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Transmission congestion management in bilateral markets: An interruptible load auction solution

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Abstract

This paper demonstrates that appropriate invocation of interruptible loads by the independent system operator (ISO) can aid in relieving transmission congestion in power systems. An auction model is proposed, for an ISO operating in a bilateral contract dominated market, for real-time selection of interruptible load offers while satisfying the congestion management objective. The proposed congestion management scheme using interruptible loads can specifically identify load buses where corrective measures are needed for relieving congestion on a particular transmission corridor. The $N-1$ contingency criterion has been taken into account to simulate various cases, and hence, examine the effectiveness of the proposed method. It has been shown that the method can assist the ISO to remove the overload from lines in both normal and contingency conditions in an optimal manner.

Keywords: congestion management; deregulated electricity market; bilateral contract; interruptible load; optimal power flow; multi-objective optimisation

1. Introduction

In a deregulated electricity market, the task of the independent system operator (ISO) is to ensure that contracted power transactions are carried out reliably. However, due to the large number of transactions that take place simultaneously, transmission networks may easily get congested. A number of methods, both technical and economic, dealing with congestion management in deregulated electricity markets, have been proposed in the literature. The technical methods are generally based on optimal generation re-dispatch with security and transmission constraints, operation of transformer taps, outage of congested lines, load curtailment, and operation of FACTS devices.

Three different methods of transmission system operation in deregulated power systems were discussed in [1]. The first is based on optimal power flow (OPF), as implemented in the UK, parts of USA, in Australia and New Zealand. The second method is the point-of-connection tariff and price area congestion model as used in Sweden and Norway, respectively. Finally, a transaction-based model as used in the USA was discussed. It was concluded that these methods are pragmatic solutions implemented in advance of a complete theoretical understanding. Each method succeeds in maintaining power system security but differs in its impact on the economics of the energy market. In [2], a minimum-distance generation re-dispatch was proposed, which disregarded the economic value of the transaction adjustment. In [3], price (marginal cost) signal was used for the generators to manage congestion and the solution under rational behavior assumption was found to be identical to an OPF solution. A similar approach was suggested for the pool model [4], where the cost of congestion was bundled within the marginal cost at each bus. A bilateral model was also investigated, and a congestion cost minimization approach was proposed.

According to North American Electricity Reliability Council (NERC) Operating Policy-10 [5], interruptible load is recognized as one of the contingency reserve services and it has been generally accepted that these have an important

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role to play as a system ancillary service. It is more so, since the operating margins available to the ISO have been reduced drastically with increasing market competition.

The role of demand elasticity in congestion management and pricing in a competitive electricity market was investigated in [6]. The action of price responsive loads could be represented in terms of the customers' willingness-to-pay. From each customer's demand curve, the elasticity of the load at different prices is known and the benefit function is derived. The load at each bus ceases to be a fixed quantity and becomes a decision variable in the ISO's optimization problem. In this way, the ISO has additional degrees of freedom in determining the necessary actions for congestion management. The design of an optimal interruptible load contract has been attempted in [7] by using the mechanism design. It is shown that the so designed contract would give the customers enough incentive to sign up voluntarily for the right contract and reveal their true value of power.

In [8], an optimization procedure for re-dispatch of generation is proposed in order to alleviate congestion. Consequently, a new approach to allocate the cost of congestion and losses to the nodes of the transmission network based on the node's responsibility is proposed. A unified framework for the representation of market dispatch and re-dispatch problems that the independent grid operator must solve in congestion management in various jurisdictions was developed in [9]. This framework is used to compare the performance of different congestion management approaches that exist today in various markets in the world. The use of basic distribution factors, such as the injection shift factor and power transfer distribution factors, for evaluation of congestion revenue rights (CRR) are presented in [10]. The paper analyzed the characteristics of these distribution factors and how their errors can impact the CRR. The results have shown that the impact is minor under a broad spectrum of conditions including contingencies.

As we have observed, congestion relief has traditionally been carried out through generators in the short-term by redispatching available generation during various contingency situations. This form of congestion service provision is referred to as *preventive management.* If, however, the cost of such preventive management is too high, then it would be more cost-effective to invest in transmission system reinforcement, which can be referred to as *long-term congestion management.* A somewhat "in-between" alternative to the above two is to create provision for load interruption in a judicious manner that could aid in transmission congestion relief, and which can be referred to as *corrective management*.

Curtailment of load is generally invoked by the ISO or an equivalent load serving entity and there have been several applications of this method to optimal system operation, in particular for providing secondary reserves [11]. In [11], a competitive market for interruptible load services has been developed. Location aspect of interruptible load offers was incorporated in the market operation through marginal loss coefficients at every load bus. An OPF based framework was proposed in [12] to determine the optimal incentive rates in an interruptible tariff mechanism. It is shown that interruptible tariffs are able to aid system operation during peak load periods by increasing the reliability margin, improving voltage profile and relieving network congestion.

In the context of deregulated markets, introducing the provision that allows customers to offer a part of their load as an interruptible load for competitive procurement by the ISO is a topical issue. Participation of the customers in this provision for congestion relief could significantly increase the number of service providers, and hence locations, available to the ISO. The economic validity of interruptible load depends on the difference in potential savings in congestion cost and costs involved in procuring interruptible load services offered by various consumers.

The present paper proposes an integrated framework for congestion management, using interruptible load service as a tool for the ISO to provide transmission congestion relief at the dispatch stage. An optimization based scheme is proposed that identifies those buses in the system, where changing the load, can effectively influence the power flow over a particular transmission line. The task of the ISO is then reduced to identifying the *most effective* set of loads to be curtailed in order to clear the existing bottlenecks, at *least-cost.* To this effect, an interruptible load auction is designed, for operation at the dispatch stage, one-hour ahead of real-time, by the ISO. In this market, participants would offer their interruptible load capacity (in MW) for the next hour and its associated price offer ($/MW h). Subsequently, with the submitted offers from interruptible load participants, a congestion relief model (CRM) is executed every hour to obtain the optimal interruption schedule for transmission congestion relief.

2. Interruptible load auction for congestion management in bilateral markets

2.1. Auction structure and time scale

In bilateral contract markets, generation scheduling and unit commitment (UC) decisions are usually outside the purview of the ISO [13]. In such markets generation rescheduling is not a straight forward exercise and often the ISO has to invoke generation re-scheduling through the *balance market mechanisms* as in the case of Nordic countries [14] and the UK [15]. Any modification to the generation-load balance in bilateral markets, therefore, has to be outside the market settlement process, unlike pool market structures, and usually through a separate auction mechanism.

The proposed competitive procurement model for interruptible loads is particularly directed towards the bilateral market structure and the auction model proposed herein is therefore *independent* of the spot-market settlement. Offers are submitted by participating customers specifying the price β ($/MW h) for energy to be interrupted and the quantity μ (MW), on an hour-to-hour basis. Being in a bilateral market,

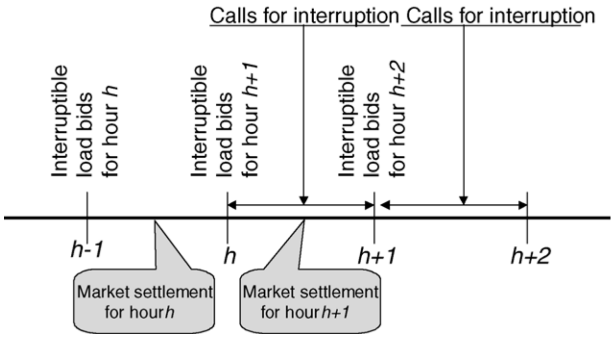

Fig. 1. Time-frame of the proposed interruptible load auction.

the UC schedules of all generators are assumed known to the ISO a priori once the spot-market is settled. Fig. 1 shows the proposed interruptible load market functioning in the time-domain. The customers submit their offers at hour $h-1$ to the ISO, who conducts the auction and obtains the optimal selection of interruptible load as per its requirement, and that is when the interruptible load auction is closed for operation during hour *h*. The ISO's task is to conduct the interruptible load auction in order to obtain the optimal set of invocation of load curtailment decisions so as to help clear the congestion that may exist in the network. The ISO's objective in the auction would naturally be to minimize the cost of congestion management service, *i.e.* the total payment to the selected interruptible load offers.

2.2. Optimal procurement of interruptible load offers

Optimal interruptible load procurement will be based on an uniform price auction, *i.e.* all selected loads shall receive the same price (interruptible price, ρ), which is the highest accepted offer price. Fig. 2 shows the working scheme of the proposed auction for interruptible load for relieving transmission congestion. The scheme can be executed in two steps as given below:

- Load flow model (LFM) – to be executed every hour to identify the congested lines.
- Congestion relief model (CRM) – a modified OPF, receiving interruptible load offers from customers and minimizing various objectives by the ISO while satisfying the congestion management objective.

It is to be noted that in order to create a fast and efficient congestion management tool as well as to demonstrate the method well, the models proposed in this paper are based on a dc load-flow formulation which assumes the system is lossless and has an unity voltage magnitude at all buses. The models, however, can always be augmented to the normal ac load-flow formulation, if required.

2.2.1. Load-flow model

2.2.1.1. Simulation of bilateral contracts. Bilateral contracts are so simulated that they adhere to two basic rules,

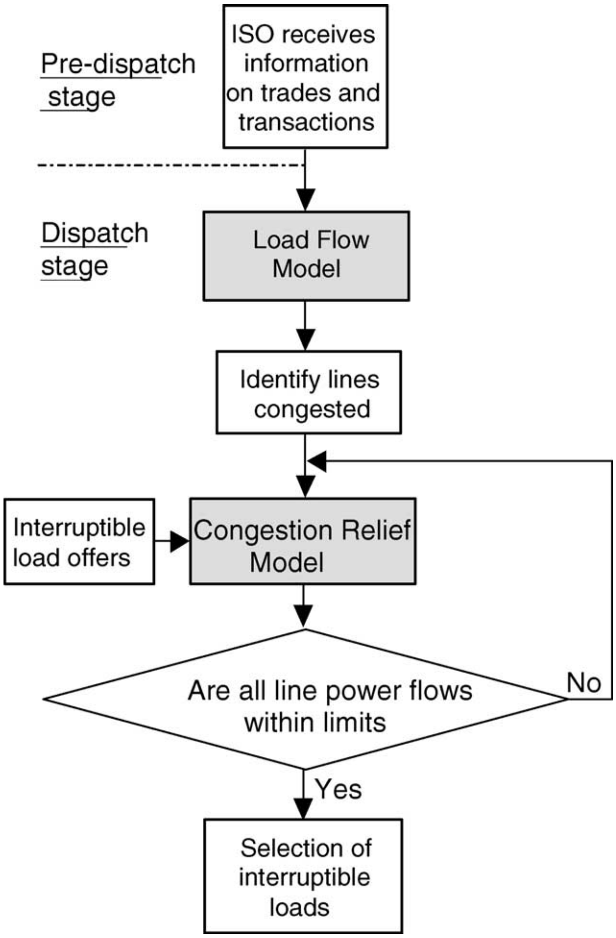

Fig. 2. Schematic diagram of the proposed interruptible load auction model for congestion management.

i.e., the sum of all energy purchase contracts at a bus equals the demand at the bus and the sum of all energy sell contracts by a generator, equals the contracted generation at that generator bus. Accordingly, we have:

$$\sum_{j} \mathrm{Pgcon}_{i,j} = \mathrm{Pd}_{i,b}, \quad \forall i = 1, \ldots, \mathrm{NL}; \quad j = 1, \ldots, \mathrm{NG} \tag{1}$$

$$\sum_{i} \mathrm{Pgcon}_{i,j} = \mathrm{Pg}_{j,b} \quad \forall i = 1, \ldots, \mathrm{NL}; \quad j = 1, \ldots, \mathrm{NG} \tag{2}$$

$$\mathrm{Pg}_j^{\max} \cdot a_1 \leq \sum_{i} \mathrm{Pgcon}_{i,j} \leq \mathrm{Pg}_j^{\max} \cdot a_2, \quad \forall i = 1, \ldots, \mathrm{NL}; \quad j = 1, \ldots, \mathrm{NG} \tag{3}$$

NG is the set of generator buses, NL the set of load buses, a_1 and a_2 are scalar multipliers on $\mathrm{Pg}^{\max}$ to constrain Pgcon, the contracted generation, between a generation-customer pair, within a set of realistic limits (3).

Although we show that $j = 1, \ldots,$ NG in (1), in a practical system all generators may not have bilateral contracts with a load at bus i. In such case, appropriate elements of Pgcon matrix will be zero. The same applies to (2) where not all loads $i = 1, \ldots, \text{NL}$ may have bilateral contracts with generator j. In such case, appropriate Pgcon elements will be zero.

2.2.1.2. Load flow equations. The basic load-flow equations, modified to include the power generation and demand separated according to those through bilateral contracts and those traded in the spot-market, is as follows:

$$\text{Pg}_{i,m} + \text{Pg}_{i,b} - \text{Pd}_{i,m} - \text{Pd}_{i,b} = \sum_j B_{ij} \cdot \delta_j \tag{4}$$

It may be noted from the above that generation and demand is accounted for by two different sources and sinks respectively. For example, we assume a generator 'i' is producing an amount $\text{Pg}_{i,b}$ to meets its bilateral contracts and an amount $\text{Pg}_{i,m}$ to sell in the spot-market. Similarly, load at bus 'i' comprises $\text{Pd}_{i,b}$ that is through bilateral contracts and a part $\text{Pd}_{i,m}$ that is purchased in the spot-market. Such representation of the generation and load balance is typical of the Swedish/Nordic system which is dominated by bilateral contracts, while also having a participation in the spot-market.

2.2.1.3. The power flow on line $i - j$ can be calculated as:.

$$P_{ij} = -(\delta_i - \delta_j)B_{ij} \tag{5}$$

Once the power flows on all transmission lines are calculated, they are compared with the respective power transfer limits $P_{ij}^{\max}$ of each line in order to identify the lines which are overloaded. If line(s) overload exits, necessary actions need to be taken, and accordingly the CRM (as described in Section 2.2.2) is executed. The LFM is a linear programming problem and is solved using the well-known solver XA in GAMS [16].

2.2.2. Congestion relief model

2.2.2.1. Objective function. First of all, it is understandable that the ISO would not like to curtail demand at too many load buses, at the same time. One of the objectives of the ISO is, therefore, to minimize the number of load buses at which interruption is called for, denoted by NILS. This objective can be expressed as in (6):

$$\text{NILS} = \sum_i^{\text{NIL}} U_i \tag{6}$$

In (6), U is a binary decision variable denoting the selection ($U = 1$) or otherwise ($U = 0$) of interruptible load at a bus, from the set of buses ($i = 1, \ldots, \text{NIL}$) where customers are participating in the interruptible load market.

The other objective of the ISO would be to minimize the total power interruption invoked, denoted by PILS, and can be expressed as in (7):

$$\text{PILS} = \sum_i^{\text{NIL}} \Delta\text{Pd}_i \tag{7}$$

The third objective of the ISO would be to find the optimal set of interruptible load contracts such that the total payment made to the loads is minimized. The total payment can be expressed as:

$$\text{PAYMENT} = \sum_i \Delta\text{Pd}_i \cdot \rho \tag{8}$$

Note that ρ is the uniform interruptible load market price determined from the CRM and payable to all selected interruptible load offers invoked by the ISO.

As we can observe from the above, the ISO has three different objectives, normally of a contradictory nature, to satisfy different goals. However, the ISO would often desire to achieve all the three goals simultaneously. To this effect, we propose a 'compromise programming' approach that attains the 'best compromise' amongst different objectives. The three objectives above can now be incorporated into a 'compromise function (9), which, when minimized, will represent the ISO's overall requirement of meeting all objectives at the same time:

$$J_{\text{COMPRO}} = \sqrt{\left(\frac{\text{NILS}}{\text{NILS}^*}\right)^2 + \left(\frac{\text{PILS}}{\text{PILS}^*}\right)^2 + \left(\frac{\text{PAYMENT}}{\text{PAYMENT}^*}\right)^2} \tag{9}$$

In (9), NILS^*, PILS^*, and PAYMENT^* are the respective optimal values, when minimized individually (Fig. 3) [17]. It is to be noted that equal weights have been assigned for each component in (9), which however need not be necessarily so, in actual markets. The ISO may choose to have different *preferences* for the three objectives, depending on the con-

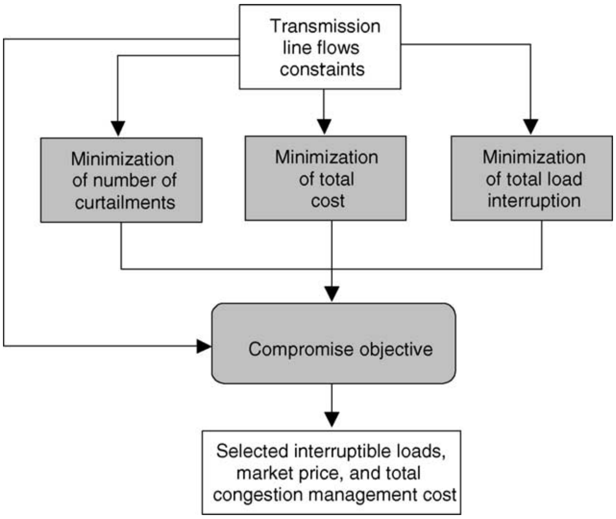

Fig. 3. Formation of the compromise objective.

tractual agreements between the ISO and the interruptible load participants as well as the market condition.

The above proposed "compromise" objective function (9) encompasses the basic concerns that the ISO should address and incorporate in its decision making while procuring the interruptible load services. This objective function is somewhat different from the classical cost or social welfare (producer plus consumer surplus) based objective functions and is designed in order to avoid the pitfalls of using the classical objective function in these classes of problems. For example, with a cost minimization function the ISO could end up with a stack of low-priced interruptible load offers irrespective of their location or impact on the system losses. It could also end up with a large number of curtailment sequences if the objective function did not address that issue in some way. On the other hand the proposed compromise function takes into account the number of interruptions, the quantity of power interrupted and the payment made by the ISO. This last term in effect does represent the social welfare under the assumption that the interruptible load service providers offer their true cost/benefit functions.

Further, it is to be noted that the cost to the ISO is not the same as the cost to the society. The cost to the ISO is the payment burden that it has to undertake in order to procure these interruptible load services. On the other hand, cost to the society is the "congestion cost", *i.e. the cost of not having enough transfer capacity* as required from the unconstrained market settlement [18,19].

2.2.2.2. Load flow equations. We also have the basic power flow equations at a bus i, similar to (4). To include the contribution of interruptible loads, it is re-written as:

$$\mathrm{Pg}_{i,m} + \mathrm{Pg}_{i,b} - \mathrm{Pd}_{i,m} - \mathrm{Pd}_{i,b} + \sum_{i}^{\mathrm{NIL}} \Delta\mathrm{Pd}_i = \sum_j B_{ij} \cdot \delta_j \tag{10}$$

2.2.2.3. The power flow constraints. The power flow on line $i-j$ has to be within its maximum limit:

$$P_{ij} \leq P_{ij}^{\max} \tag{11}$$

$P_{ij}^{\max}$ is the maximum transfer capacity of the line $i-j$.

2.2.2.4. Operating reserve constraints. This constraint ensures that a pre-specified and mandatory level of operating reserve is maintained by the ISO at all times. Since generator unit commitment decisions are beyond the ISO's purview, operating reserve from committed capacity may fall short at times and the ISO would need to make such provision from interruptible loads.

$$\sum_{i}^{\mathrm{NG}} \mathrm{Pg}_i^{\max} \cdot \mathrm{UC}_i - \sum_{i}^{\mathrm{NL}} \mathrm{Pd}_i + \sum_{i}^{\mathrm{NIL}} \Delta\mathrm{Pd}_i \geq \mathrm{RES} \tag{12}$$

In (12), RES is the operating reserve requirement for the system.

2.2.2.5. Limit on interruption. The actual interruption invoked by the ISO is constrained by the quantity offered by customers for interruption:

$$\Delta\mathrm{Pd}_i \leq \mu_i \cdot U_i, \quad \forall i = 1, \ldots, \mathrm{NIL} \tag{13}$$

2.2.2.6. Bidding for interruption. The quantity offered by an interruptible load market participant is limited by the total demand at its disposal.

$$\mu_i \leq a_{i0} \cdot \mathrm{Pd}_i, \quad \forall i = 1, \ldots, \mathrm{NIL} \tag{14}$$

In (14), a_{i0} is a scalar, $0 < a_{i0} < 1$, specifying the fraction of demand at a bus that is offered in the interruption load auction.

2.2.2.7. Market settlement. The interruptible load market is settled on second price uniform auction, where all selected offers are paid the same price ρ (interruptible load market price), which is the highest accepted offer price. The interruptible load market price is determined from the CRM using the following inequality constraint:

$$\rho \geq U_i \cdot \beta_i, \quad \forall i = 1, \ldots, \mathrm{NIL} \tag{15}$$

The CRM, as described above, is a mixed integer nonlinear programming (MINLP) problem and is solved using the well-known DICOPT solver in GAMS [16]. Each of the three objectives is executed first with the constraints Eqs. (10)–(15), in order to find their optimums – PILS*, NILS*, and PAYMENT*, respectively. Subsequently, the *compromise* objective is constructed and solved considering the constraints Eqs. (10)–(15) in order to arrive at the compromise optimal solution while clearing all the congestion in the network.

3. System studies

3.1. System description

The CIGRE-32 bus test system, which approximately represents the Swedish grid [20], has been used for the simulation studies to examine the proposed auction scheme of interruptible load for congestion management service by ISO. The single line diagram of the system is shown in Fig. 4.

3.2. Design of cases for analysis

In order to simulate the interruptible load offers, to be submitted to the ISO, we use an uniform random number generator over a range of \$30/MW h to \$40/MW h, reflecting the peak-hour spot-market price, to generate offer prices (β_i) [21]. The bid quantity (μ_i) is generated using a fraction multiplier range for a_{i0} of 20–30% of total demand at a bus. However, it should be noted that these assumptions to generate offer prices and associated quantities is only illustrative at

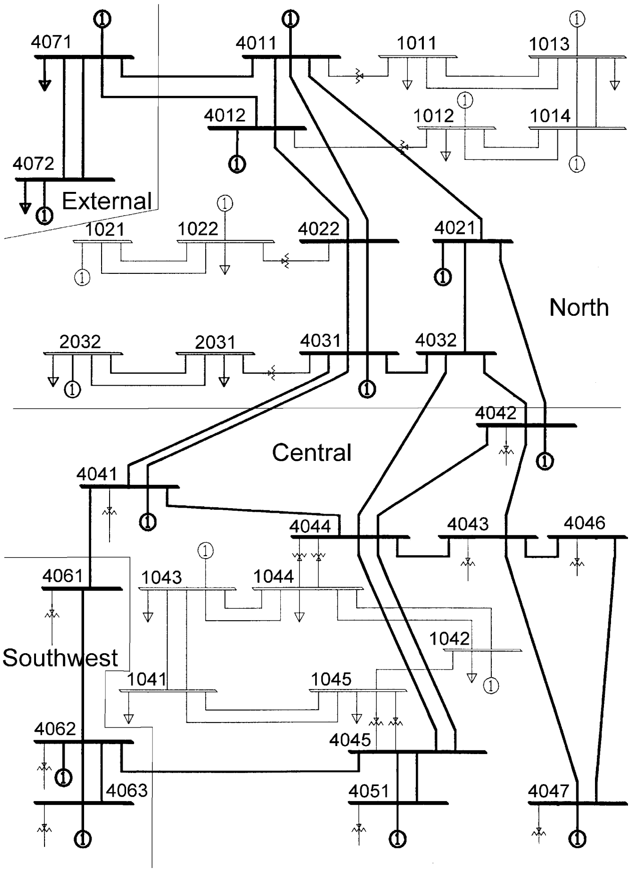

Fig. 4. CIGRE 32-bus system. (Note that the load buses which are represented by 2-digit numbers (*XX*) are not shown in this figure, they are connected to the 400 kV buses (*i.e.*, buses 40*XX*) through the 400/130 kV transformers. For example, bus 46 is connected with bus 4046 and so on.).

best and need not be true in actual auction markets. Further, we do not consider strategic bidding (imperfect competition) issues in this work – wherein interruptible load participants' offer prices might vary as a function of the level of reserve available in the system [11].

We simulate cases where congestions exist on a number of transmission corridors. A "business as usual" case, with two lines overloaded, is first considered. Subsequently, in order to demonstrate the robustness of the method, several contingency cases (with $N-1$ criterion) are also considered. The following simulation cases are considered in our analyses:

- Case A: "business as usual" (BAU).
- Case B: contingency case with the transmission line 4042–4044 out-of-service.
- Case C: contingency case with the transmission line 4021–4042 out-of-service.
- Case D: contingency case with the generator 4041 out-of-service.

3.3. Results and discussions

First of all, we identify the bottlenecks arising in the transmission system in different cases (Table 1). It is evident that lines 4022–4031 and 4031–4041, which is the two main transmission corridors of power transmission from the north (where there is abundance of generation) to the south (the load centers) of the system, are overloaded in the BAU case. In Case B, when the transmission line 4042–4044 is out-of-service, it creates even more burden on the two lines 4022–4031 and 4031–4041 which are already overloaded, and additionally, line 4042–4043 also gets overloaded. In Cases C and D, the two lines 4022–4031 and 4031–4041 are more heavily loaded, although no new congested lines are created.

Table 1
Transmission line congestion in various cases

Lines overloaded	Overload (MW)			
	Case A	Case B	Case C	Case D
4022–4031	727.95	760.30	1031.53	816.51
4031–4041	20.55	155.07	321.34	166.85
4042–4043	–	61.57	–	–
Total	748.50	976.94	1352.87	983.36

Table 2 shows the offer prices submitted by interruptible load participants. For the sake of uniformity of comparison, we assume that participants offer the same prices in all cases considered.

3.3.1. Case A (business as usual)

Table 3 shows the selected interruptible load contracts by the ISO when each objective function is considered separately, *i.e.,* minimization of NILS (hereafter, Min of NILS), minimization of PILS (hereafter, Min of PILS) and minimization of PAYMENT (hereafter, Min of PAYMENT). Also shown are the optimal procurement decisions for minimization of the *compromise* function (hereafter, Min of COMPRO). Depending on the objective function considered, the CRM selects the optimal interruptible load contracts so as to alleviate the existing congestions on the two lines 4022–4031 and 4031–4041. It also ensures that there is no new line congestion introduced because of the load interruption. The CRM also determines the market-clearing price, which is the highest accepted offer price. We refer to the bus that has the highest accepted offer price as the *price-setter* bus. The *price-setter*

Table 2
Offer prices submitted by interruptible load participants

Bus no.	Offer price ($/MW h)	*Busno.*	Offer price ($/MW h)
4072	31.18	1044	32.46
4071	33.14	1045	31.31
2032	32.84	42	39.33
1013	30.86	41	33.80
1012	31.03	62	37.83
1022	35.45	63	33.00
1043	37.92	51	31.25
1042	30.73	47	37.49
2031	33.89	43	30.69
1011	33.59	46	32.02
1041	32.43	61	30.05

Table 3
Interruptible load contracts for Case A with different objectives

Min of NILS		Min of PILS		Min of PAYMENT		Min of COMPRO	
Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)
1043	109.70	2032	103.77	1042	133.98	*1045*	318.72
1044	323.49	2031	47.65	*1045*	318.72	51	373.77
51	373.77	41	271.85	51	373.77	43	237.36
43	424.51	*62*	127.33	43	101.44	61	221.86
		63	252.02	61	221.86		
		51	77.81				
		61	221.86				

Note: the italic *bus is* the *price-setter* bus in each objective.

Table 4
Summary results for Case A

Objective (Min of)	NILS	Interruption (MW)	Payment (k$)	Market price ($/MW h)
NILS	4	1231.47	46.70	37.92
PILS	7	1102.31	41.70	37.83
PAYMENT	5	1149.78	35.99	31.31
COMPRO	4	1151.71	36.05	31.31

bus varies with different objectives and is shown in Table 3 in italic, *i.e.*, 1043 in Min of PILS, 62 in Min of PILS, 1045 in Min of PAYMENT and in Min of COMPRO are *the price-setter* buses.

Table 4 shows a summary of the number of contracts, total demand interruption, total payment for congestion management, as well as market clearing price in each of the four objectives considered for investigations in Case A.

Fig. 5 shows the plot of normalized values of the various objectives with respect to the COMPRO objective.

As can be seen from Fig. 5 that if the ISO minimizes only NILS, it would need to contract the highest amount of interruptible load as well as pay the highest market price and hence would incur the highest total congestion management cost. Now, if the ISO chooses to minimize the total load interruption requirement, it has to contract the maximum number of interruptible buses, while the market price is little lower than with the previous. Since the amount of interruptible load is minimized the total payment will reduce significantly. If we now look at the third objective of the ISO, which is the minimization of payment, we will see that the price and total cost are the least in all objectives considered, while the amount of interruption is still higher than that of the Min of PILS case. The number of interruptible load contracts required would be higher than that in the case of Min of NILS. In the compromise solution, we can see that the market price is the same as in the case of Min of PAYMENT, the amount of total load interruption is almost the same as that of Min of PAYMENT case, while it has the number of contracts required as low as in the Min of NILS case. This could well justify a little increase in total cost as compared to that of Min of PAYMENT case.

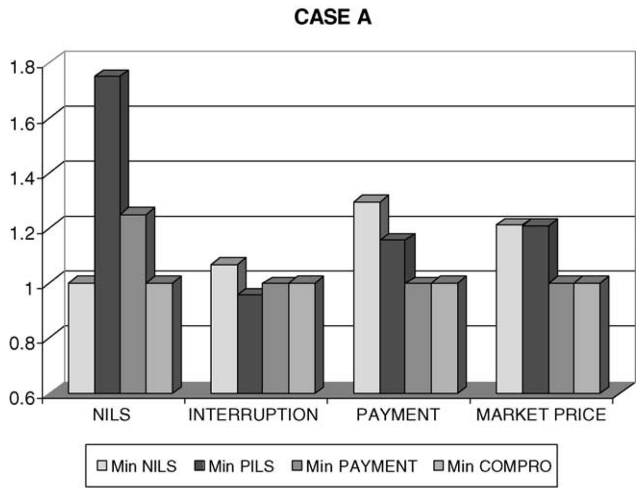

Fig. 5. Normalized (with respect to COMPRO objective) NILS, interruption, payment, and clearing price of interruptible load auction considering different objectives in Case A.

3.3.2. Case B (transmission line 4042–4044 out-of-service)

In Case B, when line 4042–4044 is out-of-service, there are three lines which are overloaded (see Table 1). It also means that more interruptible loads would be required to clear all the congestion as can be seen in Table 5. Similar to Case A, the *price-setter* bus changes with different objectives and is shown in italic, i.e., 1043 in Min of PILS, 62 in Min of PILS, 1045 in Min of PAYMENT and in Min of COMPRO.

Table 6 shows a summary of the results of the number of contracts, total demand interruption, total payment for congestion management, as well as market clearing price in each of the four objectives considered for investigations in Case B.

Fig. 6 shows the plot of normalized values of the objectives with the reference values being that of Min of COMPRO objective.

Similar to Case A, Fig. 6 show the same pattern in NILS, total interruption, total cost as well as market price. The *Compromise* objective would best satisfy all the objectives of the

Table 5
Interruptible load contracts for Case B with different objectives

Min of NILS		Min of PILS		Min of PAYMENT		Min of COMPRO	
Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)
1043	109.70	2032	103.76	1042	133.97	*1045*	318.72
1045	318.71	2031	47.65	*1045*	318.71	51	373.77
51	373.77	41	271.84	51	373.77	43	277.21
43	424.50	*62*	127.33	43	139.82	61	221.86
		63	252.02	61	221.86		
		51	119.27				
		61	221.86				

Note: the italic *bus* is the *price-setter* bus in each objective.

Table 6
Summary results for Case B

Objective (Min of)	NILS	Interruption (MW)	Payment (k$)	Market price ($/MW h)
NILS	4	1226.69	46.52	37.92
PILS	7	1143.78	43.27	37.83
PAYMENT	5	1188.16	37.20	31.31
COMPRO	4	1191.57	37.30	31.31

ISO at the same time. Total cost incurred and total demand interruption required in this contingency case is higher than those in the BAU.

3.3.3. *Case C (transmission line 4021–4042 out-of-service)*

In Case C, when line 4021–4042 is out-of-service, no new line overload is introduced unlike in the previous case. However the amount of overload is much higher now in the two lines, which would requires more interruptible loads to be invoked to clear all the congestion (Table 7). The *price-setters* in Case C are now different from the two previous cases, *i.e.*, 2032 in Min of PILS, 62 in Min of PILS, 46 in Min of PAYMENT and in Min of COMPRO. The number of interruptible load contracts is also higher in this case as compared to the previous two cases.

Table 8 shows a summary of the results of the number of contracts, total demand interruption, total payment for congestion management, as well as market clearing price in each of the four objectives considered for investigations in Case C.

Fig. 7 shows the plot of normalized values of Table 8 with the reference values being that of Min of COMPRO objective.

Fig. 7 shows the same pattern in NILS, total interruption, total payment and market price as compared to previous two cases. The Compromise objective would best satisfy all the objectives of the ISO at the same time. Total cost incurred and total demand interruption required in this contingency case is higher than those in the BAU case. It is interesting to note that the amount of demand contracted in Min of PAYMENT is almost the same as that of in Min of COMPRO, while the number of contracts in Min of COMPRO is smaller than

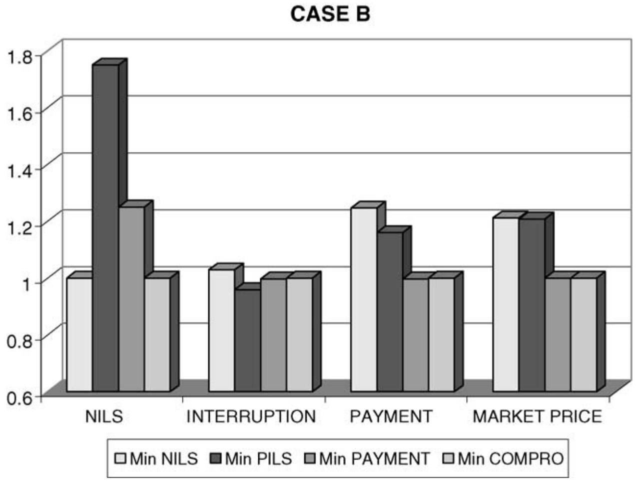

Fig. 6. Normalized (with respect to COMPRO objective) NILS, interruption, payment, and clearing price of interruptible load auction considering different objectives in Case B.

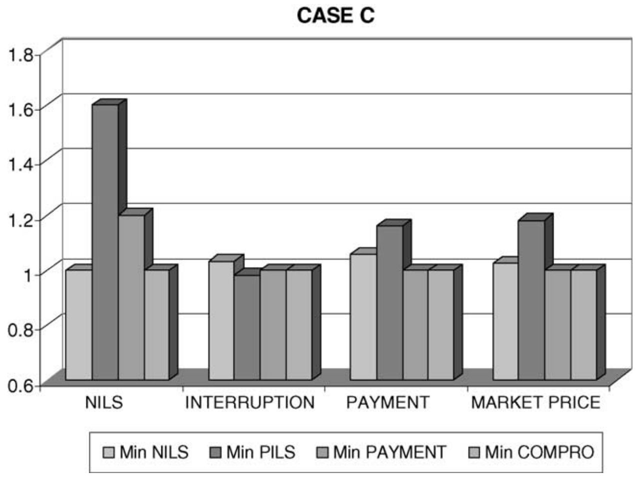

Fig. 7. Normalized (with respect to COMPRO objective) NILS, interruption, payment and clearing price of interruptible load auction considering different objectives in Case C.

Table 7
Interruptible load contracts for Case C with different objectives

Min of NILS		Min of PILS		Min of PAYMENT		Min of COMPRO	
Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)
2032	103.77	2032	103.77	1042	133.98	1045	318.72
1045	318.72	2031	47.65	1045	318.72	51	373.77
51	373.77	1045	65.33	51	373.77	43	258.39
43	424.51	41	271.85	43	424.51	*46*	315.21
46	315.21	*62*	127.34	*46*	14.67	61	221.86
		63	252.02	61	221.86		
		51	373.77				
		61	221.86				

Note: the italic *bus* is the price-setter bus in each objective.

Table 8
Summary results for Case C

Objective (Min of)	NILS	Interruption (MW)	Payment (k$)	Market Price ($/MW h)
NILS	5	1535.97	50.44	32.84
PILS	8	1463.60	55.37	37.83
PAYMENT	6	1487.51	47.63	32.02
COMPRO	5	1487.95	47.64	32.02

that of Min of PAYMENT. As it stands, Min of COMPRO is naturally the best objective in Case C.

3.3.4. *Case D (generator 4041 out-of-service)*

In Case D, when generator 4041 is out-of-service, no new line overloads are introduced. However, the amount of overload is higher in this case as compared to the BAU. It means that more interruptible loads would be required to clear all the congestions (Table 9). The *price-setter* buses in this case are 1045 in Min of PILS, 62 in Min of PILS, 1045 in Min of PAYMENT and in Min of COMPRO.

Table 10 shows a summary of the results of the number of contracts, total demand interruption, total payment for congestion management, as well as market clearing price in each of the four objectives considered for investigations in Case D.

Fig. 8 shows the plot of normalized values of Table 10 with the reference values being that of Min of COMPRO objective.

As can be seen, Fig. 8 shows the same pattern in NILS, total interruption, total cost and market price as compared to previous cases. The compromise objective would best satisfy all objectives of the ISO at the same time. It can be seen that the amount of demand contracted in the case of Min of PAYMENT is almost the same as that of in the case of Min of COMPRO, while the number of contracts in case of Min of COMPRO is smaller than that of Min of PAYMENT case. It is interesting to look at Table 9, the interruption required

Table 9
Interruptible load contracts for Case D with different objectives

Min of NILS		Min of PILS		Min of PAYMENT		Min of COMPRO	
Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)	Bus	Interruption (MW)
1045	318.72	2032	103.77	1042	133.98	*1045*	318.72
51	373.77	2031	47.65	*1045*	318.72	51	373.77
43	424.51	41	271.85	51	373.77	43	380.48
61	221.86	*62*	127.34	43	244.56	61	221.86
		63	252.02	61	221.86		
		51	218.53				
		61	221.86				

Note: the italic *bus* is the *price-setter* bus in each objective.

Table 10
Summary results for Case D

Objective (Min of)	NILS	Interruption (MW)	Payment (k$)	Market Price ($/MW h)
NILS	4	1338.86	41.91	31.31
PILS	7	1243.03	47.03	37.83
PAYMENT	5	1292.89	40.47	31.31
COMPRO	4	1294.83	40.54	31.31

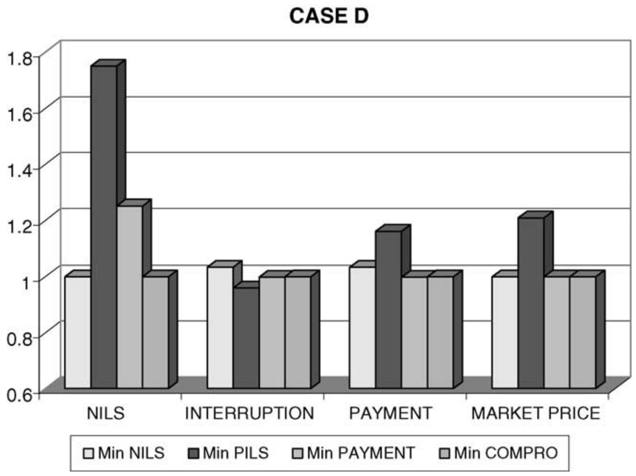

Fig. 8. Normalized (with respect to COMPRO objective) NILS, interruption, payment, and clearing price of interruptible load auction considering different objectives in Case D.

is shifting from the bus 1042 (in Min of PAYMENT) to the bus 43 (in Min of COMPRO), thereby reduces the number of interruptible contracts while sacrificing a little in PAYMENT. As it stands, Min of COMPRO is naturally the best objective in Case D.

4. Conclusions

The proposed congestion management method could specifically identify the bus locations where corrective measures need to be taken for removal of transmission bottlenecks in the system. An auction mechanism for interruptible loads has been designed and integrated with the congestion relief model. The congestion relief model can function with three different objectives of the ISO as well as satisfy the *compromise* objective of all three objectives while reducing the power flow on the congested lines to below their limits without creating new congestion in other lines. The simulation results of our case studies have clearly shown that the proposed congestion management scheme using interruptible load auction is effective in removing congestion in the transmission system in both normal loading as well as $N-1$ contingency conditions at the optimal combination of cost, number of curtailment transactions and MW demand interruption. It can therefore be concluded that with the proper contracting framework, interruptible load auction scheme should be an effective tool for congestion management of the ISO in the case of the dominant bilateral contracts market.

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List of symbols

a_1, a_2, a_{i0}	scalar multipliers
b	index for bilateral market
B	susceptance matrix
h	hour index
i,j	bus index
m	index for spot-market
NG	total number of generating buses
NL	total number of load buses
NIL	total number of interruptible load buses
Pd	real power demand (MW)
Pg	real power generation (MW)
$\mathrm{Pg}^{\max}$, $\mathrm{Pg}^{\min}$	real power generation limits (MW)
Pgcon	contracted generation (MW)
ΔPd	real power interruption (MW)
P_{ij}	power flow on line $i-j$ (MW)
$\mathrm{P}_{ij}^{\max}$	maximum transfer capacity of line $i-j$ (MW)
RES	operating reserve margin requirement (MW)
U	binary variable denoting selection of an interruptible load contract, 0/1
UC	unit commitment decision, 0/1

Greek letters

β	interruptible load bid price ($/MW h)
δ	voltage angle (rad)
μ	interruptible load bid quantity (MW)
ρ	ISO pay price to interruptible load bidders ($/MW h)

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