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MULTICRITERIA SELECTION OF OPTIMAL LOCATION OF TCSC IN A COMPETITIVE ENERGY MARKET

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The paper investigates selection of the best location of thyristor-controlled series compensator (TCSC) in a transmission system from many candidate locations in a competitive energy market such that the TCSC causes a net valuable impact on congestion management outcome, transmission utilization, transmission losses, voltage stability, degree of fulfillment of spot market contracts, and system security. The problem is treated as a multicriteria decision-making process such that the candidate locations of TCSC are the alternatives and the conflicting objectives are the outcomes of the dispatch process, which may have different importance weights. The paper proposes some performance indices that the dispatch decision-making entity can use to measure market dispatch outcomes of each alternative. Based on agreed-upon preferences, the measures presented may help the decision maker compare and rank dispatch scenarios to ultimately decide which location is the optimal one. To solve the multicriteria decision, we use the preference ranking organization method for enrichment evaluations (PROMETHEE), which is a multicriteria decision support method that can handle complex conflicting- objective decision-making processes.

K e y w o r d s: decision-making, competitive energy markets, performance indices, PROMETHEE, transmission congestion, thyristor controlled series compensator

1 INTRODUCTION

In a competitive energy market environment, the ISO or a qualified entity stands as the decision-making entity that finds the optimal dispatch schedules of the generators and demands participating in the bidding process. The traditional objective function in this process is a social welfare function which is built from offer and bid curves of the generators and demands participating in the market bidding process. The constraints include system physical constraints and constraints on bids and offers provided by market participants. The outputs of the electric energy dispatch decision process include wining values of power generations and demands and energy price at each bus of the system. If transmission congestion is reached in this process, energy prices vary from bus to bus in the system, and consequently congestion costs can be determined and imposed on transmission system users. Both congestion and transmission losses contribute to changes in energy prices at different locations of the system, where a flat profile of LMPs is a situation that accompanies a lossless congestion-free dispatch. If demands are elastic, total optimal demand served and total optimal generation produced will be different from those obtained from transmission unconstrained dispatch or those obtained from the dispatch with inelastic loads [1–4].

The basic task of transmission network is to effectively convey electrical energy from generation resources to demands, while maintaining necessary standards of security and quality of power supply. Even though transmission system has been recognized as a key element in regulated monopolies, however, importance of transmission system has gained more attention in a restructured environment, as it is the sender of the price signals to many participants and investors and because sufficient transmission capacity guarantees equitable competition of generators. The restructuring of the electric energy industry has showed that it is vital for the power system operation to have more power flow control needs [1]. Restructuring has imposed new economical and technical challenges and magnified traditional concerns. One of the main challenges is that the transmission network capability should be adequate to transport the contracted electric energy from sources to intended destinations, which ideally aims at reaching a congestion-free system. Energy prices in restructured power systems are mainly dependent on loading levels of transmission network, where congested transmission indicates that more dollars per MWh should be paid for energy. In addition, feasibility of more contracts to be held between supply and demand sides is directly related to available capability of transmission network. Earnings of transmission providers in a specific time horizon also depend on their transmission facility capabilities and whether or not transmission is constrained.

The flexible ac transmission system (FACTS) devices integrate a wide range of controlling devices and possess positive technological qualifications that make them enrich the flexibility of the existing power networks [5–23]. It would be beneficial to many power system participants to have control devices that help existing power system facilities gain more power transfer capability. The thyristor-controlled series compensator (TCSC) is FACTS control device that can considerably alter transmission system parameters. It can be operated in both inductive and capacitive modes. It can be used to help resolve some of the key issues in restructured competitive energy mar-

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ket environment. The TCSC possesses positive technical qualifications as it considerably provides control of line impedance, which is a basic power system parameter on which system performance depends. The need for series compensation is valuable and of more interest in deregulated power markets to improve the overall utilization of an electrical power network. The many qualifications of series compensation technology enrich the flexibility of the existing power networks [5–23].

The paper reviews structure and modeling of the TCSC device and its impacts on restructured energy market outcomes. Attention will mainly be focused on congestion-related concerns, bidding results, transmission utilization and losses, steady-state stability, and line loadings. In this paper, we use a hybrid model for energy market that involves both spot (pool) transactions and bilateral contracts. The paper investigates the available alternatives of locating the TCSC in the system, where the problem of selecting the best location of TSCS in the dispatch process of the competitive market is treated as a multicriteria decision-making process. The candidate locations of TCSC are the alternatives which will be evaluated based on some proposed performance measures that suit outcomes of a competitive market dispatch process. The outcomes of this process are conflicting, with possibility of having different importance factors. Therefore, one of the main targets of this paper is the selection of the best location of a candidate TCSC in a transmission system. The outcomes considered in this paper are level of system usage, measure of energy locational-marginal prices (LMPs), total system generation, measure of steady-state stability limits [2426], total transmission system losses, and line loading levels. The paper proposes some performance indices that the dispatch decision-making entity — the ISO — can use to measures these outcomes. Based on agreed-upon preferences, the measures presented may help the ISO compare and rank alternatives to finally decide which one is the optimal. For the ISO to make a compromise to decide which dispatch is better based on the established preferences or priorities, we will use a multicriteria decision support method that can handle complex conflicting-objective decision-making processes.

There are several mutlicriteria decision-aid approaches or decision-support systems that have been proposed in the literature. A comprehensive coverage of decision-aid approaches and applications can be found in [27–42]. These approaches are classified based on the type of decision model applied. In general, the different approaches are either based on a single utility function or based on pairwise comparisons. The first type of approaches is based on the notion of multi- attribute function where the criteria are aggregated in a single utility function that considers the preferences of the decision-making entity. The second type of approaches is based on the notion of outranking where alternative decisions are compared in a pairwise fashion. Both types have been also used in dealing with real world decision-making problems to help in the selection of the best compromise alternatives.

Based on the established preferences (or priorities) and the proposed measures, we suggest to use the PROMETHEE method [39–42] to prioritize the alternatives under study. PROMETHEE has been used as it is more stable and has a better performance than other methods. It is a user-friendly outranking method, which has been applied successfully in many conflicting objective decision-making fields. The method enables the decision-maker to find the optimal decision without resorting to a large number of comparisons. It has been applied successfully to many real world problems such as environmental planning, resource management and energy exploitation problems. In addition to its simplicity, PROMETHEE allows for both partial and total ranking of the alternatives [39–42]. The presented work can be applied for additional alternatives and criteria that may face the ISO during the selection process of a dispatch or alternative among many available scenarios in different competitive electricity market structures.

2 TCSC BENEFITS AND MODELING

The series compensation is mainly based on the idea of adjusting line impedance where the thyristors in the TCSC, based on their firing angle, are used to add series capacitance or inductance into a transmission line in which the TCSC is inserted. It is a basic idea that increasing the transfer capability of power between two points is attained by decreasing reactance of the circuit between the two points. On the other hand, to relieve loading of a certain line, the impedance of this line is increased or the impedance of the line adjacent to this line is decreased. These basic ideas can be implemented using TCSC to alter line power flows and support transmission congestion relief procedures and to minimize congestion-related costs or reduce losses.

Traditionally, mitigating transmission constraints results in expensive or undesired alternatives such as resorting to out-of-merit order on generation side as a short-term solution or resorting to system expansion or uprating on transmission side as a long-term solution. Series devices can be utilized in electric power networks to increase the transfer capability at an acceptable investment cost and with a short installation time compared to the building of additional lines [3, 14, 20, 22].

As an outcome of restructuring, transmission providers and ISO are increasingly asked to explore techniques of local control to resolve a number of possible problems. Therefore, they may utilize TCSCs to fulfill some of their control needs. It is anticipated that utilizing these devices in interconnected power systems improves and brings more benefits of mutual trade of electric energy between the interconnected networks, facilitates transfer of more bulk power between networks, and enables neighboring utilities and regions to economically and reliably exchange power. These devices help the system operate more securely by offering an increase in the level of power transferred between specific areas, and in some

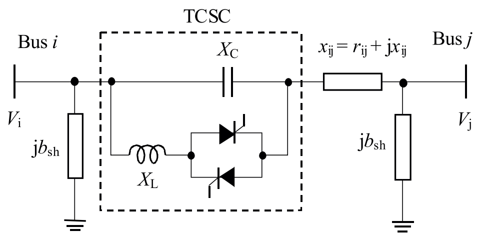


Fig. 1. Representation of a TCSC-inserted line

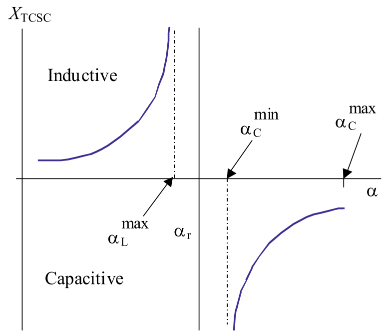


Fig. 2. Equivalent reactance of TCSC as a function of firing angle

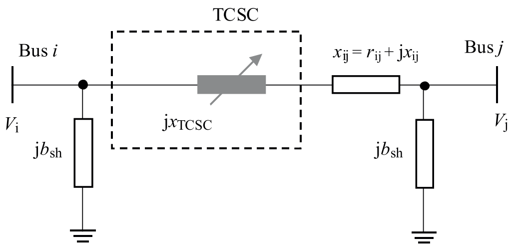


Fig. 3. Equivalent circuit of a TCSC-inserted line using reactance

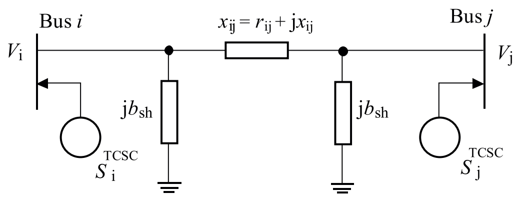


Fig. 4. Equivalent circuit of a TCSC-inserted line using complex power injections

cases may prevent or reduce loads shedding or curtailment that would be required to maintain system security.

The circuit shown in Fig. 1 represents a TCSC inserted within the equivalent pi-model of a transmission line connecting buses i and j, where z_{ij} and b_{sh} refer, respectively, to the series impedance and shunt susceptance of the line. The voltages $V_i = V_i\angle\theta_i$ and $V_i = V_j\angle\theta_j$ are the complex voltages at nodes i and j, respectively. The TCSC consists of a capacitor bank whose reactance is X_C connected in a parallel thyristor controlled inductor whose reactance is X_L [5, 6]. TCSC operates such that the TCSC is seen by the transmission system as controllable equivalent reactance. The equivalent reactance of the TCSC (x_{TCSC}), which is a function of the firing angle, can be inductive (positive) or capacitive (negative), depending on the range of firing angle in which the device is operating. The equivalent reactance of TCSC as a function of the firing angle (α) is shown in Fig. 2. A resonance condition that occurs for the inductance-capacitance parallel combination at α_r should be avoided. As shown in Fig. 2, a safety margin to resonance condition is kept by limiting the firing angle to be $\alpha \geq \alpha_r + \Delta\alpha$ for capacitive mode and $\alpha \leq \alpha_r - \Delta\alpha$ for inductive mode.

The operating limits of the equivalent reactance are determined by the limits of firing angle. Therefore, the limits of x_{TCSC} and α and are expressed as

$$X_{TCSC}^{\min} \leq x_{TCSC} \leq X_{TCSC}^{\max} \,. \tag{1}$$

For inductive mode, limits on firing angle are determined by

$$\alpha_L^{\min} \leq \alpha \leq \alpha_L^{\max};\ \alpha_L^{\min} = \pi/2 \,. \tag{2}$$

For capacitive mode, limits on firing angle are determined by

$$\alpha_C^{\min} \leq \alpha \leq \alpha_C^{\max};\ \alpha_C^{\max} = \pi \,. \tag{3}$$

If $\beta = \pi - \alpha$, the equivalent reactance of TCSC x_{TCSC}, as a function of the firing angle α, is given by [5, 6]

$$\begin{aligned} x_{TCSC}(\alpha) = -X_C + k_1(2\beta + \sin(2\beta)) \\ - k_2\big(\cos^2\beta\big)\big(\varpi\tan(\varpi\beta) - \tan\beta\big) \end{aligned} \tag{4}$$

$$\begin{aligned} k_1 &= \frac{X_C + X_{LC}}{\pi}\,,\ k_2 = \frac{4X_{LC}^2}{\pi X_L}\,, \\ X_{LC} &= \frac{X_C X_L}{X_C - X_L}\,,\ \varpi = \sqrt{\frac{X_C}{X_L}}\,. \end{aligned} \tag{5}$$

There are two approaches to model the effect of inserting the TCSC in a line [12, 16, 17, 20, 22, 24]. The first approach is by modeling the TCSC by an adjustable equivalent reactance x_{TCSC} as shown in Fig. 3. The second approach is to model the effect of inserting TCSC by adding complex power injections (withdrawals) at the ends of pi-model of the line as shown in Fig. 4. The complex powers at bus i (S_i^{TCSC}) and at bus j (S_j^{TCSC}), are defined as

$$S_i^{TCSC} = P_i^{TCSC} + jQ_i^{TCSC} \tag{6}$$

$$S_j^{TCSC} = P_j^{TCSC} + jQ_j^{TCSC} \tag{7}$$

which are calculated as

$$\begin{aligned} P_i^{TCSC} &= \Delta G_{ij}V_i^2 - V_iV_j[\Delta G_{ij}\cos(\theta_i - \theta_j) \\ &\quad + \Delta B_{ij}\sin(\theta_i - \theta_j)]\,, \end{aligned} \tag{8}$$

$$\begin{aligned} P_j^{TCSC} &= \Delta G_{ij}V_j^2 - V_iV_j[\Delta G_{ij}\cos(\theta_j - \theta_i) \\ &\quad + \Delta B_{ij}\sin(\theta_i - \theta_j)]\,, \end{aligned} \tag{9}$$

$$\begin{aligned} Q_i^{TCSC} &= -\Delta B_{ij}V_i^2 - V_iV_j[\Delta B_{ij}\cos(\theta_i - \theta_j) \\ &\quad + \Delta G_{ij}\sin(\theta_i - \theta_j)]\,, \end{aligned} \tag{10}$$

$$\begin{aligned} Q_j^{TCSC} &= -\Delta B_{ij}V_j^2 - V_iV_j[\Delta B_{ij}\cos(\theta_j - \theta_i) \\ &\quad + \Delta G_{ij}\sin(\theta_j - \theta_i)]\,, \end{aligned} \tag{11}$$

$$\Delta G_{ij} = x_{TCSC}\frac{r_{ij}(x_{TCSC} - x_j)}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)}\,, \tag{12}$$

$$\Delta B_{ij} = x_{TCSC}\frac{r_{ij}^2 - x_{ij}^2 + x_{TCSC}x_{ij}}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_{TCSC})^2)}\,. \tag{13}$$

3 PROMETHEE OUTRANKING

The PROMETHEE is a multicriteria decision support method which is based on pairwise comparisons [39–42]. It enables the decision-maker to directly use the data of the decision problem in a simple multicriteria table. Instead of having to perform a large number of comparisons, the decision-maker has only to define his own scales of measure to indicate his priorities (preferences) for every criterion under consideration. The criterion is a function used to evaluate the degree of performance of each alternative with respect to an objective of the decision-maker. Criteria can be either numerical or qualitative. In this method, a preference function must be associated to each criterion, where the function translates a deviation observed on one criterion into a degree of preference [39–42].

The method has two different rankings: partial ranking and complete ranking. To achieve ranking of available alternatives, PROMETHEE uses the so-called multicriteria preference flows, which are quantities calculated to summarize the results of the pairwise comparisons. It uses three multicriteria preference flows that provide three ways to rate the alternatives, which are the positive flow, the negative flow and the net flow. In nutshell, the method is based on forming a performance table, then selecting a preference function for each criterion, then setting the importance weight for each criterion, then calculating the aggregated preference index, then calculating outranking flows, and finally deciding the optimal alternative based on these flows [39–42].

Table 1. PROMETHEE evaluation table

Alternatives	Criterion c_1	c_2	$\dots$	c_k
a_1	$c_1(a_1)$	$c_2(a_1)$	$\dots$	$c_k(a_1)$
a_2	$c_1(a_2)$	$c_2(a_2)$	$\dots$	$c_k(a_2)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
a_n	$c_1(a_n)$	$c_2(a_n)$	$\dots$	$c_k(a_n)$

Let us refer to the set of n alternatives by A and the set of k criteria by C, where $A = \{a_1, a_2, \dots, a_i, \dots, a_n\}$ and $C = \{c_1, c_2, \dots, c_j, \dots, c_k\}$, and let $c_j(a_i)$ represents the performance of alternative a_i with respect to criterion c_j, *ie*, $c_(a_i)$ is the value of criteria j for alternative a_i. The set A represents the set of n alternatives to rank or choose from, and the set C represents the k criteria that have been considered, for each alternative $a \in A$. The decision-maker has to set weights of importance w_j of criteria j, where the higher is the weight, the more important is the criterion. Weights are allocated to the criteria to consider the priorities of the decision- maker. PROMETHEE uses the performance (evaluation) table shown in Tab. 1. The table represents a matrix of set of n alternatives evaluated on k criteria with k weights, where the weight w_j is a positive number that represents the relative importance of a criterion for the decision-maker, such that

$$W = \sum_{j=1}^{k} w_j \,. \tag{14}$$

In PROMETHEE, a preference function must be associated to each criterion, where the function translates a deviation observed on one criterion into a degree of preference. This function is used to determine the degree of preference associated to the best action in case of pairwise comparisons. The method uses six different shapes of preference functions (see Table 2), which are Usual-shape, U-shape, V-shape, Level-shape, Linear-shape and Gaussian-shape [39–42]. The U-Shape and the Level-shape preference functions are mostly used with qualitative criteria, while the V-Shape, the Linear-shape, and the Gaussian-shape preference functions are often used with quantitative criteria. The p and q values shown in Table 2 are, respectively, the indifference and the preference thresholds, which are set by the decision maker.

To rank the alternatives of set A, the algorithm for PROMETHEE can be outlined by the following five steps [24–[29]:

Step 1: A weighting factor w_j is assigned to each criterion c_j by the decision-making entity.

Step 2: Select a preference function for each criterion based on preferences of the decision-maker and depending on the situation modeled by criterion c_j. The preference function is usually assumed a function of the deviation $d = c_j(a) - c_j(b)$. Let j is the characteristic index of c_j, then for two alternatives $a, b \in A$, the preference functions, $P_j(a,b)$, are defined as

$$P_j(a,b) = P_j\big[d_j(a,b)\big], \quad a,b \in A \tag{15}$$

$$d_j(a,b) = c_j(a) - c_j(b)\,, \tag{16}$$

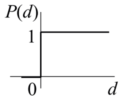
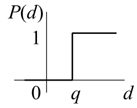
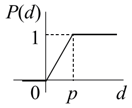
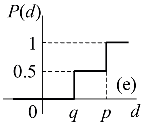
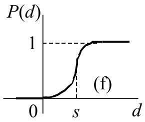
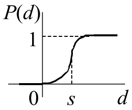
$$0 \le P_j(a,b) \le 1\,. \tag{17}$$

For each pair of alternatives, $P_j(a,b)$ varies from 0 to 1, starting at 0 if $f_j(a) = f_j(b)$ and increasing with $f_j(a) - f_j(b)$ to reach 1 when the difference is sufficiently large. The function $P_j(a,b)$ measures the degree of preference of action a over action b for criterion j, which is interpreted as follows

$P_j(a,b) = 0$	: a is not better than b with respect to criterion j	(no preference)
$P_j(a,b) \approx 0$	: a is slightly better than b with respect to criterion j	(weak preference)
$P_j(a,b) \approx 1$	: a is strongly better than b with respect to criterion j	(strong preference)
$P_j(a,b) = 1$	: a is strictly better than b with respect to criterion j	(strict preference)

Step 3: Calculate the aggregated preference index (outranking degree), $\pi(a,b)$, of every alternative a over alternative b. The index $\pi(a,b)$ expresses how and to what degree a is preferred to b over all criteria. If $\pi(a,b)$ is close to 0, it means a weak global preference of a over b. On the other hand if $\pi(a,b)$ is close to 1, it means a strong global preference of a over b. The higher $\pi(a,b)$

Table 2. Types of PROMETHEE preference functions

Type	Characteristics	Definition, $P(d) =$	Parameters
Usual-Shape		$\begin{cases} 0, & d \le 0 \\ 1, & d > 0 \end{cases}$	–
U-Shape		$\begin{cases} 0, & d \le q \\ 1, & d > q \end{cases}$	q
V-Shape		$\begin{cases} 0, & d \le 0 \\ d/p, & 0 \le d \le p \\ 1, & d > p \end{cases}$	p
Linear-Shape		$\begin{cases} 0, & d \le q \\ (d-q)/(p-q), & q < d \le p \\ 1 & d > p \end{cases}$	p, q
Level-Shape		$\begin{cases} 0, & d \le q \\ 0.5, & q \le d \le p \\ 1 & d > p \end{cases}$	p, q
Gaussian-Shape		$\begin{cases} 0, & d \le 0 \\ 1 - e^{-d^2/2s^2}, & d > 0 \end{cases}$	s

is the most preferred is alternative a. The aggregated preference index is calculated as follows

$$\pi(a,b) = \frac{1}{W}\sum_{j=1}^{k} w_j P_j(a,b)\,. \tag{18}$$

Step 4: For each alternative a, the method calculates three multicriteria preference flows, which provide three ways to rate the alternatives, which express how much an alternative is dominating the other ones. The three outranking flows are the basis of the PROMETHEE rankings, which are described below.

The positive (or leaving) outranking flow of alternative a, $\varphi^+(a)$, indicates or measures how an alternative a outranks the other alternatives, *ie*, the positive flow measures the average degree of preference with which an alternative is preferred to the other alternatives. The positive flow gives the absolute outranking power of alternative a. It is defined in the $[0,1]$ interval, where a value equal to 0 indicates that the action is not preferred at all to any other one, while a value equal to 1 indicates that the action is completely preferred to all the other ones. These are of course two extreme situations that will not appear generally. The larger is $\varphi^+(a)$ the better is the alternative$a$. The positive outranking flow is calculated as

$$\varphi^+(a) = \frac{1}{n-1}\sum_{\substack{b\in A\\ b\neq a}} \pi(a,b)\,. \tag{19}$$

The negative (or entering) outranking flow of alternative a, $\varphi^-(a)$, indicates or measures how an alternative a is outranked by the other alternatives, *ie*, the negative flow measures the average degree of preference with which the other alternatives are preferred to an alternative. The smaller is $\varphi^-(a)$ the better is the alternative a. The negative flow gives the outranked power of alternative a. It is also defined in the $[0,1]$ interval, where a value equal to 0 indicates that no other alternative is preferred to the alternative a, while a value equal to 1 indicates that all the other alternatives are completely preferred to alternative a. These are also two extreme situations that will not appear generally. The negative outranking flow is calculated as

$$\varphi^-(a) = \frac{1}{n-1}\sum_{\substack{b\in A\\ b\neq a}} \pi(b,a)\,. \tag{20}$$

The net flow of an alternative a, $\varphi(a)$, combines the values of $\varphi^+(a)$ and $\varphi^-(a)$ into a single rating. The net flow of alternative a is the difference between the positive flow and the negative flow of the alternative a. Therefore, it is defined in the $[-1,1]$ interval, where the best actions have positive values while the worst ones have negative values. The larger is the value $\varphi(a)$ the better is the alternative a. Positive net flows indicate above average alternatives, and negative net flows indicate below average alternatives. The net outranking flow is calculated as

$$\varphi(a) = \varphi^+(a) - \varphi^-(a)\,. \tag{21}$$

Step 5: Use positive flows (φ^+) and negative flows (φ^-) to rank the alternatives if partial ranking is wanted, which is called PROMETHEE I (partial) ranking method.

On the other hand, if complete ranking s wanted, use net flows (φ), which is called PROMETHEE II (complete) ranking method.

A partial ranking of alternatives can be determined from the positive and negative outranking flows. Partial ranking includes strict preference, indifference, and incomparability of alternatives, which are determined as follow

a outranks b if

$$\begin{cases} \varphi^+(a) > \varphi^+(b) \text{ and } \varphi^-(b) > \varphi-(a), \text{ or} \\ \varphi^+(a) > \varphi^+(b) \text{ and } \varphi^-(b) = \varphi-(a), \text{ or} \\ \varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(b) > \varphi-(a)\,, \end{cases} \quad (22)$$

a and b are indifferent if

$$\varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(b) = \varphi^-(a)\,, \quad (23,24)$$

a and b are incomparable in all other cases.

When both positive and negative flows are providing conflicting information, PROMETHEE I does not rank the alternatives, and the alternatives are considered as incomparable.

For the complete ranking (PROMETHEE II), it is easier to interpret because all the actions are ranked from the best to the worst one and there are no incomparabilities. A complete ranking of alternatives can be determined from the net outranking flows. Complete ranking includes strict preference and indifference of alternatives, which are determined as follow

$$a \text{ outranks } b \text{ if } \varphi(a) > \varphi(b)\,, \quad (25)$$

$$a \text{ and } b \text{ are indifferent if } \varphi(a) = \varphi(b)\,. \quad (26)$$

4 MATHEMATICAL MODEL OF ENERGY MARKET

In this paper, we use a hybrid model of energy market that involves both spot (pool) transactions and firm (non-curtailable) bilateral contracts. In the bilateral contracts, the transacted parties are free to negotiate their quantities, duration, prices and other terms, and the transacted parties pass their transaction values and associated source and destination points into the independent system operator (ISO) who use them to ensure feasibility and system security. We assume that generator (or seller) at bus i is producing an amount P^s_{Gi} to sell in the spot market and a fixed amount P^t_{Gi} to meet its bilateral contracts, and load (or buyer) at bus i is consuming an amount P^s_{Di} that is bought from the spot market and a fixed amount P^t_{Di} from bilateral contracts.

Using the generator and load bidding data, the ISO or the qualified entity maximizes the social welfare objective function, where system constraints are respected in this process. At the end of this optimization process, the final schedules of generators, demands, and energy locational prices are available and then congestion costs based on final schedules and prices are determined. We assume that reactive power is provided by spot market participants and the ISO will compensate for transmission losses from the pools generation.

In the following formulation, the superscript refers to the type of transaction, where s and t refer to spot and bilateral transactions, respectively, subscripts are used to refer to bus number, variables P_G/Q_G, P_D/Q_D are used to refer to active/reactive powers of generations and demands, respectively. Equality constraints include the active and reactive power balance equations at each bus. The inequality constraints include limits on generation and demand participating in the bidding process, voltage levels, line active power limits, and series impedance of TCSC. Note that total bilateral transacted generation should balance out total demand involved in bilateral contacts. In the following equations, ℓ refers to the index of the line connecting buses j and m, N_L is number of lines, N_B is number of buses, C^s_{Gi} is an offer price of a pool generator at bus i, C^s_{Di} is a bid price of a pool load at bus i, α_i is linear coefficients of a pool generator offer price at bus i, β_i is linear coefficients of a pool load bid price at bus i, S^s_D is set of load buses of the pool transactions, S^s_G is set of generation buses of the pool transactions, S^t_D is set of load buses of the bilateral transactions, and S^t_G is set of generation buses of the bilateral transactions. The problem is formulated as

Minimize

$$\sum_{i\in S^s_G} C^s_{Gi}(P^s_{Gi}) - \sum_{i\in S^s_D} C^s_{Di}(P^s_{Di}) \quad (27)$$

subject to

$$V_i \sum_m V_m[g_{im}\cos(\theta_i-\theta_m) + b_{im}\sin(\theta_i-\theta_m)] = P_{Gi} - P_{Di} - P^{TCSC}_i;\ i = 1,2,\ldots,N_B\,, \quad (28)$$

$$V_i \sum_m V_m[g_{im}\sin(\theta_i-\theta_m) - b_{im}\cos(\theta_i-\theta_m)] = Q_{Gi} - Q_{Di} - Q^{TCSC}_i;\ i = 1,2,\ldots,N_B\,, \quad (29)$$

$$-P^{\max}_\ell \le P_\ell \le P^{\max}_\ell\,;\ell = 1,2,\ldots,N_L\,, \quad (30)$$

$$\underline{P}^s_{Gi} \le P^s_{Gi} \le \overline{P}^s_{Gi}\,;\ i\in S^s_G\,, \quad (31)$$

$$\underline{Q}^s_{Gi} \le Q^s_{Gi} \le \overline{Q}^s_{Gi}\,;\ i\in S^s_G\,, \quad (32)$$

$$\underline{P}^s_{Di} \le P^s_{Di} \le \overline{P}^s_{Di}\,;\ i\in S^s_D\,, \quad (33)$$

$$\underline{P}_i \le v_i \le \overline{v}_i\,;\ i = 1,2,\ldots,N_B\,, \quad (34)$$

$$X^{\min}_{TCSC} \le x_{TCSC} \le X^{\max}_{TCSC}\,, \quad (35)$$

$$P_\ell = V_j^2 g_{jj} + V_j V_m[g_{jm}\cos(\theta_j-\theta_m) + b_{jm}\sin(\theta_j-\theta_m)]\,;\ \ell = 1,2,\ldots,N_L\,, \quad (36)$$

$$P_{Gi} = P^s_{Gi} + P^t_{Gi}\,;\ i\in S^s_G\,, \quad (37)$$

$$P_{Di} = P^s_{Di} + P^t_{Di}\,;\ i\in S^s_D\,, \quad (38)$$

$$C^s_{Gi} = \alpha_I P^s_{Gi}\,;\ i\in S^s_G\,, \quad (39)$$

$$C^s_{Di} = \beta_I P^s_{Di}\,;\ i\in S^s_D\,, \quad (40)$$

where P_i^{TCSC} and Q_i^{TCSC} n (28) and (29) are given by (8–11), and the conductances/susceptances given in (28), (29) and (36) are the conductances/ susceptances associated with the traditional admittance matrix of the original system without the series control device. In (31–33), $\underline{P}_{Gi}^s/\overline{P}_{Gi}^s$ and $\underline{Q}_{Gi}^s/\overline{Q}_{Gi}^s$ are minimum/maximum limits of active and reactive power limit of spot market generator at bus i, respectively and $\underline{P}_{Di}^s/\overline{P}_{Di}^s$ is minimum/maximum limits of of spot market demand at bus i.

If λ_i represents the Lagrangian multiplier of real power equality constraint at bus i, then at the optimal solution, the energy Locational Marginal Price (LMP) [1] at bus i is $\lambda_i^{\rm opt}$ that satisfies Kuhn-Tucker condition of the Lagrangian function at the optimal point [1–3], *ie*,

$$LMP_i = \lambda_i^{\rm opt}\,;\ i = 1, 2, \dots, N_B\,. \tag{41}$$

The LMPs are used in recently restructured power systems to evaluate energy payments of generators and loads and to allocate transmission congestion charges and credits among system users [1–3]. An LMP is the marginal cost of supplying the next increment of electric energy at a specific location (bus) considering generation marginal cost and the physical aspects of the transmission system.

5 PERFORMANCE MEASURES (CRITERIA)

5.1 Performance measures of energy market

In this paper some measures are proposed to quantify energy market outcomes, which are among the measures that will be used to select best dispatch alternative. These measures are:

1) Total System Generation (TSG): It is the total generation in MW due to both spot and bilateral transactions. It is expressed as

$$TSG = \sum_{i\in S_G^s} P_{Gi}^s + \sum_{i\in S_G^b} P_{Gi}^b. \tag{42}$$

This measure enables us compare different alternatives as related to the degree of using the transmission system or honoring market participants. The alternative becomes more preferred over other alternatives as the TSG value gets larger. The best dispatch is the one that gives TSG as that of the unconstrained transmission case.

System Utilization (SU): It is a percent value that indicates system usage compared to the unconstrained situation. The 100 % value of a certain dispatch is the ideal dispatch that indicates that TSG of this dispatch is the same as the optimal TSG associated with the unconstrained case (S^{unc}) . As the SU value decreases, system utilization becomes worse. The SU is given by

$$SU = (TSG/TSG^{unc}) \times 100\,. \tag{43}$$

2) Total Congestion Charge (TCC): This \$/h value is the difference between what loads pay and what generators are paid, and can be calculated using the following relation

$$\begin{aligned} TCC = \sum_{i\in S_G^s} P_{Gi}^s\lambda_i + \sum_{i\in S_G^b} P_{Gi}^b\lambda_i \\ - \sum_{i\in S_D^s} P_{Di}^s\lambda_i - \sum_{i\in S_D^b} P_{Di}^b\lambda_i\,. \end{aligned} \tag{44}$$

Index of Total Congestion Charge (I_{TCC}): It is a \$/MWh value that enables us to compare congestion charges of different alternatives, where every alternative may have different TCC or/and different TSG from others. As the I_{TCC} value of a dispatch gets smaller, the dispatch becomes more preferred. The index I_{TCC} is defined as

$$I_{TCC} = TCC/TSG\,. \tag{45}$$

3) Index of Locational Marginal Prices (I_{LMP}): It is a \$/MWh value that enables us to compare LMP values at system buses of different alternatives with the LMP values of the unconstrained dispatch (LMP_i^{unc}), ie, it measures the deviations in LMPs from those obtained from congestion-free situation. When congestion occurs in a certain dispatch, LMPs will differ from bus to bus, and as differences get larger the I_{LMP} becomes larger, which indicates more server congestion situation. The performance index I_{LMP} is defined as

$$I_{LMP} = \sum_{i=1}^{N_b}(LMP_i - LMP_i^{unc})^2\,. \tag{46}$$

4) Index of Total Transmission Loss (I_{TTL}): It is a percent value that indicates system losses compared to TSG. As the I_{TTL} value decreases, system performance becomes better. If TSD and $TTL = TSG - TSD$ indicate, respectively, total system demand and total transmission loss in the dispatch alternative under study, then the value I_{TTL} is given by

$$I_{TTL} = (TTL/TSG) \times 100. \tag{47}$$

5.2 Steady-state voltage stability

Let N_g number of generator buses, N_d number of load buses, and $V_i = V_i\angle\theta_i$ and $V_j = V_j\angle\theta_j$ are complex voltages at buses i and j, respectively. Using nodal analysis, the power system can be described by the equation

$$\boldsymbol{I} = \mathbf{Y}\boldsymbol{V} \tag{48}$$

where $\mathbf{Y}$ is bus admittance matrix, $\boldsymbol{V}$ is vector of bus voltages, and $\boldsymbol{I}$ is vector of net injected bus currents. If system buses are numbered such that the first N_g buses

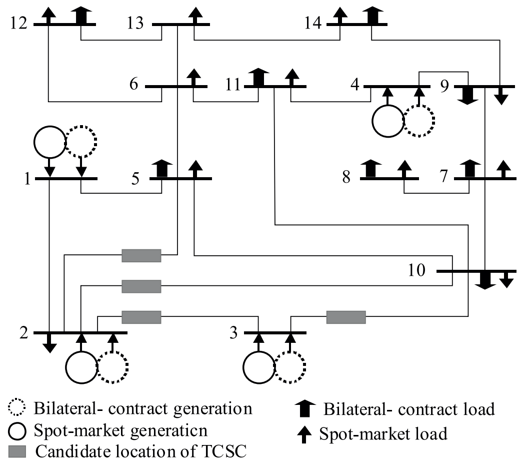


Fig. 5. The 14-bus test system

Table 3. Line data of the 14-bus test system pu

Line ℓ	From i	To j	r_{ij}	x_{ij}	$B/2$	P
1	1	2	0.01	0.2	0.02	0.60
2	1	5	0.01	0.3	0.03	2.00
3	2	3	0.03	0.32	0.04	1.00
4	2	10	0.01	0.20	0.03	2.50
5	2	5	0.03	0.36	0.03	1.50
6	3	10	0.02	0.40	0.01	2.00
7	10	5	0.01	0.10	0.01	1.00
8	10	7	0.01	0.08	0.01	2.50
9	10	9	0.01	0.10	0.01	2.00
10	5	6	0.01	0.10	0.01	2.00
11	6	11	0.05	0.40	0.01	1.00
12	6	12	0.02	0.50	0.01	1.00
13	6	13	0.04	0.30	0.01	1.00
14	7	8	0.01	0.10	0.01	1.00
15	7	9	0.01	0.08	0.01	1.50
16	9	4	0.03	0.20	0.01	2.00
17	9	14	0.02	0.12	0.01	1.50
18	10	11	0.04	0.40	0.01	1.50
19	12	13	0.05	0.25	0.01	0.50
20	13	14	0.02	0.50	0.01	0.50

Table 4. Generator data of the 14-bus test system

Bus i	P_{Gi}^{B} (pu)	$P_{Gi}^{s,\min}$ (pu)	$P_{Gi}^{s,\max}$ (pu)	α_i ($/MW)
1	1.00	0	2.000	9.0
2	0.80	0	2.700	9.5
3	1.20	0	1.800	10.0
4	0.60	0	2.900	10.5
$\sum$	3.60			

are the generator buses and the rest N_d buses are the load buses, then (47) can be written as [24–26]

$$\begin{bmatrix} \boldsymbol{I}_G \\ \boldsymbol{I}_D \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{GG} & \mathbf{Y}_{GD} \\ \mathbf{Y}_{DG} & \mathbf{Y}_{DD} \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_G \\ \boldsymbol{V}_D \end{bmatrix}. \tag{49}$$

With some manipulations, the system of equations in (2) can be written in the following hybrid from

$$\begin{bmatrix} \boldsymbol{V}_D \\ \boldsymbol{I}_G \end{bmatrix} \begin{bmatrix} \mathbf{Z}_{DD} & \mathbf{F}_{DG} \\ \mathbf{K}_{GD} & \mathbf{Y}_{GG} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_D \\ \boldsymbol{V}_G \end{bmatrix} \tag{50}$$

$$\mathbf{Z}_{DD} = \mathbf{Y}_{DD}^{-1}, \tag{51}$$

$$\mathbf{F}_{DG} = -\mathbf{Y}_{DD}^{-1}\mathbf{D}_{DG}\,, \tag{52}$$

$$\mathbf{K}_{GD} = \mathbf{Y}_{GD}\mathbf{Y}_{DD}^{-1}\,, \tag{53}$$

$$\mathbf{Y}_{GD} = \mathbf{Y}_{GG} - \mathbf{Y}_{GD}\mathbf{Y}_{DD}^{-1}\mathbf{Y}_{DG}\,. \tag{54}$$

The sub-matrix $\mathbf{F}_{DG}$ is the one that we will use for steady-state stability purposes. This sub-matrix is a $N_d \times N_g$ complex matrix, whose j^{th} row refers to the j^{th} load bus and i^{th} column refers to the i^{th} generator bus. If the ji^{th} complex entry of $\mathbf{F}_{DG}$ is referred to as $F_{DG_{ji}}$, then this entry can be expressed in rectangular form as

$$F_{DG_{ji}} = M_{ji} + jN_{ji}\,. \tag{55}$$

The steady-state voltage stability indicator (index) at bus load bus j, which is referred to as L_j, can be expressed as [24–26]

$$L_j = \Big|1 - \sum_{i=1}^{N_g} \frac{F_{DG_{ji}} V_i}{V_j}\Big|\,;\; j \in S_L \tag{56}$$

where S_L is the set of load buses. By substituting the values of the complex quantities in rectangular form in the last equation we can express the L-index as follows

$$L_j = \Big|1 - \sum_{i=1}^{N_g} \frac{V_i}{V_j} \frac{M_{ji} + jN_{ji})(\cos\theta_i + j\sin\theta_i)}{(\cos\theta_i + j\sin\theta_i)}\Big|;\; j \in S_L\,. \tag{57}$$

The L-index values lie in the range $[0,1]$. As L-index decreases towards zero the stability margin increases and as it increases towards 1 the stability margin decreases, where $L_j = 1$ indicates that stability limit at load bus j is reached, which in turn indicates that the system is approaching point of voltage collapse. On the other hand, the index $L_j = 0$ indicates maximum stability margin. Based on steady-state voltage stability indicators at load buses, we propose to use the following index of steady-stability (I_{stab}) of the system

$$I_{stab} = \sum_{j \in S_L} L_j^2\,. \tag{58}$$

This index measures the total of stability margins of all load buses. A smaller value of this index indicates a better dispatch alternative as related to stability margin.

5.3 Performance measure of line loading

The real power performance Index (PI_{MW}) gives a measure of line MW overloads. It is given by the following equation

$$PI_{MW} = \sum_{\ell=1}^{N_L} w_\ell \Big(\frac{P_\ell}{P_\ell^{\max}}\Big)^2 \tag{59}$$

where w_ℓ is a weighting factor that indicated importance of line ℓ.

6 TEST SYSTEM

Figure 5 represents a 14-bus test system, where bus 1 is the reference bus. Data and results in this section are based on a 100 MVA base. Line data, in p.u. are given in Table 3 where $B/2$ represents the half total line charging susceptance of the lines. Table 4 shows bilateral contract data and offer data of generators and Table 5 shows bilateral contract data and bidding of loads. Reactive power minimum and maximum limits of each generators are considered as -1.5 and 1.5 p.u., respectively.

The results of this test system are shown for the following six cases:

case 0: no TCSC, with line limits are ignored (unconstrained transmission dispatch).

case 1 (alternative 1): No TCSC, with line limits are considered (base case: traditional dispatch scenario).

case 2 (alternative 2): TCSC is inserted in line 3, with line limits are considered.

case 3 (alternative 3): TCSC is inserted in line 4, with line limits are considered.

case 4 (alternative 4): TCSC is inserted in line 5, with line limits are considered.

case 5 (alternative 5): TCSC is inserted in line 6, with line limits are considered.

The cases 1–5 are the candidate alternatives to be outranked while case 0 is used as a setup for energy market dispatch performance measures. The results of the sex cases under study, which include LMPs, line flows, and values of performance measures are shown in tables 6, 7 and 8, respectively. Even though case 0 (line unconstrained case) would be unrealistic, as this dispatch would give some line flows above their limits, results of this case will be used to calculate reference values to compare subsequent cases because case 0 represents the most economic dispatch and is accompanied by the maximum system utilization.

Table 5. Load data of the 14-bus test system

Bus j	P_{Dj}^{B} (pu)	$P_{Dj}^{s,\min}$ (pu)	$P_{Dj}^{s,\max}$ (pu)	β_j ($/MW)
5	0.40	0.0	0.60	14.00
6	0.00	0.0	0.50	13.75
7	0.80	0.0	0.20	13.00
8	0.40	0.0	0.40	12.00
9	0.60	0.0	1.20	16.00
10	0.40	0.0	0.40	15.25
11	0.20	0.0	0.40	13.00
12	0.40	0.0	0.40	14.75
13	0.00	0.0	1.20	15.50
14	0.40	0.0	1.10	16.00
$\sum$	3.60			

As can be seen from Table 8, each of cases 1–5 gives different outcomes compared to other cases. Case 1 represents the traditional outcome of the social-welfare maximization that the system operator usually runs. As the table shows, TSG of this case is less than TSG of case 0, as reaching line limits causes transmission congestion, which requires generators to operate in out-of-merit order. Compared to case 0, TSG of this case has decreased from 1057.654 MW to 943.783 MW because of congestion, which is indicated by TCC, I_{LMP}, SU, and I_{TCC}. For example, TCC has increased from $789.547/h (for case 0, due to losses) to $2628.900/h (for case 1, due to losses and congestion) and SU of case 0 has decreased from 100 % to 89.23 %. Cases 1–5 will be judged better or worse compared to case 1, based on values of I_{LMP}, SU, I_{TCC}, I_{stab}, $ITTL$, and PI_{MW}, which change from case to case.

Table 6. Locational marginal prices for the seven cases

	LMP_i ($/MWh)					
Bus i	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
1	10.221	9.000	9.000	9.000	9.000	9.000
2	10.248	1000	1000	1000	1000	9.886
3	10.000	10.000	10.000	10.000	10.000	10.000
4	10.500	10.500	10.500	10.500	10.500	10.500
5	10.972	11.269	11.168	11.703	11.257	10.965
6	11.451	13.750	13.750	13.750	13.750	13.750
7	11.390	11.902	11.858	11.861	11.871	11.714
8	11.544	12.000	12.000	12.000	12.000	11.874
9	11.406	11.828	11.769	11.777	11.789	11.624
10	11.020	11.679	11.604	11.610	11.624	11.449
11	11.481	12.984	12.948	12.950	12.960	12.866
12	12.091	14.750	14.750	14.750	14.750	14.750
13	12.159	15.008	15.011	15.041	15.038	15.018
14	12.113	16.000	16.000	16.000	16.000	16.000

Compared to the base case, each of the subsequent cases becomes better in some measures and worse in others, for example, case 2 is better than case 1 in terms of deviations in $LMPs$ (as indicated by I_{LMP}), system usage (as indicated by SU or TSG), transmission charges (as indicated by TCC or $ITCC$), but worse than case 1 in terms of stability margin (as indicated by I_{stab}), transmission loss (as indicated by TTL or I_{TTL}), and line loading (as indicated by PI_{MW}). Ranking of dispatch alternatives based on each of I_{LMP}, SU, I_{TCC}, I_{stab}, I_{TTL} and PI_{MW} criteria is shown in Table 9.

If one criterion is of interest, it is easy to decide which dispatch among available ones is the best from Table 9. For example, if serving (honoring) maximum demand is more important than maintaining minimum TCC, then dispatches of cases 2–5 are better than traditional dispatch (case 1), and cases 2 and 5 would be better than case 1 if minimizing TCC is more preferred over serving maximum demand. However, when conflicting multicriteria are considered such as the presented measures, the PROMETHEE method can be adopted to assess dispatch decision process.

The PROMETHEE evaluation table of the five alternatives is shown in Table 10. This table also shows the

Table 7. Line active power flows in MW

				P_ℓ					
ℓ	i	j	$P_\ell^{\max}$	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
1	1	2	60.0	67.568	60.000	60.000	53.656	60.000	60.000
2	1	5	200.0	232.432	200.000	200.000	200.000	200.000	200.000
3	2	3	100.0	-54.492	-43.219	-51.974	-27.056	-37.307	26.926
4	2	10	250.0	309.199	250.000	250.000	250.000	250.000	250.000
5	2	5	150.0	162.484	132.700	132.954	150.000	150.000	132.760
6	3	10	200.0	191.885	160.282	184.824	163.455	158.888	200.000
7	10	5	100.0	-42.075	-24.569	-24.817	-40.337	-40.274	-24.628
8	10	7	250.0	207.449	158.560	174.730	172.898	169.877	182.923
9	10	9	200.0	185.438	133.915	141.000	140.419	138.833	147.161
10	5	6	200.0	241.101	200.000	200.000	200.000	200.000	200.000
11	6	11	100.0	5.802	8.524	8.618	10.456	10.526	8.546
12	6	12	100.0	71.139	63.512	63.744	62.937	63.054	63.744
13	6	13	100.0	109.301	98.839	99.546	100.000	100.000	100.000
14	7	8	100.0	80.536	48.982	71.604	69.287	64.776	80.541
15	7	9	150.0	23.243	7.499	0.577	1.138	2.693	-0.389
16	9	4	200.0	-154.130	-190.078	-190.079	-190.079	-190.079	-185.025
17	9	14	150.0	179.855	150.000	150.000	150.000	150.000	150.000
18	10	11	150.0	55.242	52.414	52.323	50.431	50.363	52.393
19	12	13	50.0	-9.708	-6.201	-5.881	-3.796	-4.026	-5.368
20	13	14	50.0	-24.406	-30.626	-29.643	-27.123	-27.354	-28.703

Table 8. Values of performance measures of the six cases

Case	TSG	TCC	I_{LMP}	$\sum P_{Gi}^s$	SU	I_{TCC}	I_{stab}	TTL	I_{TTL}	PI_{MW}
0	1057.654	789.547	0.000	697.654	100.00	0.747	4.419	57.654	5.451	14.538
1	943.783	2628.900	41.059	583.783	89.23	2.785	3.462	44.665	4.732	10.569
2	968.795	2610.741	40.740	608.795	91.59	2.695	3.632	47.404	4.893	11.265
3	964.025	2686.153	41.428	604.025	91.14	2.786	3.765	46.749	4.849	10.878
4	959.656	2633.163	41.020	599.656	90.73	2.744	3.453	46.906	4.888	11.026
5	977.686	2449.585	39.625	617.686	92.44	2.505	3.205	47.429	4.851	11.375

selected preference function, threshold parameters, and weight of each criterion. An optimal dispatch is the dispatch that has maximum system usage ($\text{Max}\, SU$), minimum Index of Total Congestion Charge ($\text{Min}\, I_{TCC}$), maximum voltage stability margin ($\text{Min}\, I_{stab}$), minimum Total System Loss ($\text{Min}\, I_{TTL}$), minimum Index of LMPs ($\text{Min}\, L_{LMP}$), and minimum value of line loading performance index ($\text{Min}\, PI_{MW}$).

Table 9. Case rank for each of the five measures (criteria)

	performance measure (criteria)					
Rank	I_{LMP}	SU	I_{TCC}	I_{stab}	I_{TTL}	PI_{MW}
1(best)	a_5	a_5	a_5	a_5	a_1	a_1
2	a_2	a_2	a_2	a_4	a_3	a_3
3	a_4	a_3	a_4	a_1	a_5	a_4
4	a_1	a_4	a_1	a_2	a_4	a_2
5(worst)	a_3	a_1	a_3	a_3	a_2	a_5

The three multicriteria preference flows have calculated for the market dispatch alternatives using (14–21). The positive flows, negative flows and net flows are shown in Table 11. Using PROMETHEE complete rankings, as the net flows show, the best alternative is case 5.

Note that when the PROMETHEE has been used and multiple criteria are considered, the best dispatch selected is not necessarily the same dispatch that considers single criterion. As we have shown, the values of net flows indicate that case 5 is much better than case 1. Remember that case 1 is the case that is usually obtained in the traditional energy market dispatch process. If other weighting factors or preference functions are considered by the ISO, the ranking may change.

7 CONCLUSIONS

TCSC can be employed to help resolve some of the main problems of restructured power system environment. Utilizing TCSC during generator dispatch may reduce the additional cost incurred due to security concerns that require generators to operate in out-of-merit order. The electric power utilities can integrate their existing systems with TCSC to improve capability of system without resorting expensive or unfavorable alternatives. This

Table 10. PROMETHEE evaluation table the five alternatives and six criteria

alternatives	criteria					
	$C_1(I_{LMP})$	$C_2(SU)$	$C_3(I_{TCC})$	$C_4(I_{stab})$	$C_5()I_{TTL}$	$C_6(PI_{MW})$
(case 1)	41.059	89.23	2.785	3.462	4.732	10.569
(case 2)	40.740	91.59	2.695	3.632	4.893	11.265
(case 3)	41.428	91.14	2.786	3.765	4.849	10.878
(case 4)	41.020	90.73	2.744	3.453	4.888	11.026
(case 5)	39.625	92.44	2.505	3.205	4.851	11.375
Min/Max	Min	Max	Min	Min	Min	Min
Weight (w_i)	1	2	2	3	1	2
Preference function	V-shape	Linear-shape	Linear-shape	V-shape	V-shape	Linear-shape
Parameters	$q = 0, p = 1.5$	$q = 0.5, p = 3.5$	$q = 0.1, p = 0.2$	$q = 0, p = 0.5$	$q = 0, p = 0.15$	$q = 0.2, p = 0.8$

Table 11. Flows of alternatives and PROMETHEE II ranking

Alternatives	Flows			PROMETHEE II
	φ^+	φ^-	$\varphi = \varphi^+ - \varphi^-$	Ranking
a_1 (case 1)	0.2621	0.2146	0.0474	2
a_2 (case 2)	0.0713	0.2465	-0.1752	4
a_3 (case 3)	0.0709	0.2987	-0.2278	5 (worst)
a_4 (case 4)	0.1051	0.1788	-0.0737	3
a_5 (case 5)	0.5268	0.0976	0.4293	1 (best)

paper reviewed the representation of the TCSC in system load flow equations and investigated their valuable impacts on energy market dispatch outcomes, especially congestion-related consequences. Using a model for energy market that involves both spot and bilateral transactions, the paper showed that placing TCSC in service may bring beneficial advantages to the system.

The paper has explored the selection of the best location of a candidate TCSC in a transmission system in a competitive market structure as a multicriteria decision process. We have focused on the valuable impacts of the TCSC on congestion management outcome, transmission utilization, transmission losses, voltage stability, degree of fulfillment of spot market contracts, and line loadings. In this multicriteria decision problem, the candidate locations of TCSC have been treated as alternatives and the conflicting objectives are the outcomes of the dispatch process. The outcomes observed for all alternatives are system utilization, transmission congestion cost, steady-state voltage stability, transmission system losses, and energy prices. The paper has presented some performance indices (criteria) that measure the conflicting outcomes of a competitive energy market environment, which have been used to compare different alternatives and prioritize them. The first alternative investigated in the paper was the traditional (base-case) dispatch that would only consider the maximization of the social welfare function. In each of the other alternatives, the TCSC has been inserted in a candidate location of the transmission system. As the decision process involved conflicting criteria, we adopted the PROMETHEE method, which would used by the dispatch decision-making entity (ISO) to decide which dispatch would be the optimal one based on the established preferences or priorities. The results of the test system in the paper have shown that when the dispatch process is considered as multicriteria, the best alternative can be different from the traditional dispatch that is based on one criterion.

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