International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 01, January-June 2016
www.arresearchpublication.com
IJEEE
ISSN 2321 - 2055

IMPACT OF OPTIMALLY PLACED TCSC ON TRANSMISSION PRICING

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ABSTRACT

The electrical power industry worldwide has been regulated since many years and is operated by a single entity. Recently, the electrical power industry across the globe is experiencing a radical change in its business as well as in its operational model where, the vertically integrated utilities are being unbundled and opened up to compete with the private players which led the power industry shift to deregulated environment. In a deregulated environment, private companies enter into the market and compete with in generation and distribution activities. The main objectives of a deregulated power industry are to provide electricity for all reasonable demands, to encourage competition in the generation and supply of electricity, to improve the continuity of the supply and the quality of services so as to promote efficiency and economy of the power system. IPPs make use of third-party owned transmission network to "wheel" the electrical energy to its customers and the wheeling party is paid 'wheeling cost' annually for its service and also for meeting the line losses. The wheeling cost can be minimized to a much higher extent by reducing the line losses, thereby improving the line power carrying capability. This can be achieved upon incorporating Flexible alternating current transmission system (FACTS) devices at a suitable location in the power system network. Thyristor-controlled series compensation (TCSC), one of the FACTS devices lessens the line losses via reducing line reactance. This paper gives brief introduction on wheeling, effect of wheeling, wheeling cost computation methodologies and a detailed explanation on power flow based Line-by-Line transmission pricing scheme, TCSC and the results obtained after applying a software package developed to depict the effect of optimally placed TCSC on wheeling cost when applied on an IEEE 30 bus system.

Keywords: Deregulation, Line-by-Line method TCSC, Transmission pricing, Wheeling,

NOMENCLATURE

P - active power (MW)
Q - reactive power (MVAr)
P_L - Active power loss in line-pq (MW)
Q_L - Reactive power loss in line-pq (MVAr)
m - Number of branches of the bus system
n - Number of nodes of the bus system
P_L - (nx1) sized matrix of nodal generations
F - (mx1) sized matrix of branch flows

I. INTRODUCTION

The electrical power industry is one where the generation, transmission, distribution and the ultimate look for utilization of electrical energy takes place. With the growing economic needs and the safety concerns had led to the regulation of electrical power industry. Regulated power industry is the one in which generation, transmission and distribution are operated by a single entity. The electric power industry probably being the largest and the most complex industry in the world and it being a form of energy that can't be stored and reused in large quantities, it is difficult to meet the drastically increasing load demand as well as to maintain continuous supply at an economical cost. For this to happen, generation, transmission and distribution of electricity must be accomplished at minimum cost but at maximum efficiency. Hence, the electrical power industry needs to be deregulated. Deregulation is the concept where the generation, transmission and distribution are carried out independently and there is a tough competition among generators for customers. The main benefits due to deregulation are cheaper electricity, efficient capacity expansion planning, cost minimization, more choice and better service. The need for more efficiency in power production and delivery has led to a restructuring of the power sectors in several countries which earlier were traditionally under the control of federal and state governments. During the 1990's the Indian government made many reforms and had let the private sector to participate actively in the power generation sector. Further, with the amendment of Indian electricity act in 2003, had resulted in the separation of vertically integrated state electricity boards into three entities viz., GENeration COrporation (GENCO) for generation, TRANSmission COrporation (TRANSCO) for transmission and DIStribution COMpany (DISCOM) for distribution of power. This led the IPP's to enter into the deregulated market.

II. WHEELING

IPP's do not have the power of eminent domain and generally do not own transmission lines. Therefore, they dependent on third party for moving their power to the market. In a competitive market place where IPPs are competing with utilities or their affiliates, access to transmission line can limit the participation of IPPs. Generally, IPPs in order to deliver electrical energy to its buyer, IPP's makes use the TRANSCO transmission network whose job is to "wheel" the electrical energy from a seller to a buyer.

The term "wheeling" can be defined in many ways. Wheeling involves the transmission of electrical energy from a seller to a buyer through the transmission network owned by a third party. The fig.1, shows the general wheeling diagram.

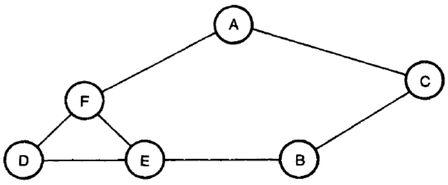

Fig.1. General wheeling diagram.

Wheeling occurs on an AC interconnected system that contains more than two utilities whenever transaction takes place.

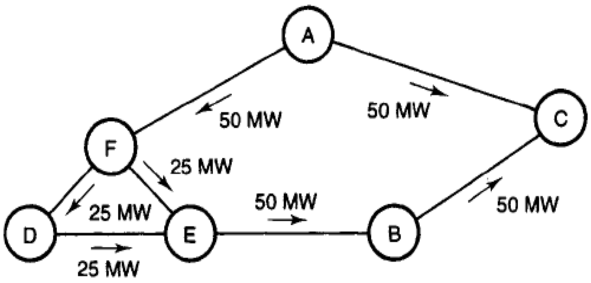

Fig 2. Six interconnected wheeling diagram

Consider the six interconnected control areas as shown in Figure2. Here, Areas A and C negotiate the sale of 100 MW by A to C. A to F transferring some amount of power and F area power is transfer to C area through the areas D & E and the remaining power is transferring areas A to C.

III. EFFECT OF WHEELING

Wheeling greatly affects the line loss, re-dispatch of generators, transmission line flow constraints, other power system security issues and recovery of embedded capital costs.

Illustration: For example, if a seller at bus 2 has to supply power to a load of 100MW to a buyer at bus no 5, considering an IEEE 30-bus system the effect on line power losses due to wheeled power flow and the results are tabulated in "Table:1".

Table:1 Line power losses of IEEE 30-bus system in presence and absence of wheeled power flow.

Line no.	Line Power Losses	
	In absence of wheeled power flow	In presence of wheeled power flow
	$P_{Loss}\pm jQ_{Loss}$	$P_{Loss}\pm jQ_{Loss}$
1	1.439-j1.424	1.405-j1.524
2	0.952-j0.529	1.460+j1.563
3	0.474-j2.470	1.055-j0.692
4	0.249-j0.177	0.390+j0.230
5	1.498+j1.946	6.682+j23.727

6	0.797-j1.537	1.849+j1.658
7	0.175-j0.338	0.443+j0.597
8	0.081-j1.864	1.517+j1.760
9	0.349-j0.684	1.610+j3.194
10	0.000-j0.941	0.000-j0.939
11	0.055+j1.134	0.053+j1.101
12	0.016+j0.881	0.015+j0.822
13	0.074+j1.539	0.076+j1.578
14	0.096+j1.058	0.092+j1.010
15	0.081+j2.074	0.091+j2.326
16	0.112+j1.568	0.114+j1.595
17	0.071+j0.148	0.074+j0.153
18	0.201+j0.397	0.215+j0.424
19	0.042+j0.088	0.051+j0.106
20	0.004+j0.004	0.005+j0.005
21	0.008+j0.018	0.012+j0.027
22	0.034+j0.069	0.038+j0.078
23	0.004+j0.007	0.005+j0.010
24	0.020+j0.040	0.019+j0.037
25	0.092+j0.206	0.087+j0.194
26	0.021+j0.054	0.019+j0.049
27	0.110+j0.237	0.110+j0.236
28	0.052+j0.107	0.052+j0.106
29	0.001+j0.002	0.001+j0.002
30	0.024+j0.049	0.028+j0.056
31	0.044+j0.069	0.043+j0.066
32	0.003+j0.006	0.005+j0.011
33	0.003+j0.006	0.003+j0.005
34	0.044+j0.066	0.044+j0.066
35	0.033+j0.063	0.031+j0.059
36	0.034+j1.350	0.033+j1.321
37	0.084+j0.159	0.085+j0.160
38	0.159+j0.299	0.159+j0.299
39	0.033+j0.062	0.033+j0.062
40	0.012-j4.424	0.012-j4.418
41	0.033-j1.237	0.032-j1.239
TOTAL:	7.614-j1.920	18.047+j35.883

From “Table:1”, it can be observed that the line power losses increase in case of a wheeled power plow.

IV. TRANSISSION PRICING

Wheeling cost or Transmission Pricing is the cost paid to the transmission network holder by the seller of electrical energy for using the transmission network to transmit the power to the buyer of electricity. The wheeling cost of the electrical energy is decided by the wheeling company. The decision regarding the cost of wheeling is based on some of the factors such as: for its service and meeting extra losses, considering the capital cost of all transmission lines as the power flow magnitude in all lines.

V. TRANSMISSION PRICING STRATEGY

Transmission service pricing plays a key role in determining whether the providing transmission service is economically beneficial to both the wheeling utility and also the wheeling customers. In fact, transmission pricing is mainly intended to meet a common set of objectives: economic efficiency, revenue sufficiency and efficient regulation. But it has to be understood and realized that transmission service pricing is not a technical aspect but an engineering problem. Generally, engineering analysis is mainly intended to determine the feasibility and also the cost required for providing transmission services, which being one of the main considerations in pricing the transmission services. But in reality there may be external influencing factors where the market and political considerations could play key roles in determining and fixing the transmission prices. Hence, it has become extremely important to understand and be able to clearly distinguish between transmission costs and prices.

Generally, the pricing of any service or a product is to be carried out strategically in such a way so as to achieve the following goals:

- to recover the capital and operating costs.
- to provide equal opportunity to all the users.
- providing the customers with a wide range of services and price options, thereby increasing the choice factor.
- to encourage efficient use and investment.
- to offer a simple and an understandable pricing structure.
- it should be easily implementable.

In fact, evaluating transmission cost is much more a difficult task as it involves mathematical approach, complex analytics which requires extensive usage of tools and data. Hence, it has become extremely difficult in determining the value of transmission services to wheeling customers.

To overcome the above mentioned problems when evaluating the transmission cost and determining the transmission pricing, the economists have advocated adherence to basic economic principles that would price the transmission prices based on the incremental cost of providing transmission services. Under these circumstances two challenges are to be addressed. One of the challenge is how to compute for the exactness of the incremental cost of providing transmission services. The other challenge being, how much premium in excess of the incremental cost should be allowed in transmission pricing so as to provide the wheeling utilities with an incentive to accommodate large number of transmission transactions. Presently, the utility industry commonly uses cost based prices for transmission services. But in cost based transmission pricing, it is extremely difficult and is a more complex task to distinguish between transmission prices and costs and are in fact very confusing particularly when the incremental transmission pricing methodologies are discussed. The emphasis on transmission costs is mainly intend to illustrate how these merits are evaluated and translated to transmission prices.

VI. TRANSMISSION PRICING METHODOLOGIES

One of the most challenging issues in a deregulated environment is fair allocation of transmission costs to the transmission network users. The tariffs can be calculated much appropriately taking into consideration load forecast, generation availabilities and possible line outages when all the necessary data is available. Also, the view point of the transmission network owners and that of the users differ greatly. From the transmission network owner's point of view, transmission pricing is intended to recover the total costs for transmission services whereas from the transmission network user's point of view there should be a reasonable pricing scheme adopted for its usage. Hence, transmission pricing undoubtedly a challenging task considering the above points and it has been a reason for introducing different schemes and methods for transmission pricing. Based on the recent studies made, there are two different methodologies to compute wheeling cost i.e., "Embedded" and "Marginal" wheeling cost computation methodologies.

Any wheeling cost computation methodology has to fulfill the following requirements:

1. Conciseness and transparency.
2. Recovery of invested cost.
3. Efficient operation of electric network.
4. Fairness and acceptability for wheeling service users.

Marginal cost computation methodology do not satisfy the first and the second requirements mentioned above. Also, it has been proven to be insufficient because network revenue surplus from transmission transactions under a spot price does not cover in long term the fixed costs of the transmission line. The embedded cost method has proven to be advantageous as this method not only charges the transmission network users the total cost based upon their usage of the system but can also recover the investment cost. Also, in embedded cost methods, network owner cannot make illegal profit much easily by exercising the market power. On the other hand, the embedded cost method may be disadvantageous too, because this method, in its general form, does not determine high or low usage of network. The marginal and embedded cost methods in common do not consider the costs for congestion and losses.

Embedded cost methods include post stamp, contract path and MW-km methods.

- Postage stamp method: based on the magnitude of the transacted power.
- Contract path method: a contract path is selected to identify the transmission facilities that are actually involved in a transaction.
- Distance-based MW-Km method: based on the magnitude of the transacted power and the aerial distance between the points of the delivery and receipt.

- Power-flow based MW-Km method: based on the extent of use of transmission facilities by the transaction.

This requires aa set of load flow analysis associated with each wheeling transaction when multiple wheeling transactions are considered.

In the first two methods load flow calculation is not performed. On the other hand, the MW-km method is based on load flow calculation. Hence, MW-km method is the best method as the transmission embedded cost is allocated to transactions in proportion to the ratio of flow magnitude contributed.

VII. LINE–BY-LINE OR MW-KM METHODOLOGY

According to this method, the cost allocation is done based on a computed set of parallel paths for a particular transaction considering line flows and line lengths. The MW-km methodology can be carried out in two ways i.e., either distance based or power flow based.

7.1 Distance based MW-Km methodology

Distance based MW-Km method is the simplest method of evaluating the usage of each transmission network user, based on the quantity of power transacted and the geographical distance between the seller and buyer in such a way that it is the product of power due to a specific transaction times the distance this power travels in the network. This method is non-power flow based and hence does not involve any power flow simulation and is easier to apply and also to compute. But this method is disadvantageous too as the transmission users do not face their actual costs as the effect of actual power is not taken into consideration and also the geographical distance does not indicate the actual transmission facilities involved in the transaction or the reinforcements required for accommodating the transaction and hence the wheeling customers are most likely to receive and act upon incorrect economic signals.

7.2 Power flow based MW-Km methodology

Power flow based MW-Km method is a better method when compared with that of distance based MW-Km method as it employs power flow simulation in order to determine the quantity of power flowing through various lines. It takes into account both the quantity of transacted power and also the electrical distance between seller and buyer, and allocates total costs in direct relation to the MW-Km of transactions.

The formula to determine the wheeling cost for a particular transaction is as follows:

$$WC_t = \sum_j \frac{P_{j,t} L_j C_j}{\sum_i P_{j,t}}$$

Where:

WC_t = wheeling cost for transaction t (Rs./MVA)

$P_{j,t}$ = flow in line j due to transaction t (MVA)

L_j = length of line j (Km)

C_j = pre-determined unit cost reflecting cost per unit capacity of the line (Rs./MVA-Km)

i = total number of transmission lines

Power Flow based MW-mile method allocates the charges of each transmission facility to a wheeling transaction based on the extent of use of that facility by the transaction. These allocated charges are then added up over all transmission facilities to evaluate the total price for using the transmission system. The charges are determined as a function of magnitude, the path, and the distance travelled by the transacted power. Two power flows are executed successively, with and without wheeling, to get the changes in MW flows in all transmission lines. This method emulates the actual system operating conditions, insensitive to the order of wheeling transactions as each transaction is treated separately, provides better cost signals for long and short distance wheeling customers and encourages the economic use of the transmission network capacity by giving a higher cost signal to transactions with several delivery points.

Some of the advantages of the above methodology are:

- It is insensitive to the order of wheeling transactions and no priority order is to be maintained by this method in case of multiple wheeling transactions. This is because every transaction is treated separately by considering only those generators and loads that are associated with that transaction. Hence, there will be no dispute about the order in which the transactions should be considered.
- It gives a correct signal to both short distance and long distance entities, unlike in postage stamp case.
- It provides correct economic signals irrespective of entities' distance involved in wheeling process.

Some of the drawbacks of the above methodology are:

- It proves to be inaccurate, when computed for the extent of use of the transmission network by a particular transaction as it uses DC approximation of the power system.
- It leads to reduction in the loading of the system as no merit is attributed to the power flow transactions giving rise to counter flows.

VIII. POWER FLOW TRACING METHODS

Wheeling can be done either by a single entity or by multiple entities. In the case of wheeling by multiple entities, the wheeling party is paid by each and every IPP who are connected to that wheeling network, based upon the contribution of each IPP to the transmission network in terms of line flows and line losses. The power flow tracing methods are extremely helpful in determining the extent of the usage of network elements by various generators and loads, contribution of transmission users to transmission usage. With the help of the above information, the total fixed costs of the transmission network can be recovered upon allotting to various network users and the transmission pricing is also done in accordance to it. Currently, two well accepted power tracing approaches are available: one is proposed by Bialek and the other by Kirschen. The former is based on the simultaneous equations approach and the latter on theoretic approach. Both these methods in common are based on proportionate sharing principle. In this paper, of the two methods Bielek's method is discussed in detail.

Bialek’s Tracing Method

Bialek’s tracing method, is based on simultaneous equations method. This tracing method is helpful in determining the quantity of power supplied by a generator to a particular load, contribution of each and every individual generator and loads to every line flow. This algorithm works particularly only on lossless flows but on both dc and ac power flows and is helpful in determining the contribution of both active power and reactive power flows. It uses either the upstream looking algorithm or the downstream looking algorithm, to determine the contribution of individual generators based on the calculation of topological distribution factors. In case of upstream looking algorithm, the wheeling charge is allocated to individual generators and the losses are distributed to individual loads and vice-versa in case of downstream looking algorithm.

The Bialek’s tracing procedure is as:

B = (mxn) sized matrix called ‘Incidence matrix’ with its elements value equal to 1 when power flows from ‘m’ bus to ‘n’ bus, -1 when power flows from‘n’ bus to ‘m’ bus and 0 when no power flows between ‘m’ bus and ‘n’ bus.

Bd = (mxn) sized matrix derived from incidence matrix, consisting of 1’s and other element values equal to zero.

Bu = (mxn) sized matrix derived from incidence matrix, consisting of -1’s and other element values equal to zero.

$$F_d = -B_d^T.\text{diag}(F).B_u \qquad (1)$$

$$A_d = I + B_d^T.\text{diag}(F).B_u.\text{diag}(P^{-1}) \qquad (2)$$

$$A_u = I + B_u^T.\text{diag}(F).B_d.\text{diag}(P^{-1}) \qquad (3)$$

Equation (1) results in an (nxn) sized matrix where the (i, j) element indicates the line flow from ith bus to jth bus where as Equations (2) and (3) provide two non-singular matrices, each of size (nxn)**.**

$$P_{Gki} = \frac{P_{Di} \cdot P_{Gk} \cdot [A_u^{-1}]_{ik}}{P_i} \qquad (4)$$

$$P_{Gkj} = \frac{F_{Dj} \cdot P_{Gk} \cdot [A_u^{-1}]_{ik}}{P_i} \qquad (5)$$

Equation (4) can be used to find the active power contribution of the kth generator to ith bus active load whereas equation (5) to determine active line power flow contribution of kth generator to jth line’s active line flow. The same equations can be dealt with reactive loads and other types of powers also. Thus these two equations can be used to determine the usage of the transmission network due to individual generators and individual loads.

IX. THRISTOR CONTROLED SERIES COMPENSATION-TCSC

FACTS Devices:

A flexible alternating current transmission system (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy, meant to improve the power flow capability and to control the power flow thereby, enhancing the system stability. It is basically a power-electronics based system.

Benefits Of FACTS:

The following is a list of few benefits that can be achieved through FACTS. They are:

- To increase power transfer capability of transmission networks.
- To direct the control of power flow over designated transmission routes
- To control the power flow as ordered so that it follows on the prescribed transmission corridors.
- Increase the loading capability of lines to their thermal capabilities.

FACT CONTROLLERS:

There are various FACTS devices available. They are broadly classified as: shunt, series and hybrid controllers.

I. SHUNT TYPE:
  - Static VAR Compensator
  - Static Synchronous Compensator
  - STATCOM

II. SERIES TYPE:
  - Thyristor Controlled Series Capacitor(TCSC).
  - Static Synchronous Series Compensator.
  - Fault Current Limiter (SC+FPD)

III. HYBRID TYPE:
  - Dynamic Power Flow Controller (DFC)
  - HVDC Light / HVDC LightB2B / UPFC

SERIES COMPENSATORS:

The concept of series compensation is well adopted in many developed countries. Let us understand how the concept is useful by considering the expressions relating to active power transfer and voltage:

$$P = V_1 V_2 \sin / X \qquad (1)$$

$$V = f(P,Q) \qquad (2)$$

From the above expression related to active power, it can be clearly understood that the active power flow can be increased upon decreasing the effective series reactance of the transmission line. The same can be even achieved even by introducing a capacitive reactance, so as to increase the angular stability of the link. Hence by adopting series compensation, optimized load sharing between the parallel circuits can be achieved thereby increasing the overall power transmission capacity further. In a way, the active losses associated with power transmission can be reduced to a greater extent.

From voltage expression mentioned above, it can be well understood that the voltage of a transmission circuit will depend on both the active power flow and the reactive power flow. Upon incorporating a capacitive element in series with the line, the reactive power contributed will help in improving the reactive power balance in the circuit, thereby stabilizing the transmission line voltage. Since, the reactive power contribution varies continuously depending upon the line load, it contribution to voltage stability is in a dynamic fashion. This proves series compensation to be a highly effective means for improving the voltage stability even when the transmission network is heavily loaded.

Hence, series compensation of power transmission can serve the following benefits:

- Increase active power transmission over the circuit
- Improve the voltage stability.
- Decrease the transmission line losses.

Out of various series compensating techniques, let us discuss TCSC in detail.

TCSC:

Thyristor controlled series capacitor (TCSC), behaves as a tunable parallel LC-circuit to the line current. As, the value of inductive reactance is varied from its maximum towards its minimum, the TCSC will increase its capacitive reactance. Therefore, the overall reactance is increased and hence the transmittable active power increases.

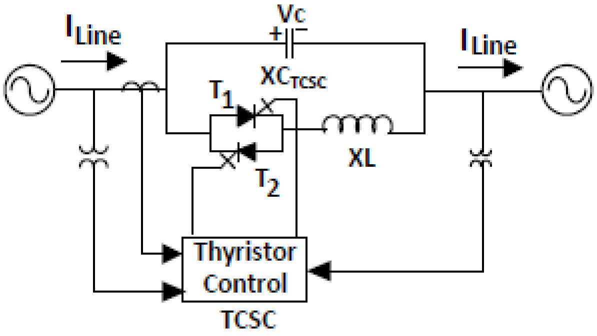

Fig: Thyristor Controlled Series Compensator

The transmission line inductive reactance can be varied upon varying the firing angle by creating a delay in the thyristor circuit connected in series with it.

TCSC operates in different modes depending on when the thyristors for the inductive branch are triggered.

The modes of operation are as listed as follows:

- locking mode: Thyristor valve is always off, opening inductive branch, and effectively causing the TCSC to operate as FSC
- Bypass mode: Thyristor valve is always on, causing TCSC to operate as capacitor and inductor in parallel, reducing current through TCSC
- Capacitive boost mode: Forward voltage thyristor valve is triggered slightly before capacitor voltage crosses zero to allow current to flow through inductive branch, adding to capacitive current. This effectively increases the observed capacitance of the TCSC without requiring a larger capacitor within the TCSC.

As TCSC operates under different operating modes depending on the system requirements, TCSC is desired for several reasons. TCSC allows for increased compensation simply by using a different mode of operation, as well as limitation of line current in the event of a fault. A benefit of using TCSC is the damping of sub synchronous resonance caused by torsional oscillations and inter-area oscillations. The ability to dampen these oscillations is due to the control system controlling the compensator. This results in the ability to transfer more power, and the possibility of connecting the power systems of several areas over longer distances.

CASE STUDY

A IEEE 30-bus system is considered to study the influence of optimally placed TCSC on line power flows, line powers losses and annual wheeling cost.

Generator-wise contribution to bus power demands including line power losses of IEEE 30-bus system is shown in “Table:2” for bus no’s 2,3,4.

Table:2 Generator-wise contribution to bus power demands of IEEE 30-bus system for bus no’s 2,3,4

bus no.	PV bus no.	$P_g \pm jQ_g$	Total
2	1	13.40+j0.00	21.90+j10.86
	2	8.50-j0.44	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j4.95	
	13	0.00+j6.35	
3	1	2.44+j0.00	2.44+j1.39
	2	0.00+j0.00	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j0.00	
	13	0.00+j1.39	
4	1	6.61+j0.00	7.79+j1.97
	2	1.18+j0.00	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j0.00	
	13	0.00+j1.97	

The same is carried for the remaining lines taking into consideration the generator-wise active power and reactive contribution to bus power demand and total power demand at load end is shown in “Table:3”

Table:3 Total bus power demand of an IEEE 30-bus system

Bus No	Power Demand	
	Active Power	Reactive Power
2	21.9	10.86
3	2.14	1.39
4	7.79	1.97
5	96.87	20.53
7	23.71	9.3
8	30	29.1
10	5.9	0.6
12	11.38	7.88
14	6.35	1.81
15	8.43	2.84
16	3.57	1.91
17	9.21	1.78
18	3.3	1.1
19	9.82	1.1
20	2.25	0.22
21	17.98	3.51
23	3.3	1.757
24	8.99	0.91
26	3.65	0.98
29	2.48	0.41
30	11.12	0.95

The generator-wise contribution to line power flows of IEEE 30-bus system is shown in the “Table:4” for line no’s 1,2,3.

Table:4 Generator-wise contribution to line power flows of IEEE 30-bus system for line no's 1,2,3

Line no.	PV bus no	Pg±jQg	Line power
1	1	90.71+j0.00	90.71+j0.019
	2	0.00-j0.001	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j0.009	
	13	0.00+j0.011	
2	1	48.08+j0.00	48.08+j2.37
	2	0.00+j0.00	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j0.00	
	13	0.00+j2.37	
3	1	18.02+j0.00	29.45+j6.55
	2	11.43+j0.00	
	5	0.00+j0.00	
	8	0.00+j0.00	
	11	0.00+j0.00	
	13	0.00+j6.55	

The same is carried for the remaining lines taking into consideration the generator-wise active-power and reactive-power contribution to the line flows and the total power flowing through the line is shown in "Table:5".

Table:5 Total Line Power flows in an IEEE 30-bus system

Line No	Line Power	
	Active Power	Reactive Power
1	90.71	0.019
2	48.08	2.37
3	29.45	6.55
4	45.63	3.77
5	58.63	1.412
6	38.25	6.24
7	40.35	2.38
8	13.66	2.085
9	37.39	7.21
10	0.75	0.891
11	15.04	20.87
12	12.82	4.89
13	17.93	23.87
14	32.97	3
15	26.93	14.68
16	16.91	31.96
17	7.81	2.1
18	17.79	5.41
19	6.82	1.88
20	1.43	0.29
21	3.24	0.034
22	5.82	1.11
23	2.51	0.009
24	7.3	1.1
25	9.57	1.32
26	5.97	1.82
27	16.36	2.85
28	7.91	1.27
29	1.609	0.65
30	4.95	1.74
31	6.3	0.62
32	1.64	0.0009
33	1.03	0.31
34	3.65	0.98
35	4.69	1.29
36	18.32	2.65
37	6.34	0.67
38	7.27	0.67
39	3.85	0.27
40	4.24	1.334
41	14.08	4

The line-wise wheeling costs and generator-wise total and annual wheeling costs of IEEE 30-bus is shown in “Table-6”.

Table:6 Line-wise wheeling costs and generator-wise total and annual wheeling costs of IEEE 30-bus for PV bus no.1

PV Bus No.	Line No.	Wheeling cost	Annual Wheeling Cost
1	1	10,069.31	92.02
	2	12,550.71	
	3	5,947.52	
	4	3,514.18	
	5	9,795.08	
	6	7,864.62	
	7	2,360.65	
	8	2,640.41	
	9	4,208.39	
	10	0	
	11	316.73	
	12	270.09	
	13	0	
	14	316.73	
	15	662.33	
	16	0	
	17	2,898.36	
	18	3,550.24	
	19	1,943.68	
	20	961.15	
	21	805.59	
	22	1,880.81	
	23	485.34	
	24	636.62	
	25	2,290.55	
	26	494.07	
	27	1,453.99	
	28	1,473.72	
	29	47.97	
	30	1,494.14	
	31	1,857.27	
	32	656.03	
	33	633.44	
	34	3,006.03	
	35	1,659.67	
	36	296.75	
	37	4,502.38	
	38	7,518.00	
	39	2,983.43	
	40	0	
	41	1,002.82	

The same is carried for the remaining buses as shown in “Table:6” and the generator-wise Annual Wheeling Cost is shown in “Table:7”

Table:7 Generator-wise total and annual wheeling costs of IEEE 30-bus system

PV Bus No.	Annual Wheeling Cost
1	92.02
2	27.91
5	0.46
8	0
11	17.89
13	16.96

The line reactances of various lines are shown in “Table:8” with an objective of minimizing various line losses such as active power and reactive power losses both in the presence and absence of TCSC.

Table:8 Line Reactances in the presence and absence of TCSC

Line No.	Line Reactance(in ohms)			
	With objective of minimizing Line losses			
	Active power loss P_L		Reactive power loss Q_L	
	In	In	In	In Presence
1	0.0575	0.0575	0.0575	0.0575
2	0.1852	0.1852	0.1852	0.1852
3	0.1737	0.1737	0.1737	0.1737
4	0.0379	0.0379	0.0379	0.0379
5	***0.1983***	***0.1487***	***0.1983***	***0.0595***
6	0.1763	0.1763	0.1763	0.1763
7	0.0414	0.0414	0.0414	0.0414
8	0.1160	0.1160	0.1160	0.1160
9	0.0820	0.0820	0.0820	0.0820
10	0.0420	0.0420	0.0420	0.0420
11	0.2080	0.2080	0.2080	0.2080
12	0.5560	0.5560	0.5560	0.5560
13	0.2080	0.2080	0.2080	0.2080
14	0.1100	0.1100	0.1100	0.1100
15	0.2560	0.2560	0.2560	0.2560
16	0.1400	0.1400	0.1400	0.1400
17	0.2559	0.2559	0.2559	0.2559
18	0.1304	0.1304	0.1304	0.1304
19	0.1987	0.1987	0.1987	0.1987
20	0.1997	0.1997	0.1997	0.1997
21	0.1932	0.1932	0.1932	0.1932
22	0.2185	0.2185	0.2185	0.2185
23	0.1292	0.1292	0.1292	0.1292
24	0.0680	0.0680	0.0680	0.0680
25	0.2090	0.2090	0.2090	0.2090
26	0.0845	0.0845	0.0845	0.0845
27	0.0749	0.0749	0.0749	0.0749
28	0.1499	0.1499	0.1499	0.1499
29	0.0236	0.0236	0.0236	0.0236
30	0.2020	0.2020	0.2020	0.2020
31	0.1790	0.1790	0.1790	0.1790
32	0.2700	0.2700	0.2700	0.2700
33	0.3292	0.3292	0.3292	0.3292
34	0.3800	0.3800	0.3800	0.3800
35	0.2087	0.2087	0.2087	0.2087
36	0.3960	0.3960	0.3960	0.3960
37	0.4153	0.4153	0.4153	0.4153
38	0.6027	0.6027	0.6027	0.6027

39	0.4533	0.4533	0.4533	0.4533
40	0.2000	0.2000	0.2000	0.2000
41	0.0599	0.0599	0.0599	0.0599

From the “Table:8”, it is observed that the optimal placement of TCSC in the T&D network is found to be at 5th line when the reduction of active power losses is taken into prior consideration as experimental results show that upon placing TCSC in the 5th line, the overall reactance in that line is reduced from 0.1983 ohms to 0.1487 ohms thereby reducing the active power losses from 7.6140MW to 7.3025 MW. Also, the optimal placement of TCSC in the T&D network is found to be at 5th line when the reduction of reactive power losses is taken into consideration as experimental show that upon placing TCSC in the 5th line, the overall line reactance is reduced from 0.1983 ohms to 0.0595 ohms thereby reducing the reactive power losses from -1.9200 MVAr to -7.9411MVAr

The generator-wise annual wheeling cost upon optimal placement of TCSC in the transmission line with an objective to minimize line losses is shown in “Table:9”

Table:9 Generator-wise annual wheeling cost upon optimally placing TCSC on the transmission line.

PV Bus No.	Annual Wheeling cost (in crores)		
	With objective of minimizing Line losses		
	Base Case	Active power,P_L	Reactive power Q_L
		In Presence of TCSC	In Presence of TCSC
1	92.02	90.17	87.96
2	27.91	26.9	25.54
5	0.46	0.5	3.03
8	9.8	9.83	9.91
11	17.89	17.23	17.15
13	16.96	16.98	17.6
Total	**165.04**	**161.61**	**161.19**

From “Table:9”, it is observed that upon optimally placing TCSC in the transmission line, generator-wise annual wheeling cost is found to be decreased. Optimal placement of TCSC has shown a decrease in the annual wheeling cost from 165.04 Cr to 161.61 Cr when aimed with an objective to minimize active power loss and from 165.04 Cr to 161.19 Cr when aimed with an objective to minimize reactive power loss.

X. CONCLUSIONS

The line power losses increase when wheeling network is considered to exist in a transmission network. Upon optimally placing TCSC in the transmission line, the wheeling cost decreases when placed with an objective to minimize line losses i.e., active power loss and reactive power loss. Also, optimal placement of TCSC in the line with an objective to reduce reactive power losses showed a greater decrease in the line reactance compared to that carried out with an objective to reduce active power losses. The generator-wise annual wheeling cost is reduced upon optimally placing TCSC in the transmission line. Also, optimally placed of TCSC showed greater decrease in generator-wise annual wheeling cost when placed with an objective to reduce reactive power losses rather than that of active power losses. Though the optimal placement of TCSC has shown an overall decrease in the total annual wheeling cost considering all the generators, the annual wheeling cost may not necessarily decrease when generator-wise contribution to the load flow is considered.

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