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An approach to Determine the Revenue Share of Each FACTS Device under Deregulated Environment

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Abstract: Under deregulated environment, transmission networks are operated close to their constraints. In this situation, FACTS devices can be useful in secure system operation. The obtained benefits of these devices have not been quantified and distinguished. In this study, for the first time, a method is proposed to calculate the revenue share of each FACTS device in the network by considering the role of FACTS devices in congestion management, reliability improvement and voltage profile improvement. Moreover, this method provides suitable economic signals for optimal FACTS devices expansion planning. To verify the proposed method, a 9-bus power system has been simulated in MATLAB/Simulink and Optimization Toolboxes.

Key words: Marginal benefit, Incremental benefit, LMP, congestion management, voltage profile, reliability

INTRODUCTION

Under the deregulated electricity industry, electricity concept changes over from a service to a commodity. By separation in generation, transmission and distribution sections in electricity market, transmission networks have an important role in the earned benefits of producers and consumers. In vertical integrated system, reliability and security of transmission networks are the first operation priority and transmission networks usually are operated far from their operational constraints. After deregulation, transmission networks are operated near their security constraints due to the economical issues. In these cases, FACTS devices could have important roles, because they provide flexible transmission operation and affect the revenue of consumers and producers. These devices represent services such as voltage control and voltage profile improvement, reliability improvement and network loading control (Hingorani, 2000).

The role of FACTS devices in transmission network operation have been described earlier by Srivastava and Verma (2000) and Shrestha and Feng (2005), the role of FACTS devices in transmission pricing and market spot price (Yao *et al*., 2005; Huang and Yan, 2002; Shi *et al*., 2007; Singh and David, 2000, 2002; Phichaisawat and Song, 2002; Brosda and Handschin, 2001; Reddy *et al*., 2006) using FACTS devices to resolve congestion in transmission system, in (Mansour *et al*., 1994; Singh, 2001; Cheng *et al*., 2001) the role of FACTS devices in voltage variation control and system security improvement has been analyzed. The effect of optimal location of FACTS devices in market clearing price and social welfare has been evaluated. Nadarajah and Naresh (2007) has proposed a new method to calculate the revenue of all available FACTS devices in the transmission network to recover FACTS devices requirement investment.

Our contribution in this study is developing an algorithm for calculating the revenue share of each FACTS device. In the proposed method, the revenue of FACTS devices has been divided into three components i.e., system reliability improvement, voltage profile improvement and congestion management. It is necessary to determine the revenue share of each FACTS device, because there are different FACTS devices, which have different owners and the revenue share of each owner should be calculated. Moreover, this method, provide a suitable economic signal for future investment.

FACTS DEVICES MODELING AND THEIR COST FUNCTIONS

FACTS devices are categorized into three groups, the first, current injection in parallel, second, voltage injection in series and the third, combination of first and second groups. SVC and STATCOM are in the first group. TCSC and SSSC are in second group. TCPAR and UPFC are in third group.

Static model of FACTS devices: In this study, integrated power injection model has been used for static modeling

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of FACTS devices. In this model, FACTs devices modeling as injection power sources in related buses. The static model of SVC and TCSC is described below (Chanana and Kumar, 2006).

SVC: Static VAR compensator (SVC) is a parallel compensator which injects reactive current and regulates injected current continuously. SVC usually is used for bus voltage controlling in no load and peak load conditions. In steady-state studies, SVC is modeled as an injection power source QSVCi in bus i. Maximum and minimum reactive power injection constrains are considered by follow equation:

$$ur_i * Q_{SVCi}^{min} \le Q_{SCVi} \le ur_i * Q_{SVCi}^{max} \tag{1}$$

where, $ur_i = \{0, 1\}$ is a binary variable defining presence or absence of SVC in a bus.

This equation is incorporated in OPF formulations.

TCSC: Thyristor Controlled Series Capacitor (TCSC) is a series compensator which increases transmission line capacity by decreasing lines' series impedances and increase network reliability. In steady-state studies, TCSC can be modeled as a series reactance -jc. A transmission line with TCSC model is shown in Fig. 1.

Active and reactive power flow from bus i to bus j (Q_{ij}^c and P_{ij}^c) and from bus j to bus I (Q_{ji}^c and P_{ji}^c) are calculated by the following equations when TCSC is considered in transmission line between bus i and j:

$$P_{ij}^c = V_i^2 G_{ij}^{'} - V_i V_j (G_{ij}^{'} \cos\delta_{ij} + B_{ij}^{'} \sin\delta_{ij}) \tag{2}$$

$$Q_{ij}^c = V_i^2 (B_{ij}^{'} + B_{sh}) - V_i V_j (G_{ij}^{'} \sin\delta_{ij} + B_{ij}^{'} \cos\delta_{ij}) \tag{3}$$

$$P_{ji}^c = V_j^2 G_{ij}^{'} - V_i V_j (G_{ij}^{'} \cos\delta_{ij} + B_{ij}^{'} \sin\delta_{ij}) \tag{4}$$

$$Q_{ji}^c = V_j^2 (B_{ij}^{'} + B_{sh}) - V_i V_j (G_{ij}^{'} \sin\delta_{ij} + B_{ij}^{'} \cos\delta_{ij}) \tag{5}$$

Where:

$$G_{ij}^{'} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$$

$$B_{ij}^{'} = \frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$$

These equations are incorporated in OPF formulations.

Cost function of FACTS devices: Costs of FACTS devices have been modeled by quadratic function. It has been taken for TCSC and SVC from (Cai *et al*., 2004). These functions are incorporated in OPF formulation. The quadratic cost functions used to estimate overall costs are given as:

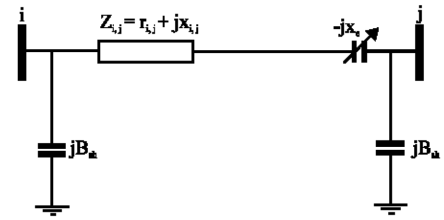

Fig. 1: TCSC between bus i and j

$$C(FACTS) = a_{fi}.S_i^2 - b_{fi}.S_i + d_{fi} (\frac{\$}{MVAR}) \tag{6}$$

Average annual cost of each FACTS device is calculated as:

$$C(FACTS)^{Annual} = C(FACTS).\frac{r(1+r)^n}{(1+r)^n - 1} (\frac{\$}{year}) \tag{7}$$

Where:

n = Project lifetime
r = Discount rate

Annual revenue of FACTS devices are calculated as:

$$R(FACTS)^{Annual} = R(FACTS)^{huor}.u.8760_i (\frac{\$}{year}) \tag{8}$$

where, u is the average utilization factor of FACTS devices in a year.

MARKET MODELING

In competitive electricity market, the bid of participators is corresponding to their marginal cost (for suppliers) or their marginal benefit (for consumers). Some consumers don't offer price for their electricity demand and buy their needed energy from spot market. These consumers are called Fixed Loads (FL).

Generator (supplier) marginal cost functions are given as:

$$C(P_{gi}) = b_{pi} P_{gi} + d_{pi} P_{gi}^2 \tag{9}$$

Dispatchable load (consumer) marginal benefit functions are given as:

$$B(P_{DLi}) = e_{pi}P_{DLi} + f_{pi}P_{DLi}^2 \quad (10)$$

For existing fixed loads in the network, the Value of Loss Load (VOLL) is considered as their bid.

Generator production dispatch and dispatchable load arrangement are calculated by Optimal Power Flow (OPF) algorithm. The objective function of the OPF formulation is the social welfare maximization. It has been formulated as follows:

$$\text{Maximize} \sum_i [B(P_{DLi}) + (VOLL - LMP_i)P_{FLi} - C(P_{gi})] \quad (11)$$

Subject to: $h(x) = 0$, $g(x) \le 0$

$h(x)$ specified a set of equality constraints which mainly include the load balance equations. $g(x)$ specified a set of inequality constraints which include generator limits, dispatchable load limits, bus voltage limits and line flows limits.

In LMP based electricity markets, market clearing price is equal to Lagrange factor in each bus. The Revenue of generators and dispatchable loads are calculated by the following equations:

$$PR = \frac{1}{2}\sum_{i \in NG}(LMP_i - b_{pi})(P_{gi} - P_{gi}^{min}) \quad (12)$$

$$DLR = \frac{1}{2}\sum_{i \in NDL}(e_{pi} - LMP_i)(P_{DLi} - P_{DLi}^{min}) \quad (13)$$

Where:
PR = Producer revenue
DLR = Dispatchable load revenue

Fixed Load Revenues (FLR) and Congestion Cost (CC) are given by following equations:

$$FLR = \sum_{i \in NFL}(VOLL - LMP_i)P_{FLi} \quad (14)$$

$$CC = \sum_{i \in NDL} LMP_i.P_{DLi} + \sum_{i \in NFL} LMP_i.P_{FLi} - \sum_{i \in NG} LMP_i.P_{gi} \quad (15)$$

REVENUE COMPONENTS

Usually transmission network costs contain two main sections. One of them is transmission operation and maintenance costs and another is capital and expansion costs.

FACTS devices decrease operation costs of transmission network by reducing congestion, improving voltage profile and reliability and postpone new expansion investment by change power flow direction and congestion management. Therefore, they should get revenue because of their services. So, in this study, FCTAS device services are divided into three components i.e., voltage profile improvement, reliability improvement and congestion management by considering different roles of these devices. The revenue of FATCS devices from each component has been described in the following.

Voltage profile improvement: Bus voltage is an important parameter in transmission network operation. Its limitations are unequal constraints in OPF formulation which must have the standard deviation. FACTS devices can control bus voltages in both under voltage and over voltage cases.

For secure transmission network operation, occasionally, transmission operators used either load shedding or FACTS devices to keep bus voltages in their standard limits. In the first case, the system operators should pay the penalty for load shedding and in the second case, they should pay for FACTS devices capital costs. For system operators, a case with lower payment is acceptable economically.

For calculating the revenue of FACTS devices in voltage profile improvement, a situation in which voltage of some buses deviate from their standards has been supposed. In the first case (without any FACTS devices in the transmission network), system operators reject a part of loads (minimum size) to return bus voltages into their permitted limits. Then, by solving an OPF algorithm, the revenue of market participators is calculated by Eq. 12-15. In the second case (with all existing FACTS devices), system operators don't reject any load because bus voltages have been returned into their standard limits by using FACTS devices. Then, the corrected OPF algorithm is solved. In the corrected OPF formulations, the static model of FACTS devices and their corresponding cost functions are incorporated. In this case, the revenue of Market participators is calculated similar to the first case.

Total revenue of FACTS devices is a part of summation of positive difference of revenues on two cases. In this study, the proposed algorithm in Eq. 16 for assigning FACTS devices revenues has been improved by considering the role of fixed load in FACTS devices revenues, as follows:

$$R_{FACTS,V} = \Delta FLR + \Delta DLR + \sum_{i \in NG} P_{gi}^{*1}(LMP_i^{*2} - LMP_i^{*1}) \quad (16)$$

$$\Delta DLR = DLR^{*2} - DLR^{*1} \; \Delta DLR = DLR^{*2} - DLR^{*1} \quad (17)$$

$$\Delta FLR = FLR^{*2} - FLR^{*1} \quad (18)$$

where, index ($*^1$) shows the first case and index ($*^2$) shows the second case. Total increased load revenue is allocated to FACTS devices. In the second case, loads pay equal the first case and all demands are supplied (no rejected load). Therefore, they have sufficient motives to pay all of their increased revenues. In order to increasing generators' motivation for increasing their generation in the second case, increased generations are purchased by new market clearing price. This algorithm is used to calculate the revenue of FACTS devices in congestion management and reliability improvement too.

Congestion management: The role of transmission line congestion on market participants' revenue is undeniable. Congestion in transmission lines will be decreased by using FACTS devices in the transmission network. Therefore, this is an important revenue component of FACTS devices.

For calculating the revenue of FACTS devices in congestion management, a situation in which power flow in some branches have increased from their standards has been supposed. the OPF is solved for two cases (with and without FACTS devices) and calculate the revenue of market participators by Eq. 12-15. A part of the increased revenue of participators caused by FACTS devices is allocated to FACTS devices. In both cases, all bus voltages are in their standard limitations. The revenue of FACTS devices in this component are calculated by the following equation:

$$R_{FACTS,C} = \Delta FLR + \Delta DLR + \sum_{i\in NG} P^{*1}_{gi} (LMP^{*2}_{i} - LMP^{*1}_{i}) \tag{19}$$

Reliability improvement: Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and make electricity supply more secure by reducing the number of line trips.

In some cases, a line has been out of service for maintenance. In these cases, the transmission network reliability can be increased by using FACTS devices.

For calculating FACTS device revenues in reliability improvement, it is supposed that only one transmission line has been out of service simultaneously. Then for each line outage, the revenue of market participants and FACTS devices is calculated.

Here, the revenue of FACTS devices is given as follows:

$$R_{FACTS,R} = \sum_{j\in NL} [\Delta FLR_j + \Delta DLR_j + \sum_{i\in NG} P^{*1}_{gi} (LMP^{*2}_{i} - LMP^{*1}_{i})_j] \tag{20}$$

Index j is related to out of serviced line and is sum of FACTS devices revenue in reliability improvement. NL is the set of network lines and NG is the set of network generators.

Proposed method: After restructuring in electricity industry, private investors have invested in different parts of electricity industry. In these situations, there are different facilities with different owners and then it is necessary to determine the revenue share of each facility.

The revenue of all installed FACTS devices in the transmission network have been calculated in three components. In the following, our new algorithm is explained to determine the revenue share of each FACTS device and describe the advantages of this method.

Postage stamp method is an easy method for determining the revenue share of each FACTS device, but in this method, the role of each device in voltage control, congestion management and reliability improvement is not considered and the revenues aren't allocated fairly between FATCS devices. So, this method doesn't provide a correct economic signal for optimal installation of FACTS devices.

Our proposed algorithm is based on OPF algorithm and allocates the revenue between FACTS devices by considering the role of each FACTS device in each revenue component and provides a suitable economic signal. This method is based on both marginal and incremental concepts for considering FACTS devices in the network that are explained individually in the following.

Marginal benefit method: Considering each FACTS device as the first added device to the transmission network is the first primary concept which has been used to determine the revenue share of each FACTS device and called marginal benefit method which is calculated in two steps.

In the first step, the transmission network is considered without any FACTS devices and the benefits of market participators are calculated by Eq. 12-14. In the second step, FACTS device i is added to the transmission network and calculate the revenue share of market participators by Eq. 12-14 and the revenue share of device i by Eq. 16, 19 and 20 that called Marginal Revenue (MR_i). These steps are repeated for all FACTS devices.

When the revenue shares of all FACTS devices are summed together in each component, these summations are more than related actual values which calculated in section 4. For eliminating this problem, the revenue of each device in each component is multiplied in an amendatory factor. The amendatory factor and the revenue share of each FACTS device are calculated for voltage control component by the following equations:

$$\alpha_{M,V,i} = \frac{MR_{FACTS,V,i}}{\sum_{i\in NF} MR_{FACTS,V,i}} \quad (21)$$

$$MREV_{FACTS,V,i} = \alpha_{M,V,i}.R_{FACTS,V} \quad (22)$$

where, $\alpha_{M,\ V,\ I}$ is the amendatory factor, $MR_{FACTS,\ V,\ I}$ is calculated by Eq. 16, when only FACTS device i has been installed in the transmission network. $MREV_{FACTS,\ V,\ I}$ is the net revenue of FACTS device i in voltage control component and NF is the set of installed FATCS devices For other revenue components, corresponding equations are obtained.

Calculation of each FACTS device's benefit share by considering its effect on additional revenue of market participators is exactly the advantage of this method.

Incremental benefit method: The second primary concept which has been used to determine the revenue share of each FACTS device is considering each FACTS device as the last added device to the transmission network and called incremental benefit method which is calculated in two steps.

In the first step, the transmission network is considered with all FACTS devices except device i and the benefits of market participators are calculated by Eq. 12-14. In the second step, FACTS device i is added as the last device to the transmission network and calculate the revenue share of market participators by Eq. 12-14 and the revenue share of device i by Eq. 16, 19 and 20 that called Incremental Revenue (IR_i). These steps are repeated for all FACTS devices.

Like marginal benefit method, a new amendatory factor is determined. Related equations have been shown for voltage profile improvement component in the following:

$$\alpha_{I,V,i} = \frac{IR_{FACTS,V,i}}{\sum_{i\in NF} IR_{FACTS,V,i}} \quad (23)$$

$$IREV_{FACTS,V,i} = \alpha_{I,V,i}.R_{FACTS,V} \quad (24)$$

where, $IR_{FACTS,\ V,\ I}$ is the incremental revenue of device i for voltage profile improvement. This is calculated by Eq. 16 for two described steps. $\alpha_{I,\ V,\ I}$ is the amendatory factor, $IR_{FACTS,\ V,\ i}$ is the net revenue of FACTS device i in voltage control component and NF is the set of installed FATCS devices.

These two methods allocate the total revenue of each component between FACTS devices by two different concepts. In marginal benefit method, each device added as the first device but in incremental method each device added as the last device.

Compound benefit method: In this novel algorithm, marginal and incremental concepts are combined by minimizing the sum of squared difference between the actual revenue and marginal and incremental benefits in each component to use the advantages of both concepts.

By using the new algorithm, the problems of fair resource allocation are solved. In this method, sum of revenue share of all FACTS devices in each component is equal with the actual value which is calculated earlier and amendatory factor doesn't require.

The compound benefit method can distribute each revenue component to each FACTS device by minimizing the sum of squared difference between the actual revenue and marginal and incremental values. The formulation below shows an example on voltage profile improvement component.

$$\text{Min}\sum_{i\in NF}[(CREV_{FACTS,V,i} - MREV_{FACTS,V,i})^2 + (CREV_{FACTS,V,i} - MREV_{FACTS,V,i})^2] \quad (25)$$

In the compound benefit method, the impact of the studied FACTS device i on each benefit component as both the first and the last FACTS device are considered.

CASE STUDY

Components of FACTS devices revenue and proposed methods for determining the benefit share of each device are implemented on a 9-bus test system with two FACTS devices. The proposed method does not depend on kind and number of FACTS devices and network structure. These methods can be implemented on any network.

The studied network has nine buses, three generators, five fixed loads, ten branches and a dispatchable load, shown in Fig. 2. A SVC at bus 4 and a TCSC between lines 1 and 4 have been installed. A full AC Optimal Power Flow (OPF) program capable of handling FACTS devices was used to determine the ISO's optimal dispatch strategy.

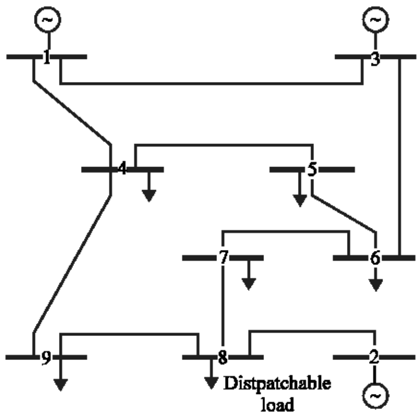

Fig. 2: Network configuration of nine-bus test system

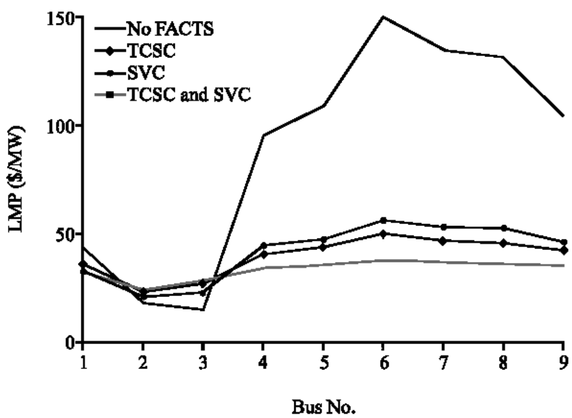

Fig. 3: LMP values at different buses for voltage profile improvement

Voltage profile improvement: For calculating the voltage profile improvement revenue component, a state of network is considered that one or more bus voltages are not in their standard limitations. In the first case, no FACTS devices has been placed in the network, the OPF algorithm is solved when 3% of base load had been rejected for eliminating bus voltage violations. In second case, the OPF has been solved when a SVC placed in the network. In the third case, the OPF has been solved when a TCSC placed in the network. In the 4th case, the OPF has been solved when a SVC and a TCSC placed in the network. By use of FCATS devices, a considerable reduction in marginal price in the system has been observed as shown in Fig. 3.

Figure 3 shows LMP values of all system buses for four different situations: without any FACTS devices, with TCSC, with SVC and with TCSC and SVC together. As shown in Fig. 3, by using FACTS devices, the LMP values decrease in load buses and they increase in generation buses, so that the nodal price spread is small.

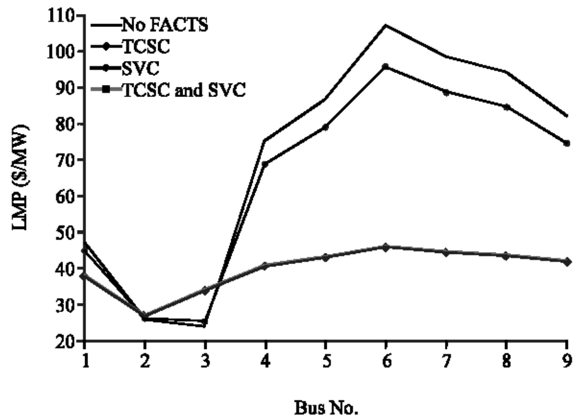

Fig. 4: LMP values at different buses for congestion management

Table 1: Annual share of each FACTS device for voltage profile improvement

Method	SVC[$/year]	TCSC[$/year]
Marginal benefit	1,400,733	1,549,467
Incremental benefit	1,053,333	1,896,867
Compound benefit	1,227,783	1,722,417

Table 2: Annual share of each FACTS device for congestion management

Method	SVC[$/year]	TCSC[$/year]
Marginal benefit	627,770	3,513,900
Incremental benefit	7,570	4,134,100
Compound benefit	317,670	3,824,000

The effect is that both load and generator revenue increases.

The Total annual revenue of FACTS devices in voltage profile improving component by average utilization of 2% is 2,950,200$. The revenue share of each device is shown in Table 1.

Congestion management: In this state, one or more lines of network are congested and all bus voltages are in their permanent limitations. The OPF algorithm has been solved four times: the network without any FACTS devices, with SVC, with TCSC and with SVC and TCSC. The LMP values at different buses for four cases are shown in Fig. 4.

The total revenue of FACTS devices in congestion management component by average utilization of 3% is 4,141,670 $ per year. Revenue share of each device is shown in Table 2.

Comparison of SVC's revenue share in incremental and marginal benefit methods in Table 2 clearly shows that considering SVC as the first added device (marginal benefit method) and the last added device (incremental benefit method) has an important effect on revenue share of SVC in congestion management.

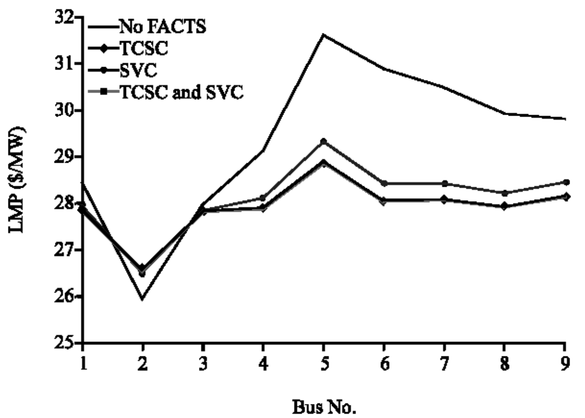

Fig. 5: LMP values at different buses for reliability improvement

Table 3: Annual share of each FACTS device for reliability improvement

Method	SVC[$/year]	TCSC[$/year]
Marginal Benefit	100,997	89,031
Incremental Benefit	25,219	164,809
Compound Benefit	63,108	126,920

Table 4: Total annual revenue of each FACTS device

Method	SVC[$/year]	TCSC[$/year]
Marginal benefit	2,129,500	5,152,398
Incremental benefit	1,086,122	6,195,776
Compound benefit	1,607,811	5,674,087

Reliability improvement: For reliability revenue analysis, in each case, one line is broken off and the OPF is solved for four times: without FACTS devices, with SVC, With TCSC and with SVC and TCSC. In this method, reliability of each line is considered individually and the related revenue share is calculated exactly. In this study, the reliability of all lines is same. The LMP values at different buses are shown in Fig. 5 when one line is broken off. It is assumed that lines are broken off for maintenance purposes; therefore, network lines have been loaded under 25%.

The Total annual revenue of FACTS devices in reliability improvement component is 185,836 $ per year by average utilization of 2%. Revenue share of each device is shown in Table 3.

Total annual revenue of each FACTS device: The total annual revenue of each FACTS device is calculated by summation of corresponding revenue of three revenue components.

As shown in Table 4, the installed SVC's revenue in Marginal benefit method (SVC is considered as the first added FACTS device in Transmission network) is around twice more than Incremental benefit method (SVC is considered as the last added FACTS device in Transmission network). By considering the role of each FACTS device in both situations in compound benefit method, a good economical signal is provided to increase investor's motivations.

Table 5: Annual cost of FACTS devices

Method	SVC	TCSC
Size (MVar)	35.00	85.00
Total capital cost (million $)	1.925	12.325
Discount rate (%)	8.00	8.00
Project lifetime (year)	5.00	5.00
Annual capital cost (million $)	0.48	3.10

Economic evaluation: In this stage, exciting SVC and TCSC are evaluated from an economic point of view and also, provided economic signal for expansion planning of each FACTS device are analyzed. The range of cost of major FACTS devices is presented in Siemens AG Database (Habur and O'Leans, 2004).

By comparing annual revenue of each device with corresponding annual cost from Table 4 and 5 respectively, it's understood that payback period for SVC is less than 1.5 years and payback period for TCSC is less than 2.5 years. The faster investment payback rate of SVC is a suitable economic signal for installing additional capacity of SVC in the network.

CONCLUSION

In this study, the roles of FACTS devices in voltage profile improvement, congestion management and reliability improvement are considered. The total earned revenue of FACTS devices was allocated between existing FACTS devices fairly. In our proposed method, the benefit share of each FACTS device is determined by considering the role of each device in mentioned earned revenue and suitable economic signals are provided for investigation on installing these devices in the network. In Marginal benefit method, each FACTS device is considered as the first added device which considers the role of each device correctly when calculates the revenue share of each device. In Incremental benefit method, each FACTS device is considered as the last added device which considers the effect of other devices when calculates the revenue share of each device. In our proposed method (compound benefit method), two concepts (marginal benefit and incremental benefit) have been combined by minimizing the sum of squared difference between the actual revenue and marginal and incremental values that allow us to use the benefits of both marginal and incremental methods together. For observing quantified results of proposed methods in this study, proposed algorithm have been implemented on a nine- bus test system and results have been analyzed (Appendix).

Table 6: Line data

From bus	To bus	R[pu]	X[pu]	B[pu]	Thermal limit
1	4	0.0	0.12	0.0	150
4	5	0.017	0.092	0.158	250
5	6	0.039	0.17	0.358	150
3	6	0.0	0.0586	0.0	300
6	7	0.0119	0.1008	0.209	90
7	8	0.0085	0.072	0.149	250
8	2	0.0	0.0625	0.0	250
8	9	0.032	0.161	0.306	250
9	4	0.01	0.085	0.176	250
1	3	0.0	0.08	0.0	250

Table 7: Generator and dispatchable load data

Gen.	Q_{max} [MVar]	Q_{min}[MVar]	P_{max} [MW]	P_{min} [MW]
G1	300	-300	250	10
G2	300	-300	300	10
G3	300	-300	270	10
Dispatchable load	0	0	0	-50

Table 8: Bus data

Bus No.	Bus type	P Load[MW]	Q load[MVar]	U_{max}[pu]	U_{min}[pu]
1	3	0	0	1.1	0.9
2	2	0	0	1.1	0.9
3	2	0	0	1.1	0.9
4	1	50	10	1.1	0.9
5	1	90	30	1.1	0.9
6	1	40	20	1.1	0.9
7	1	100	35	1.1	0.9
8	1	0	0	1.1	0.9
9	1	125	50	1.1	0.9

APPENDIX

This appendix provides the data of 9 bus system data (Anderson, Fouad, 1977) which has some minor modifications like changing bus names and adding a line between bus 1 and 3 (Table 6-8).

ABBREVIATIONS AND SYMBOLS

P_{gi} : Real power generation at bus i
P_{DLi} : Real power dispatchable load at bus i
P_{FLi} : Real power fixed load at bus i
b_{pi}, d_{pi} : First and second order coefficients of active power generator cost function at bus i
e_{pi}, f_{pi} : First and second order coefficients of consumer benefit function at bus i
a_{fi}, b_{pi}, d_{fi} : Cost coefficient of FACTS devices
S_i : Nominal capacity of FACTS devices
n : Project lifetime
r : Discounting rate
u : Utilization factor
NG, NDL, NFL, NF: Set of generator, dispatchable load, fixed load and FACTS devices
$\alpha_{M,V,i}$, $\alpha_{M,C,i}$, $\alpha_{M,R,i}$: Amendatory factor for voltage profile improvement, congestion management and reliability improvement in marginal benefit method
$\alpha_{I,V,i}$, $\alpha_{I,C,i}$, $\alpha_{I,R,i}$: Amendatory factor for voltage profile improvement, congestion management and reliability improvement in incremental benefit method

REFERENCES

Anderson, P.M. and A.A. Fouad, 1997. Power System Control and Stability. Iowa State University Press, USA., pp: 38.

Brosda, J. and E. Handschin, 2001. Congestion management methods with a special consideration of FACTS devices. IEEE Porto Power Tech Proc., 1: 6-6.

Cai, L.J., I. Erlich and G. Stamtsis, 2004. Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms. Proceedings of the IEEE PES Power Systems Conference and Exposition, Oct. 10-13, Essen, Germany, pp: 201-207.

Chanana, S. and A. Kumar, 2004. Effect of optimally located FACTs devices on active and reactive power price in deregulated electricity markets. Proceedings of the IEEE Power India Conference, Apr. 10-12, New Delhi, pp: 7-7.

Cheng, J.W.M., F.D. Galiana and D. McGillis, 2001. The application of FACTS controllers to a deregulated system. Proceedings of the IEEE 7th International Conference on AC-DC Power Transmission, Nov. 28-30, IEE London, pp: 10-14.

Habur, K. and D. O'Leans, 2004. FACTS-flexible alternating current transmission systems: For cost effective and reliable transmission of electrical energy. www.orldbank.org/html/fpd/em/transmission/factssiemens.pdf.

Hingorani, N.G., 2000. Role of FACTS in deregulated market. Proceedings of the IEEE Power Engineering Society Summer Meeting, Jul. 16-20, Seattle, WA., USA., pp: 1463-1467.

Huang, G. and P. Yan, 2002. TCSC and SVC as re-dispatch tools for congestion management and TTC improvement. Proceedings of the IEEE PES Winter Meeting, 2002, New York, pp: 660-665.

Mansour, Y., W. Xu, F. Alvardo and C. Rinizin, 1994. SVC placement using critical modes of voltage instability. IEEE Trans. Power Syst., 9: 757-763.

Nadarajah, M. and A. Naresh, 2007. A proposal for investment recovery of FACTS devices in deregulated electricity markets. Electric Power Syst. Res., 77: 695-703.

Phichaisawat, S. and Y.H. Song, 2002. Combined active and reactive congestion management with FACTS devices. Electric Power Components Syst., 30: 1195-1205.

Reddy, K., S. Reddy, N.P. Padhy and R.N. Patel, 2006. Congestion management in deregulated power system using FACTS devices. Proceedings of the IEEE Power India Conference, 2006, New Delhi, pp: 8-8.

Shi, Y.M. and K.L.A. Tuan, 2007. Valuation of facts for managing congestion in bilateral contract markets. Proceedings of the IEEE Power Engineering Society General Meeting, Jun. 24-28, Tampa, FL., USA., pp: 1-7.

Shrestha, G.B. and W. Feng, 2005. Effects of series compensation on spot price power markets. Int. J. Electrical Power Energy Syst., 27: 428-436.

Singh, S.N. and A.K. David, 2000. Congestion management by Optimizing FACTS device location. Proceedings of the IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2000, City University, London, pp: 23-28.

Singh, S.N., 2001. Location of FACTS devices for enhancing power systems security. Electric Power Syst. Res., 70: 7-15.

Singh, S.N. and A.K. David, 2002. Optimal location of FACTS devices for congestion management. Electric Power Syst. Res., 77: 352-360.

Srivastava, S.C. and R.K. Verma, 2000. Impact of FACTS devices on transmission pricing in a de-regulated electricity market. Proceedings of the IEEE Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2000, London, pp: 642-648.

Yao, L.Z. P. Cartwright, L. Schmitt and X.P. Zhang, 2005. Congestion management of transmission systems using FACTS. Proceedings of the IEEE PES Transmission and Distribution Conference, 2005, Dalian, China, pp: 1-5.