lines' operation is restricted by limitations of network parameters and operating variables, thereby demanding an equivalent transmission facility. The optimal usage of the prevailing system may diminish the build-up of new parallel lines. The escalation of transmission network capacity, enhancement of controllability, and improvement of power quality can be attained by FACTS controllers in an electricity network. FACTS device application ensures improved utilization of extant transmission network resources, increases transmission system reliability, increases dynamic and transient grid stabilities, increases the quality of supply, and reduces loop flows.

Figure 2 shows a TCSC encompassing a series compensating capacitor bank, C, connected in series with the transmission facility and shunted by a thyristor-controlled reactor branch comprising a thyristor valve, T, cascaded with a reactor, L. At fundamental system frequency, the thyristor-controlled reactor is delay-angle controllable with continuously variable reactive impedance [15]. The TCSC's steady-state impedance is that of a parallel LC circuit with fixed capacitive impedance and variable inductive impedance as a function of firing angle, as shown in Eq. (9).

$$X_{TCSC} = \frac{X_L(\alpha) . X_C}{(X_L(\alpha) - X_C)} \qquad (9)$$

The working range of reactance of the TCSC is from –0.8X_{ij} to 0.2X_{ij}, where X_{ij} is the transmission line reactance with the TCSC installed in it.

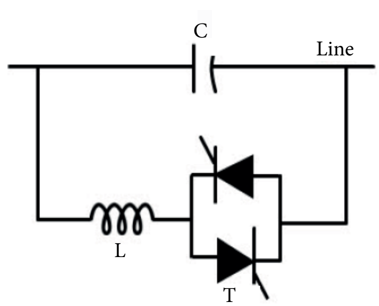

Figure 2. Basic structure of TCSC.

Optimal power flow (OPF) is a power flow problem with controllable variables fine-tuned to curtail any objective function such as power generation cost or transmission loss, while satisfying the operating limits. In this paper, the location and the rating of the TCSC are fixed with the optimization of network losses to reduce the wheeling cost.

6. Unit commitment

Price-based UC (PBUC) in the regulated power environment involves the optimization of generating units to meet the load at minimum generation cost, whereas security-constrained UC (SCUC) involves security maintenance too in the UC solution. PBUC involves UC by individual power generating stations for maximizing the profit in scheduling generation resources. The most distinguishing feature of PBUC is that the market price reflects all of the market information. SCUC involves an independent system operator (ISO) running the transmission security and the voltage-constrained UC [16]. The ISO plans the day-ahead schedule using SCUC. Also, the ISO collects each generating unit characteristic, wheeling network fitness, and accessibility and then fixes the optimal allocation of generating units. Once the UC schedule is fixed, the optimal dispatch issue is prepared and settled to confirm the viability of the original UC solution. The determination of transmission pricing for wheeling transactions is due to the dispatching of generators and change of transmission losses. PBUC is used in determining the wheeling cost by the power flow-based line-by-line wheeling cost computation methodology in this paper.

In an interconnected power system, different power plants have different fuel costs and are located at different distances from the load centers. The OPF problem involves determination of the active and reactive power scheduling of each unit, allowing both powers to fluctuate within definite limits so as to encounter a specific load demand with the least transmission loss. The OPF optimizes the load flow result of huge power systems by lowering nominated objective functions while preserving an allowable system performance in terms of generating unit fitness limits and compensating devices' output [17]. A technique similar to the heuristic one is proposed to achieve the reduction of line losses to drop the wheeling cost of some generators, which would increase the transmission network usage cost of other generators. Figure 3 shows the flow chart for the technique proposed. The standard optimal power flow simply involves the generation dispatch at minimum generation limits of generating units with the objective of minimization of network loss, whereas the unit commitment technique involves the mechanism of completely shutting down the generating units, which are very expensive to operate. The proposed algorithm runs an optimal power flow combined with unit commitment, completely shutting down the expensive generating units and finding a least cost with the least transmission loss commitment as well as finding generation dispatch at minimum generation limits, aiming at the reduction of both generating cost and wheeling cost.

7. Results and analysis

The IEEE 30-bus system is considered to study the effect of optimal placement of the TCSC on the wheeling cost with and without the application of the proposed unit commitment technique using a software package developed in the MATLAB language. The generated reactive power at each generator bus is assumed to be zero MVAr primarily. The generator fuel cost coefficient, α, is assumed to be zero rupees for all generators of the power system considered. The assumed hour-wise, load bus-wise daily apparent power demand curves of the bus system considered are presented in Figure 4. Figure 5 illustrates the per unit inductive reactance of the 5th transmission line, whose original reactance equals 0.1983 per unit, after the placement of the TCSC

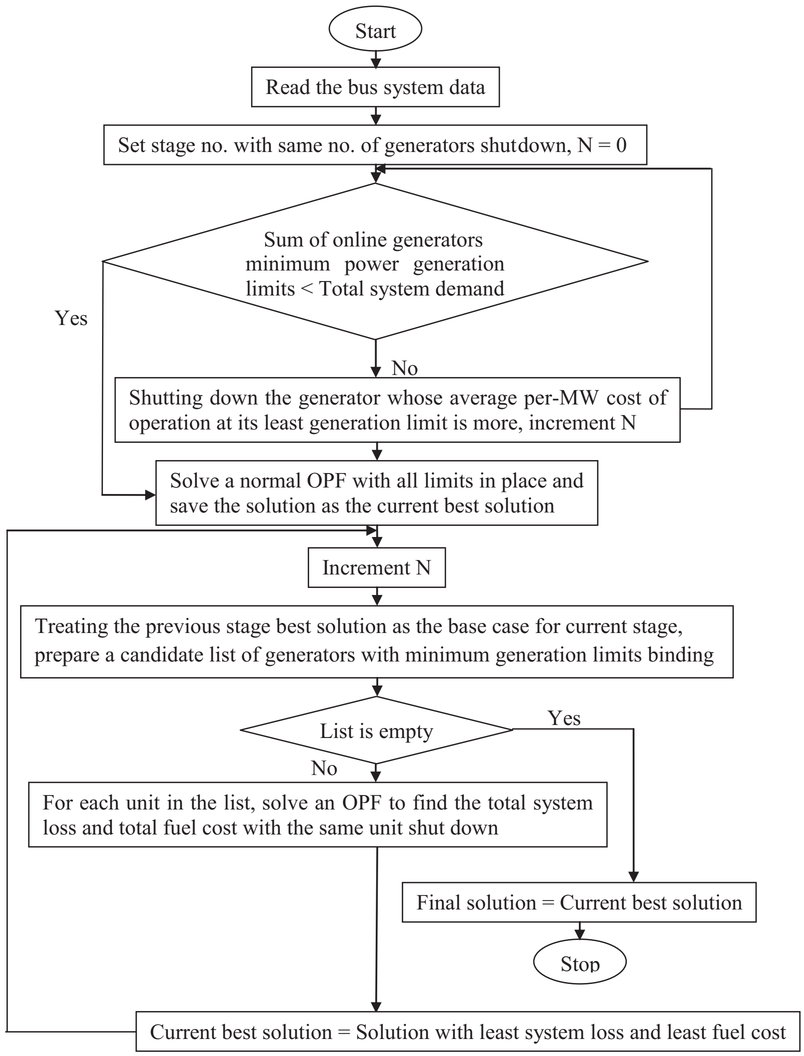

Figure 3. Flow chart for the unit commitment.

under load-flow and UC conditions to achieve the reduction of network power losses during each hour of a day. The presence of a properly rated TCSC at a suitable location reduced the per unit line inductive reactance much more under UC conditions than under load-flow conditions. Figure 6 and Figure 7 show the real and reactive power losses of the bus system during each hour of study period, respectively. During each hour, both losses of the bus system are found to be condensed with proper placement of a suitable TCSC. However, the TCSC influenced the network active power loss much less and impacted the network reactive power loss much more. Table 1 exhibits the generator-wise daily generation and wheeling costs along with total daily generation and wheeling costs without the TCSC, with optimally placed TCSC, and with optimally placed TCSC under UC state. The properly designed TCSC when optimally placed with the objective of reduction of the bus system power losses led to the change of power generation of generating units available in the bus system. In an interconnected power system, the change of power generations and difference in fuel cost coefficients among individual generating units interconnected reduced the generation cost of a few generators and burdened the remaining units, irrespective of the bus system operating conditions. The reduction of the bus system power losses implies the shrinkage of line power flow magnitudes. In an interconnected power system, the generator-wise contribution towards each line power flow and line length magnitudes relieved a few generators from the wheeling cost to some extent and burdened the other units with higher wheeling cost, irrespective of the network operating conditions. The overall generation cost and the overall wheeling cost of the interconnected generating units are reduced with the reduction of network losses.

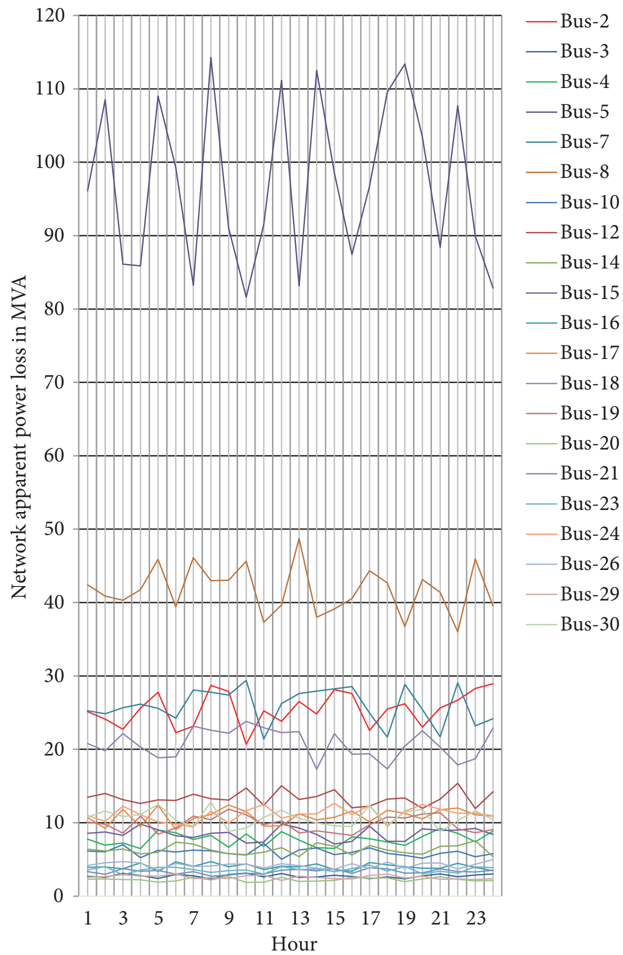

Figure 4. Bus-wise daily apparent power demand curves.

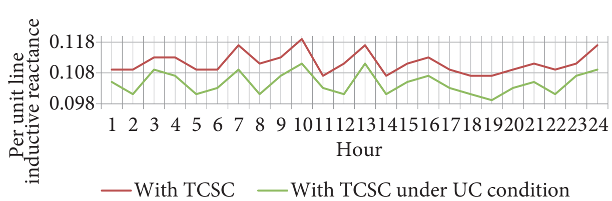

Figure 5. Hour-wise 5th transmission line inductive reactance per unit.

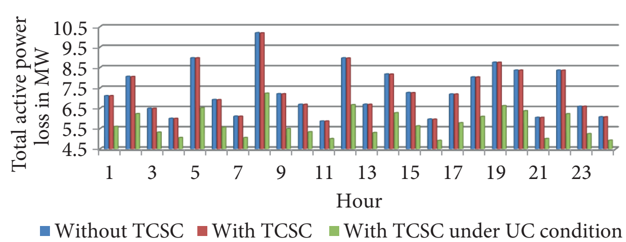

Figure 6. Hour-wise network active power loss.

Shrinkage of the daily generation cost and the daily wheeling cost of the combination of the interconnected generating units in the presence of the optimally placed suitable TCSC leads to the reduction of annual

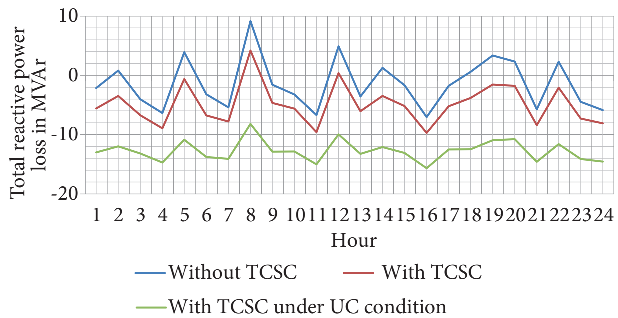

Figure 7. Hour-wise network reactive power loss.

Table 1. Generator-wise daily generation and wheeling costs.

PV	Daily generation cost in rupees			Daily wheeling cost in lakhs		
bus no.	wo_tcsc	w_tcsc	w_tcsc_uc	wo_tcsc	w_tcsc	w_tcsc_uc
1	11,442.80	11,442.23	7790.30	5.04	4.73	3.57
2	3809.04	3809.04	4985.43	1.74	1.59	1.93
5	1494.23	1494.23	1794.39	0.07	0.09	0.12
8	2975.20	2975.20	2975.19	0.53	0.53	0.61
11	1483.85	1483.85	2334.93	0.72	0.65	0.44
13	1389.09	1389.09	2227.59	0.59	0.56	0.38
Total	22,594.21	22,593.64	22,107.83	8.69	8.15	7.05

generation cost and annual wheeling cost of the same combination for the same daily load demand claimed throughout the year. For better understanding, both annual generation and wheeling costs are computed with the assumption that the daily load data presented in Figure 1 are demanded every day across the year. Table 2 shows the gross annual generation and wheeling costs. The presence of a suitable TCSC at the optimal location lowered the gross generation and wheeling costs.

Table 2. Gross annual generation and wheeling costs.

Annual generation cost in lakhs			Annual wheeling cost in crores		
wo_tcsc	w_tcsc	w_tcsc_uc	wo_tcsc	w_tcsc	w_tcsc_uc
31.71	29.79	25.69	82.468	82.466	80.693

8. Conclusion

Wheeling cost computation methodology considering apparent power flow wheeling is essential for arriving at the actual wheeling cost. Optimal placement of the TCSC in the standard IEEE 30-bus system for the reduction of network losses is proposed owing to physical and economic constraints. An optimal unit commitment algorithm has been proposed for the reduction of transmission losses so as to reduce the wheeling cost. An IEEE 30-bus system case study is performed for verifying the proposed algorithm efficacy for finding the shrinkage in annual transmission pricing in conjunction with the placement of a properly rated TCSC in the optimal location. The TCSC influences the generation and wheeling costs much when placed optimally and operated under UC conditions.

Nomenclature

no.	Number
X_{TCSC}	TCSC reactance in ohms
wo_tcsc	Without TCSC
w_tcsc	With TCSC
w_tcsc_uc	With TCSC under UC condition

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