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Congestion management in dynamic security constrained open power markets

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Abstract

The greatest challenge facing deregulated and unbundled electricity supply industry is the operation of the grid in a non-discriminatory and equitable manner. Transmission pricing and congestion management have been at the center of the debate over facilitating greater competition of electric power generation. This paper studies dynamic security constrained congestion management in an unbundled electric power system. It is possible to reschedule the real power generation along with curtailment of real power loads/transactions to make the system dynamically secure after a fault. A conceptually reasonable and computationally feasible approach for the solution of this problem has been developed for a system with a mix of pool and contract dispatches.

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1. Introduction

Congestion in a power system is a consequence of network constraints characterizing a finite network capacity that limits the simultaneous transfer of power from all required transactions. The main tool used for dispatch in a vertically organized power system where generation, transmission and distribution control functions are within the control of the energy management system, is an optimal power flow (OPF). In addition to its role in minimizing production cost, it also provides the possibility of avoiding congestion in a minimum cost manner.

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In deregulated electricity market, congestion management has been debated much for increasing competition of electric power generation [1–5] in both pool and bilateral dispatch models. Congestion management, furthermore, becomes even more complex in the event that dynamic security is taken into consideration. Making a system dynamically secure will require the re-dispatch of generators, and achieving a commercially transparent and technically justifiable approach, therefore, is very important. There are several ways to eliminate congestion including cost-free and non-cost-free means. In some cases, congestion can be avoided by using a costlier generator, which increases the nodal prices of the system. In this paper, it has been assumed that congestion cannot be alleviated by cost-free means (or rather that all cost-free means for congestion control have already been exercised) and re-dispatch of generation along with curtailment of pool loads and of bilateral transactions are the only way to remove remaining congestion.

The presence of new market participants and changing the demand patterns mean that the power system is now being operated in states far away from those contemplated during planning. Moreover, increasing demands placed on the transmission network itself mean that system is running near to security levels. Services providing system security and quality are called ancillary services. Dynamic security, which is addressed in this paper, is a part of ancillary services.

The importance of dynamic security analysis has been increasingly recognized because power systems are being operated near their stability limits, and new operational requirement are imposed in an open access environment. Dynamic security analysis is the evaluation of the ability of the system to withstand contingencies by surviving the transient conditions to acceptable steady-state operation states. When any potential instability due to a prospective contingency is detected, some preventive action is required. A powerful tool for dynamic security assessment is the transient energy function (TEF) used as a screening tool followed by detailed simulation [6]. The considerable progress has been achieved in the TEF method for dynamic security [7–10]. Several methods have been reported which can be used to compute the energy margin (EM) for a given fault clearing time t_{cl}. The hybrid approach has been used in this paper to calculate the unstable equilibrium point (u.e.p) and thus, the EM. The inherent advantage of the TEF method is the availability of a qualitative measure of the degree of stability in terms of the transient energy margin (TEM) that can be analyzed as a function of generation shift among generators.

In this paper dynamic stability constrained congestion management, using the sensitivity of EM with respect to the change in generation from critical generators to non-critical generators, has been proposed. The TEM using the TEF approach has been used to calculate the stability margin of the system after clearing a typical fault. Re-dispatch is undertaken if this margin is inadequate. The proposed algorithm is tested on a sample system.

2. Transient energy function

2.1. Energy margin

For a system with n generators, the dynamics of the classical model [11] of ith synchronous generators with respect to center of inertia (COI) as reference is given by,

$$M_i\dot{\tilde{\omega}}_i = P_i\{= P_{mi} - E_i^2 G_{ii}\} - P_{ei}\left\{ = \sum_{\substack{j=1\\ j\neq i}}^{n} [C_{ij}\sin(\theta_i - \theta_j) + D_{ij}\cos(\theta_i - \theta_j)] \right\} - \frac{M_i}{M_T} P_{\mathrm{COI}} \tag{1}$$

$$\dot{\theta}_i = \tilde{\omega}_i \tag{2}$$

where $M_T = \sum_{i=1}^{n} M_i$, $P_{\mathrm{COI}} = \sum_{i=1}^{n}(P_i - P_{ei})$ and $C_{ij} = E_iE_jB_{ij}$, $D_{ij} = E_iE_jG_{ij}$ and, for generator i,

P_{mi}	mechanical power input
G_{ii}	driving point conductance
E_i	constant voltage behind direct axis transient reactance
$\tilde{\omega}_i$, θ_i	generator rotor speed and angle, respectively, w.r.t. COI frame of reference
M_i	moment of inertia
$B_{ij}(G_{ij})$	transfer susceptance (conductance) in the reduced Y-matrix

Associated with Eqs. (1) and (2), the transient energy of the system can be represented as follows [11]:

$$V = \frac{1}{2}\sum_{i=1}^{n} M_i\tilde{\omega}_i^2 - \sum_{i=1}^{n} P_i^{\mathrm{pf}}(\theta_i - \theta_i^{\mathrm{s}}) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left[C_{ij}^{\mathrm{pf}}(\cos\theta_{ij}. - \cos\theta_{ij}^{\mathrm{s}}) - \int_{\theta_i^{\mathrm{s}}+\theta_j^{\mathrm{s}}}^{\theta_i+\theta_j} D_{ij}^{\mathrm{pf}}\cos\theta_{ij}\,\mathrm{d}(\theta_i + \theta_j)\right] \tag{3}$$

where superscript $(\cdot)^{\mathrm{pf}}$ stands for the values of these variables in the final post-fault system configuration and θ^{s} is the vector of stable equilibrium points at the end of the disturbance. The first term in Eq. (3) represents kinetic energy and the remainders of the terms represent the potential energy of the system. The TEM is defined as $\mathrm{EM} = V_{\mathrm{cr}} - V_{\mathrm{cl}}$, where V_{cr} is the transient energy at the controlling u.e.p. and V_{cl} is the transient energy at fault clearing time. For a given contingency, the system is stable for a positive value of EM and unstable for a negative value of EM.

2.2. Unstable equilibrium point

The approximate controlling u.e.p. ($\theta_{\mathrm{app}}^{\mathrm{u}}$) is calculated using a hybrid method that is used as starting point for solving the post-fault system equation. The computational steps for calculating u.e.p. are as follow [11]:

Step-1: For a given contingency, calculate the reduced Y-bus matrices of the pre-fault, faulted and post-fault systems. The stable equilibrium points (θ^{s}) of post-fault system are computed.

Step-2: Integrate the faulted system (Eqs. (1) and (2)) while looking for a sign change in the following function.

$$[\mathbf{f}^{\mathrm{pf}}(\theta)]^T[\theta - \theta^{\mathrm{s}}]$$

where $(f_i^{\mathrm{pf}}(\theta) = (P_i - P_{ei} - (M_i/M_T)P_{\mathrm{COI}})$ and θ is obtained from the faulted trajectory. The dot product will be negative initially and becomes positive after the potential energy boundary surface (PEBS) is crossed. At the PEBS crossing $f_i^{\mathrm{pf}}(\theta)$ is zero. Let t^* is the instant when PEBS is crossed, and the value of θ at this point is θ_{PEBS}.

Step-3: After the PEBS is crossed, the reduced-order system in that only the θ dynamics are considered, are integrated while looking for a minimum of $\sum_{i=1}^{n} |f_i^{\mathrm{pf}}(\theta)|$. At the first minimum of this norm, $\theta_{\mathrm{app}}^{\mathrm{u}}$ is almost the relevant or controlling u.e.p.

Step-4: Solve $f_i^{\mathrm{pf}}(\theta) = 0$, with $\theta_{\mathrm{app}}^{\mathrm{u}}$ as a starting point to get θ^{u}.

2.3. Sensitivity analysis

If the calculated energy margin, EM^0, is positive for the given contingency and a breaker (fault clearing) time, the system is stable and no further action is required in respect of that contingency. However, if the EM^0 is negative then some corrective action must be taken to ensure system security. The sensitivity $\eta_{i\to j}$ is defined as the ratio of the change in system EM (ΔEM) to a shift in real power generation from critical generator-*i* to non-critical generator-*j* while continuing to satisfy system demand in full. Therefore, it may be defined by,

$$\eta_{i\to j} = \frac{\Delta \mathrm{EM}}{\Delta P_{i\to j}} \tag{4}$$

where $\Delta\mathrm{EM} = \mathrm{EM}^{\mathrm{new}} - \mathrm{EM}^0$. The sign of $\eta_{i\to j}$ indicates the direction in which generation is to be shifted to enhance the EM. The magnitude of sensitivity corresponding to the change in the generation from the most advanced critical generator to the least advanced (non-critical) generators will be high and hence, the best candidate for the rescheduling. The power generation of the critical and non-critical generators should be set as

$$P_i = P_i^0 + \frac{\mathrm{EM}^0}{\eta_{i\to j}} \quad \text{and} \quad P_j = P_j^0 - \frac{\mathrm{EM}^0}{\eta_{i\to j}} \tag{5}$$

It was observed during studies that the change in the EM with respect to the change in the generated power from a critical generator to a non-critical one is approximately linear for reasonable critical clearing time, t_{cl}, assumptions (practically acceptable value). This fact is also reported in some other studies [12,13]. If t_{cl} is excessively high, there is a possibility that change in power from any one generator to another generator will not be sufficient to bring the system to a dynamically secure state. That is to say, if it is found that, for generator-*i* (critical) and *j* (non-critical), the following limitations occur (note that EM^0 is negative in unstable case),

$$-\frac{\mathrm{EM}^0}{\eta_{i\to j}} \geqslant P_i^0 - P_i^{\min} \quad \text{or} \quad -\frac{\mathrm{EM}^0}{\eta_{i\to j}} \leqslant P_j^{\max} - P_j^0 \tag{6}$$

where P^0 is the generator base loading at which the system EM has been calculated, then the maximum or minimum power limit of the critical and non-critical generators $P_i^{\min}$ or $P_j^{\max}$ would limit the permissible rescheduling between these generators.

If the limit on critical or non-critical generator loading is reached, a new EM (EM^{n}) can be calculated after utilizing the total possible change in power between *j* and *i*. Starting with this new

EM, further rescheduling between other pairs of generators can be undertaken. For critical generator limit violation, the new EM will be

$$\mathrm{EM}^{\mathrm{n}} = -(P_i^0 - P_i^{\min})\eta_{i\to j} \tag{7}$$

and if limit on non-critical generator-j is reached, the EM^{n} will be

$$\mathrm{EM}^{\mathrm{n}} = -(P_i^{\max} - P_i^0)\eta_{i\to j} \tag{8}$$

The rescheduling between another pair of critical (m) and non-critical (n) generator can be undertaken in a similar way. The sensitivity calculated at base loading can be utilized for this purpose also. The reason being that it has been observed in our studies that change in the sensitivity with small change in generator loading is small. For shift in some generation from one critical to non-critical generator pair, the actual sensitivity for another pair of critical and non-critical generators is reduced slightly. The rescheduling with base case sensitivity gives little over correction but the system still remains in a transient stable mode.

3. Transmission dispatch

3.1. Normal dispatch

Transmission dispatch in an unbundled environment will be a mix of pool and bilateral/multilateral transactions. The optimal dispatch will be the delivery all bilateral and multilateral transactions in full and to supply of all pool demand at least cost without any security violations. This case can be termed the normal condition. It has been assumed that the independent system operator (ISO) provides all loss compensation services that are caused by bilateral or multilateral transactions and dispatches pool power to make good transmission losses including the losses associated with the delivery of contract transaction [4]. Mathematically, the normal dispatch problem can be written as,

$$\min_{P_{pi}} \quad \sum_{i\in I_G} C_i(P_{pi}) - \sum_{j\in I_D} B_j(D_{pj}) \tag{9}$$

$$\text{s.t.} \quad \widetilde{\boldsymbol{L}}(\boldsymbol{P}_p, \boldsymbol{D}_p, \boldsymbol{P}_t, \boldsymbol{Q}, \boldsymbol{V}, \theta) = 0 \tag{10}$$

$$\boldsymbol{G}(\boldsymbol{P}_p, \boldsymbol{D}_p, \boldsymbol{P}_t, \boldsymbol{Q}, \boldsymbol{V}, \theta) \leqslant 0 \tag{11}$$

where

I_G a set of pool generator buses
I_D a set of pool load buses
P_{pi} active power of pool generator-i
C_i bid price of pool generator-i
D_{pj} active power of pool load-j
B_j bid price of pool load-j
$\boldsymbol{P}_p$ vector of pool power injections

$\boldsymbol{D}_p$ vector of pool power extractions
$\boldsymbol{P}_t$ vector of bilateral contracts
$\boldsymbol{Q}$ vector of reactive powers
$\boldsymbol{V}$ vector of voltage magnitudes
θ vector of voltage angles
$\widetilde{\boldsymbol{L}}$ set of contracted transaction relationships and the power balance equations
$\boldsymbol{G}$ set of inequality constraints

3.2. Congestion

In practice, it may not be possible to deliver all bilateral and multilateral contracts in full and to supply all pool demand at least cost due to violation of operating constraints such as voltage limits and line over-loads (congestion). Congestion in a transmission system, whether vertically organized or unbundled, cannot be tolerated, since this may cause cascade outages with uncontrolled loss of load. Congestion can be relieved, sometimes, by cost-free means such as:

- outage of congested branches (lines or transformers),
- operation of FACTS devices,
- operation of transformer taps.

It is not always possible by cost-free means and some non-cost-free congestion control methods which include, are exercised to do so

- re-dispatch of generation,
- curtailment of pool loads and/or bilateral contracts.

Congestion management essentially has to do with rationing transmission access. Rationing has to follow a user-pay philosophy where willingness to pay so as not to be constrained is an indicator of the importance that the parties to a transaction place on unfettered dispatch. The objective function of the dispatch problem in a system with bilateral and multilateral dispatches only that is without pool loads would be

$$\min \boldsymbol{f}\ (\boldsymbol{u}, \boldsymbol{x}) = [(\boldsymbol{u} - \boldsymbol{u}^0) \cdot \boldsymbol{A}] \cdot \boldsymbol{w} \cdot [(\boldsymbol{u} - \boldsymbol{u}^0)^T \cdot \boldsymbol{A}] \qquad (12)$$

where

$\boldsymbol{w}$ a diagonal matrix whose elements are "willingness-to-pay" price premiums to avoid transmission curtailment
$\boldsymbol{u}$ a set of control variables consisting of active power injected or extracted at generator buses and load buses, respectively
$\boldsymbol{u}^0$ the desired or target value of $\boldsymbol{u}$ (bilateral and multilateral contracts)
$\boldsymbol{x}$ the set of dependent variables
$\boldsymbol{A}$ a constant matrix reflecting curtailment strategies used by market participants

3.3. Problem formulation

When pool and bilateral transaction co-exist, combining the ideas of Sections 3.1 and 3.2, the following mathematical model describes an optimal "curtailment" problem where the dispatch of all pool demand and all bilateral transaction in full would have resulted in the violation of operating constraints.

$$\min \quad \sum_{i\in I_G} C_i(P_{pi}) - \sum_{j\in I_D} B_j(D_{pj}) + \sum_{j\in I_D} w_{Dj}(D_{pj} - D^0_{pj})^2 + \sum_{k\in I_T} w_{Dk}(P_{tk} - P^0_{tk})^2 - \sum_{k\in I_T} X_k(P_{tk}) \quad (13)$$

$$\text{s.t.} \quad \widetilde{\boldsymbol{L}}(\boldsymbol{P}_p, \boldsymbol{D}_p, \boldsymbol{P}_t, \boldsymbol{Q}, \boldsymbol{V}, \theta) = 0 \quad (14)$$

$$\widetilde{\boldsymbol{G}}(\boldsymbol{P}_p, \boldsymbol{D}_p, \boldsymbol{P}_t, \boldsymbol{Q}, \boldsymbol{V}, \theta) \leqslant 0 \quad (15)$$

where D^0_{pj} and P^0_{tk} are the desired value of pool demand at bus-j and bilateral contract-k respectively. X_k is the charge for delivering P_{tk}. I_T is set of bilateral/multilateral transactions $\boldsymbol{P}_t$. Equality constraints (14) is similar to Eq. (11) but expression (15) is a set of inequality constraints indicating the magnitude (mathematically upper limits) of pool demands in addition to the usual system operating constraints such as bus voltage levels and line overloads. The weights, w_{Dj} and w_{tk} are introduced to accommodate the interests of both pool and bilateral participants during congestion by levying extra charges to reduce curtailments. These weights, therefore, are called willingness-to-pay factors.

A measure of degree of curtailment, along with the spot prices, is required for market participants to respond in the event of congestion. The degree of curtailment can be defined as

$$\boldsymbol{d}(\boldsymbol{C}) = \sqrt{(\boldsymbol{u}^* - \boldsymbol{u}^0)^T(\boldsymbol{u}^* - \boldsymbol{u}^0)} = \sqrt{\sum_{j\in I_D}[D_{pj} - D^0_{pj}]^2 + \sum_{k\in I_T}[P_{tk} - P^0_{tk}]^2} \quad (16)$$

where $\boldsymbol{u}^*(\boldsymbol{D_p}, \boldsymbol{P}_t)$ is the optimal value obtained from above minimization.

4. Solution algorithm

In this optimal transmission dispatch problem all power transfers are required to be as close as possible to the initial desired power transfers and curtailment decisions are based on market participants' willingness to pay and dynamic security constraints to achieve secure operation. For a set of critical contingencies with optimal dispatch, the u.e.p. (θ^{u}) is estimated as described in Section 2.2. The EM for each case is then calculated using (3). The algorithm provides a method for security evaluation and preventive control, and can be summarized as follows:

1. Choose a contingency from the given set.
2. Obtain the optimal dispatch using Eqs. (13)–(15) (ensuring post-fault system static security is a part of this problem).
3. Compute (θ^{u}) and corresponding EM (3).
4. If EM is positive, then go to step-1 and select next contingency. If EM is negative, go to step-5.
5. Compute the numerical sensitivities, $\eta_{i\to j}$ for the set of system generators-i and j.

6. Compute the constraints on generators and perform the optimal dispatch (Eqs. (13)–(15)) to obtain the new generation schedule.
7. If all critical contingencies are tested, then stop. Otherwise go to step-1.

The key feature of this approach, then, is the extension of congestion management in response to static security concerns (e.g. [2–5]) to include dynamic security, that is transient stability concerns, and the incorporation of both pool type and contract type loads in the model.

5. Case studies

The coordinated dispatch procedure is illustrated on the five-bus system, consisting of three source buses and two load buses shown in Fig. 1. Buses 2 and 3 are connected to two economic generating stations while bus-1 has a more expensive generating station. The two circuits 1–2 and 3–5 are of impedance $0.1\angle 75°$ pu each while other four lines have an impedance of $0.05\angle 75°$ pu each, all to a 100 MVA base. The line flow limit is set to 100 MW. Bus-1 has been taken as the reference bus.

The generators at buses 1 and 2 bid into the pool and the load at bus-4 is divided into two equal parts, one half takes power from pool and the other enters into a bilateral contract with the independent generator at bus-3. The pool transactions (P_{p1}, P_{p2}, D_{p4}, D_{p5}) and the bilateral contract (P_{t3} to D_{t4}), denoted by T_l, are shown in Table 1. The specified voltage of the generator at bus-3 is 1.05 pu. Voltage magnitudes at load buses are kept within the range of 0.95–1.10.

The example illustrates the results of implementing the algorithm for a 3-phase to ground fault at bus-2 with a subsequent trip of line 2–5. The fault is cleared in 0.45 s, which is greater than the critical clearing time.

A full AC OPF program which included real and reactive power dispatch representation and provision for modeling voltage limits, reactive power limits and generator capacity limits, was used to determine the ISO's optimal dispatch strategy. The prices bid by generators are given in Table 1 where P is in MW and \$ is a monetary unit which may be scaled by any arbitrary constant without affecting the results.

The normal optimal dispatch with line loading constraints was performed to meet all pool demands and bilateral contract. It was observed that the OPF was infeasible due to violation of

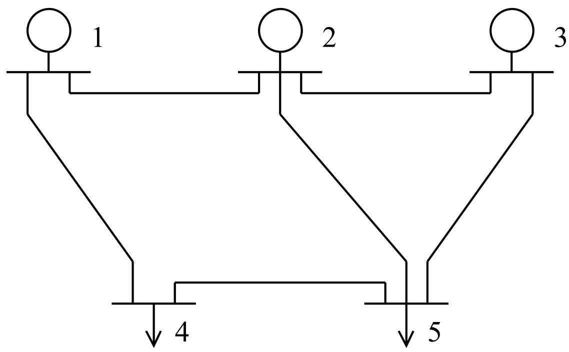

Fig. 1. Example system.

Table 1
Pool and bilateral transactions

Bid generation	Rating (MW)		Bid price ($/h)	Voltage magnitude (pu)
P_{p1}	100.0		$6.0P_{p1} + 0.06P_{p1}^2$	1.02
P_{p2}	200.0		$6.0P_{p2} + 0.06P_{p2}^2$	1.04
Pool load	Demand		Pool price ($/h)	Willingness, w ($/MW^2 h)
	MW	MVAR		
D_{p4}	100.0	20.0	9.0 D_{p4}	20.0
D_{p5}	80.0	20.0	10.0 D_{p5}	20.0
Bilateral contract	Transfer (MW)		Delivery price ($/h)	Willingness, w
T_l	100.0		4.0 P_{t3}	20.0

Table 2
Optimal result with uniform willingness-to-pay

Transactions (MW)	Base case	Static security (line 2–5 out)	Case-1	Case-2
P_{p1}	55.9	14.8	67.2	29.2
P_{p2}	116.2	116.4	64.1	106.5
D_{p4}	93.3	72.7	63.6	71.7
D_{p5}	73.4	53.0	64.4	58.9
T_l	95.4	72.8	39.3	58.4

line loading constraints. The feasible solution was obtained by omitting the constraints on the lines 2–5 and 4–1 and allowed the lines to become overloaded. A load curtailment strategy (Eqs. (13)–(15)) was performed with the willingness-to-pay factors that are given in Table 1. The optimal pool dispatch for this case (base case shown in column 1 of Table 2) is $P_{p1} = 55.9$ MW and $P_{p2} = 116.2$ MW. The pool demands at buses 4 and 5 were curtailed to 93.3 and 73.4 MW. Furthermore, the bilateral contract was limited to 95.4 MW.

5.1. Free mode

The term free mode is used to denote the case when all participants are modeled with the same willingness-to-pay (w); that is there will be no bias in favor of any pool or contract user.

After outage of line 2–5, the statically secure optimal dispatch shown in column 2 of Table 2, is $P_{p1} = 14.8$ MW, $P_{p2} = 116.4$ MW, $D_{p4} = 72.7$ MW and $D_{p5} = 53.0$ MW. The bilateral transaction is 72.8 MW. However, it was found that the system is statically secure but dynamically not. With this initial dispatch, the EM was found to be −0.4350, which shows that system is unstable. This result has also been verified with time-domain simulation using a conventional step-by-step transient stability program, which showed unstable swing curves. Both generator-2 and generator-3 are critical generators, which was also determined from the time-domain simulations. The sensitivities $\eta_{2\to1}$ and $\eta_{3\to1}$ were calculated using (4) and found to be 0.8310 and 3.009 respectively. From this it is clear that shift in generation from generator-3 to generator-1 will be more effective than a shift from generator-2 to generator-1 for bringing the system into a dynamically stable

Table 3
Line flows with uniform willingness-to-pay

Lines	Base case	Static security	Case-1	Case-2
1–2	−44.9	−86.8	−33.6	−72.1
5–3	−65.0	−100.0	−68.7	−90.8
5–4	89.9	45.5	3.5	30.8
4–1	−100.0	−100.0	−100.0	−100.0
2–3	−29.7	28.6	30.1	33.6
2–5	100.0	–	–	–

condition. Positive sensitivity shows that the power generation has to be reduced from generator-2/3 and it has been increased at generator-1.

In all of the cases including the base cases as well as cases 1–6 below, the optimal dispatch problem equation (13)–(16) was solved. In case 1–6, this was done after generation re-dispatch was implemented.

Case-1: The required shift from generator-2 to generator-1 for making the system stable was found to be 52.3 MW ($= \mathrm{EM}/\eta_{2\to1}$). Generation at bus-2 is decreased by 52.3 MW and it is increased at bus-1 by the same amount. Swing curves from time-domain simulation showed the system to be dynamically stable. The bilateral transaction is further reduced from 72.8 to 39.3 MW due to the unloading of generator-3 while the gross pool load increased slightly from the static security case (see columns 2 and 3 of Table 2). Only line 4–1 reached it maximum power limit as can be seen in Table 3.

Case-2: Although, generator-3 is more critical than generator-2 it is not a pool generator. Let us now examine the case where a coordinated response between pool and contract generators is possible. If bilateral generator-3 enters into a contract with pool generator-1 to supply some power to enhance the security of the system, the required shift in generation from generator-3 to generator-1 would be 14.4 MW. Optimal dispatch was obtained for this case and it was found that the total pool demand met is almost same as case-1. Generator-2 is supplying less power than case-1. From time simulation, it was observed that the dispatch after rescheduling is dynamically stable. From Table 2, it can be seen that if this type of coordinated response is implemented, the power curtailed of both pool consumers and bilateral contract is smaller, that is, in the interests of all system users.

5.2. Effect of willingness-to-pay factor

Case-3 and case-4 were studied to see the effect of willingness-to-pay factors. For these cases, the pool demand willingness-to-pay has been increased from \$20/MW^2 to \$40/MW^2 while keeping the bilateral contract willingness-to-pay (w) unchanged at \$20/MW^2. This base case in Table 4 is, therefore, different from Table 2 and both pool loads show a small gain at the expense of the contract. The optimal dispatch with the same line 2–5 outage has also been simulated and the result in column 3 of Table 4 show a substantial advantage for pool loads at the expense of the contract load compared to column 3 of Table 2. Clearly, greater willingness to pay is purchasing more dispatch right during high congestion. The pool demands, D_{p4} and D_{p5}, as expected, were

Table 4
Optimal result with different willingness-to-pay

Transactions (MW)	Base case	Static security (line 2–5 out)	Case-3	Case-4
P_{p1}	57.0	11.5	27.0	31.4
P_{p2}	117.1	133.8	102.2	102.2
D_{p4}	94.4	79.4	69.0	71.9
D_{p5}	74.5	59.5	54.6	56.6
T_l	92.3	59.0	67.4	59.0

Table 5
Line flows with different willingness-to-pay

Lines	Base case	Static security	Case-3	Case-4
1–2	−43.9	−90.2	−74.4	−69.9
5–3	−64.0	−100.0	−93.0	−89.3
5–4	87.9	39.1	37.2	31.6
4–1	−100.0	−100.0	−100.0	−100.0
2–3	−27.7	42.5	26.9	31.4
2–5	100.0	–	–	–

increased to 79.4 and 59.5 MW, respectively while the bilateral contract is reduced from 72.8 MW (column 3 of Table 2) to 59.0 MW (column 3 of Table 4).

However, from time simulation, it was found that system is dynamically unstable. The calculated EM was −2.108 which also showed the system transient instability. The sensitivities $\eta_{2\to1}$ and $\eta_{3\to1}$ were calculated and found to be 4.324 and 6.997 respectively. The pool generator-2 (critical) and generator-1 (non-critical) pair has been selected for rescheduling to bring the system into a dynamic stable state. The required shift of power from generator-2 to generator-1 was 31.6 MW. With this generation shift, the following cases were studied.

Case-3: From Table 4, it was observed that the pool consumers get less power while bilateral transaction is increased from 59.0 to 67.4 MW. The static security case in Table 4 shows that pool customers benefit by their greater willingness to pay compared to the same case in Table 2. However, comparison of the two cases when dynamic security is taken into account (case-1 and case-3), shows somewhat paradoxically from willingness to pay point of view, that one of the pool loads suffers a significant reduction (64.4–54.6 MW) while the contract makes a very substantial gain (39.3–67.4 MW).

Case-4: In this case, it is assumed that the bilateral contract is held at its static security value i.e. 59.0 MW and pool generators were dispatched optimally which is shown in Table 4. It was observed that pool consumers get more power than case-3. Table 5 shows the line flow corresponding to these cases.

5.3. Pool-protected mode

The proposed algorithm was used for what may be called the pool-protected mode in which all pool consumers obtain their full demand but contracts may be curtailed. With outage of line 2–5,

Table 6
Optimal result in pool-protected mode

Transactions (MW)	Base case	Static security (line 2–5 out)	Case-5	Case-6
P_{p1}	62.3	2.40	53.0	43.3
P_{p2}	122.0	185.1	118.4	118.4
D_{p4}	100.0	100.0	93.1	87.6
D_{p5}	80.0	80.0	74.3	69.7
T_l	76.8	18.0	0.0	18.0

Table 7
Line flows in pool-protected mode

Lines	Base case	Static security	Case-5	Case-6
1–2	−38.5	−99.1	−47.9	−57.8
5–3	−59.0	−100.0	−68.8	−76.8
5–4	77.5	18.7	−6.2	6.3
4–1	−100.0	−100.0	−100.0	−100.0
2–3	−17.4	83.0	69.8	59.4
2–5	100.0	–	–	–

Table 8
Degree of curtailment (in pu)

Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
0.7248	0.5456	0.5166	0.5449	1.0004	0.8357

the optimal dispatch was obtained which is shown in Table 6. The EM, which was −2.100, showed that system is dynamically unstable. The sensitivities $\eta_{2\to1}$ and $\eta_{3\to1}$ were calculated and found to be 3.147 and −2.635 respectively. The sign of sensitivity $\eta_{3\to1}$ shows that shift of power from generator-3 to generator-1 will not bring the system to dynamic stability. In other words, generator-3 and generator-1 are non-critical generators. The shift of power from generator-2 to generator-3 has not been considered because generator-3 is not a pool generator.

The required shift of power from generator-2 to generator-1 was found to be 66.7 MW. With this change in power, the optimal dispatch became infeasible, which shows that it is not possible to supply all the pool demand with the exiting operating constraints. The problem was solved with some minimal curtailment of pool loads, case-5 in Table 6. It can be seen that the bilateral contract has been reduced to zero. If the bilateral contract is held at its static security value of 18.0 MW and the pool generators dispatched optimally, case-6 is obtained. Table 7 shows the line flows corresponding to these cases.

These examples give interesting alternatives about different methods of applying pool protection.

The degree of curtailment has been calculated for all the cases and presented in Table 8. From this table, it can be seen that case-3 is least congested and while case-5 is the most congested.

6. Conclusions

This paper addresses on the dispatch curtailment problem in a competitive power marketplace constrained by dynamic security. An optimal transmission dispatch methodology which takes into account consumer willingness-to-pay to avoid curtailment and which uses sensitivity information of TEM with respect to the change in generation from critical generators to non-critical generators has been proposed. The case studies, in the paper, illustrate that the critical and non-critical generator pair that has the highest sensitivity is the first choice suitable for scheduling. However, depending on contractual and price obligations, other pairs with high sensitivity may be preferentially selected.

It was also observed that with some priority arrangement and coordination among generator would reduce the power curtailment in both pool and bilateral transactions. Willingness-to-pay factor gives some insight into the nature of competition in the emerging market participants. The results of the algorithm were confirmed by step-by-step transient stability time-domain simulation methods. The most significant result of these findings is that different philosophies of curtailment management, rescheduling in response to static and dynamic security concerns, and mixes of these strategies can be explored using these methodologies.

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