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Model of Information Exchange for Decentralized Congestion Management

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Abstract – The present study examines an efficient congestion management system compatible with the evolving environment. The key is to build an information model shared and exchanged for market-based solutions to alleviate congestion. Traditional methods for congestion management can be classified into two categories, i.e., the centralized scheme and the decentralized scheme, depending on the extent to which the independent system operator (ISO) is involved in market participants' (MPs) activities. Although the centralized scheme is more appropriate for providing reliable system operation and relieving congestion in near real-time, the decentralized scheme is preferred for supporting efficient market operation. The minimum set of information between the ISO and MPs for decentralized scheme is identified: i) congestion-based zone, ii) Power Transfer Distribution Factors, and iii) transmission congestion cost. The mathematical modeling of the proposed information is expressed, considering its process of making effective use of information. Numerical analysis is conducted to demonstrate both cost minimization from the MP perspective and the reliability enhancement from the ISO perspective based on the proposed information exchange scheme.

Keywords: Decentralized congestion management, System clustering, Power Transfer Distribution Factors (PTDF), Congestion Distribution Factors (CDF)

1. Introduction

Congestion management has been a major focus of reliable system operation and efficient market operation since the electric power industry reforms. Market activities by network users increase the uncertainties in network operation, often resulting in bottlenecks at unexpected places within the system [1].

Two fundamental schemes are used for performing transmission congestion management and pricing: (i) financial transmission rights (FTR) for nodal pricing under a centralized pool market scheme [2] and (ii) flowgate rights (FGR) for zonal pricing associated with decentralized markets [3, 4]. The centralized scheme refers to the methods in which the ISO schedules the dispatch by proactively collecting and accepting only the bids from market participants that do not result in congestion. The decentralized scheme refers to the methods in which the ISO only reveals the potential congestion problems to the planned dispatch schedule constructed by the market participants (MPs). Under the decentralized scheme, MPs are required to revise the dispatch schedule and iterate this process until the ISO reveals no congestion problems.

FTR and FGR are first proposed as purchased rights that can be used to hedge the risks related to the congestion charges. Although the efficiency and rationality of FTR and FGR have been under extensive discussion, both FTR and FGR can achieve the same optimal social welfare under perfect market conditions [5].

FTR, as a centralized scheme, employs the optimal power flow (OPF)-type auction method using MPs' bid information to announce the megawatt allocation of transmission capacities and the associated congestion charge to each participant. The centralized OPF is a popular method for controlling congestion problems and setting the congestion costs in many regional markets in the US. However, the use of the method in a competitive market environment has been criticized often because it requires detailed MP information, and it may lead to gaming [6].

FGR is a decentralized method for congestion management in which ISO offers the MPs information of power transfer distribution factors (PTDF) and cost signal with respect to each congested line. This FGR approach is appropriate for the market environment preferring the decentralized decision-making process [6-8].

In the current study paper, the model of information exchange between ISO and MPs for practical market operation is examined. The result aims to identify the minimum set of information: i) congestion-based zone, ii) zone-based PTDF, and iii) transmission congestion cost. Some mathematical models are introduced to process information for making effective use of it, such as congestion distribution factors (CDF) for creating zones [9] and OPF in the DC approach for computing the expected

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congestion cost in advance [10]. Numerical analysis is conducted to show how the identified information can be utilized from the MP and ISO perspectives.

2. Background

A large number of previous studies have been conducted on congestion management. Directly related to the current paper is the study of Hao [11, 12], which proposes an ex-ante congestion pricing model for decentralized markets under the assumption that the use of FTR can be problematic because of the complexity of managing the short-term scheduling function. He formulates the decentralized congestion management model with coordination between the market operator and the system operator. To remove the drawbacks of the nodal-based approach, the combination of FTR and zonal-based schemes using locational marginal price (LMP) is proposed in [13]. Based on the compatibility for implementing FTR and FGR, the decentralized zonal-based FGR scheme is applied to the deregulated centralized market structures for congestion management [14]. These studies lead to the assumption that the decentralized scheme reflecting MPs' intentions should be encouraged in the market environment.

Technically, allowing sufficient time for MPs to find market innovative solutions to congestion problems requires overcoming the weaknesses of the decentralized scheme listed in [5], i.e., difficulty in defining (i) the flowgates, (ii) PTDF values, and (iii) transfer limits because of the constantly changing network topology. For this, all plausible contingencies with high probability and high impact are first considered. All flowgates and their corresponding clusters based on well-defined technical criteria are identified. Then, the ISO can be assumed to take on some risks with respect to the changing PTDF and transfer limits, and publish the information on flowgates in the form of weighted average costs, considering the probability according to network topology. Averaging costs for changing topology is possible, but averaging transfer limits is not, as in the case of Available Transfer Capacities.

Table 1. Model of information exchange: Type, update, and process

Type of information	Update frequency	Information processing approach
Zone	• Long-term: year-ahead or season-ahead basis	• Congestion-based zones by juxtaposing every contingency case
PTDF	• Mid-term: season-ahead or month-ahead basis • Whenever network topology changes	• Zone-based PTDF
Transmission congestion cost	• Short-term: Hour-ahead basis etc.	• Weighted average costs considering the probability according to network topology

3. Model of Information Exchange

We identify the information primarily needed for decentralized congestion management: i) congestion-based zone, ii) PTDF, and iii) transmission congestion cost, as shown in Table 1. The table explains the type of information required for the decentralized scheme, update frequency of information, and information processing approach for effectively exchanging information.

Based on Table 1, Section 3 explains the type of information and its requirements, including update frequency. Section 4 addresses in detail the mathematical model for the identified information process.

3.1 Long-term information: Zone

To introduce some certainty into long-term transactions, flowgates are first defined over any and all transmission interfaces prone to congestion through an extensive contingency analysis (of high probability and high impact). At the same time, various topology changes and other uncertainties in system operation are considered, i.e., seasonal change in demand pattern including peak load and off-peak load, installation of new generators, and reinforcement of transmission lines.

Then, the congestion-cluster/zone ($Zone[k]$) is defined with respect to each flowgate based on well-defined technical criteria to avoid intra-zonal congestion. Each zone can be divided based on the flowgate by identifying groups of network users that have similar effects on the cost signal in proportion to the system topology change. Finally, this information is posted on a season-ahead or month-ahead basis.

3.2 Mid-term information: PTDF

MPs can compute the amount of flowgate rights to be reserved for their transactions based on PTDF, which provides information on the network flow caused by power injection at the nodes [15]. In the proposed information, PTDF information is posted and updated whenever network topology is changed. Using this information, MPs reschedule their transactions for higher profit with the changed conditions.

3.3 Short-term information: Transmission congestion cost

The key information in realizing the decentralized market operation is the congestion cost ($\mu_l^{(m)}[t]$) with each transaction m. The ISO should provide MPs with this information reflecting the spot market cost by estimating the average μ. This information helps MPs formulate the most profitable transactions and in turn guides them to react to the changing system conditions. In particular, decision making by individual MPs is preferred in the market environment by offering the cost information rather than the amount to be controlled directly. MPs adjust their transactions through market activities of trading long-term transmission contracts using congestion cost information. Such activities result in the alleviation of congestion problems if the cost signal properly reflects the reliability level of the system operation. As the system condition deteriorates, the congestion cost will become very costly, exerting serious effects on the LMP.

Some assumptions and requirements are required to give each participant the expected congestion cost:

- ISO should reliably offer information of the estimated cost.
- ISO should assume the responsibility for the estimated cost and take the risk sharing for it.
- Incentive regulation should be established so that ISO can expect the exact cost.
- MPs should be able to perform reasonable decision-making and self-controlling measures with the cost information.

Overall, the reliable estimated cost can be offered by considering the probability of several uncertain factors, such as line outage, demand pattern, and MPs' bidding behaviors.

4. Mathematical Formulation

In this section, the mathematical equations for constructing different types of information described earlier are formulated.

4.1 Construction of congestion-based zones

The congestion-based zone can be constructed by computing Congestion Distribution Factors (CDFs), an effective measure of system affecting transmission congestion [9]. Unlike the conventional method of using costs to group the nodes, the CDF uses the technical criteria for clustering. The result guarantees that the nodes grouped into the same zone will have nodal prices similar with the intra-cluster flow created by a transaction between any two buses having negligible effects on the congested line. Only inter-cluster transactions are considered to contribute significantly to the flow of congested lines, taking away the intra-zonal congestion problems. The system clustering process is as follows:

(a) Determine the CDF, which can be calculated using the PTDF. First, calculate the two PTDF matrices based on the two buses connected by the congested line. Second, compute the PTDF values from the only congested line in the two buses related to the congested line. Eqs. (1) and (2) show two different PTDF matrices based on the congested line (n-m line is congested).

(b) CDF can be determined by averaging each element of two vectors, i.e., $\mathbf{H}_n$ and $\mathbf{H}_m$. Following Eq. (3) shows the CDF vector of the congested line n-m, and N is the number of buses.

$$\mathbf{H}_n = \begin{bmatrix} | \\ \mathbf{D}_n^{nm} \\ | \end{bmatrix} (\text{'n' th bus reference}) \tag{1}$$

$$\mathbf{H}_m = \begin{bmatrix} | \\ \mathbf{D}_m^{nm} \\ | \end{bmatrix} (\text{'m' th bus reference}) \tag{2}$$

$$\mathbf{CDF}_{nm} = \left[\{\mathbf{D}_n^{nm}(1) + \mathbf{D}_m^{nm}(1)\}/2 \quad \cdots \quad \{\mathbf{D}_n^{nm}(N) + \mathbf{D}_m^{nm}(N)\}/2 \right] \tag{3}$$

(c) Group the nodes with similar CDF value into a cluster.

(d) After this process is completed for each likely congestion line considering all plausible contingencies, mix and patch the clustering to avoid possible intra-zonal congestion problems, as shown in Fig. 1. The clusters can become multi-congestion.

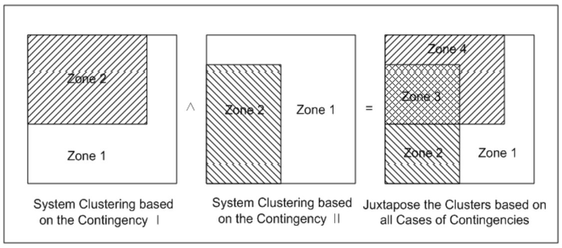

Fig. 1. System clustering (Multi-congestion clusters)

Multi-congestion clusters can be obtained through the mechanisms of cluster divisions as mentioned above. These clusters enable ISO to provide timely MPs with long-term information regardless of the minor topology change. The reason is that these mechanisms are based on the analysis of contingencies with high probability and high impact. They also make MPs quite stable with respect to actual transactions, as long as there is no major transmission line outage. In addition, information on multi-congestion clusters is no longer dynamic in the long term.

4.2 Zone-based PTDF

Using the DC approximation, the mathematical formulation for PTDF can be given by

$$\mathbf{H}_{li} = diag\left(\frac{1}{X_{ij}}\right)\mathbf{AY}^{-1} \tag{4}$$

where

l : Line index

i, j : Bus Index
X_{ij} : Reactance between bus i and bus j
A : Incidence Matrix (line number × bus number), a_{ij} (Entries of $\mathbf{A}$) are 1, -1 or 0 according to the network topology
Y : Admittance Matrix

Here, $\mathbf{A}$ is a matrix useful for describing purely topological properties of the system: how buses are connected by transmission lines in the system. Its dimensions are (line number × bus number), and its entries, a_{ij}, are given by 1 (if there is a transmission line connecting buses i and j, and $i < j$), -1 (if there is a transmission line connecting buses i and j, and $i > j$), and 0 (otherwise).

PTDF values mentioned previously can be transformed into the zone-based PTDF by averaging them within the same zone. The dimensions are reduced by (flowgates number × zone number). This more simplified information helps MPs trade transmission contracts with ease.

4.3 OPF modeling for congestion cost estimation

To avoid the line flow violation in terms of system operation and to satisfy the transactions in terms of market operation, providing timely and supportive information on congestion costs is important. This way, MPs can make decentralized decisions on whether to pay for usage-based congestion charge or curtail their transactions. When a line contingency occurs, the system constraints are violated, and the congested line cost increases. Such cost information is then published through the proposed information exchange, and MPs react to the change and adjust their market activities in the direction of increased profit. Ultimately, these decentralized activities lead to the reduced physical flow on lines, with their physical limits violated.

Accordingly, the ISO should estimate the congestion cost transparently and timely and then publish the cost such that the estimated cost must closely reflect real-time operation. Usually, the DC model of OPF is applied for the online solution of the OPF problem of a huge system and for fast solution in real-time operation mode [16].

For this purpose, the OPF formulation using the DC model [10] is employed as the congestion cost estimation technique considering the line contingencies. Objective function (5) is the minimization of the total generation costs under the pre-contingency or normal operation mode ($k = 0$) as well as all the other plausible post-contingency ($k = 1, \cdots, K$) conditions. In Eq. (5a), the equality constraint refers to the power balance to be achieved regardless of the pre-contingency states and post-contingency states. Inequality constraints (5b) represent the transmission constraints, in which $\mathbf{H}^{(k)}$, $\mathbf{P}^{(k)}$, and $\mathbf{F}_l^{\max (k)}$ are changed if the system topology changes.

$$\min \sum_{i=1}^{Ng} C_i(P_i^{(k)}) \tag{5}$$

$$s.t. \sum_{i=1}^{Ng} P_i^{(k)} = \sum_{j=1}^{Nd} P_j^{(k)} \tag{5a}$$

$$\mathbf{H}^{(k)} \cdot \mathbf{P}^{(k)} \le \mathbf{F}_l^{\max (k)} \tag{5b}$$

$$for \quad k = 0, \cdots, K$$

where
$C_i(P_i^{(k)})$: Total generation cost under *k* condition
$P_i^{(k)}$: Generation under *k* condition
$P_j^{(k)}$: Demand under *k* condition
$\mathbf{H}^{(k)}$: PTDF matrix under *k* condition
$\mathbf{P}^{(k)}$: Generation vector under *k* condition
$\mathbf{F}_l^{\max (k)}$: Maximum of line capacity vector under *k* condition

In general, the DC model of OPF is implemented in linear programming for robustness and efficiency. Linear programming with the Lagrange multiplier is used for solving the optimization problem. The computed Lagrange multipliers with respect to the marginal costs of transmission constraints (μ_l) are averaged using the contingency probability as weights to calculate the expected congestion costs, as shown in Eq. (6).

$$E[\mu_l] = \sum_{k=0}^{K} p^{(k)} \cdot \mu_l^{(k)} \tag{6}$$

where
μ_l : Lagrange multiplier showing the transmission charge of each line
p : Probability of each line outage
$E[\mu]$: Expected value of μ_l

Averaging the costs for changing topology is useful for minimizing the risk of expecting the exact cost in the changing system conditions. Moreover, the modeling of stochastic OPF can be a possible alternative to the congestion cost estimation technique, as referred to in [10].

5. Case Study

The case study focuses on how to obtain the proposed information and how to apply it at the final state after implementing the decentralized scheme. The case study shows the accomplishment of system reliability and market efficiency in the market environment through the decentralized decision of MPs.

The IEEE 39-bus system (Fig. 2) is used in the case study. It is modified for the feasible solution by setting some data, such as the probability of line outage and the bid function of generator buses, as shown in Tables 2 and 3. The congestion line is summarized in Table 2 through the contingency analysis in terms of every line.

We utilize the following conditions and assumptions to demonstrate the proposed solutions:

- MPs always take their rational and economic behavior.
- Many factors, such as line contingencies and generator contingencies, result in congestion. In this simulation, however, generators are supposed to be MPs who take rational and economic behavior. Only N-1 line contingency is considered for illustration.
- Two cases are provided considering the normal condition and a line contingency condition. This simulation focuses on the line cost information through which decentralized congestion management can be implemented.

Table 2. Probability of outage and congestion line according to contingency

Contingency	Prob. of outage	Congestion line
Line 16–17	(0.15)	Line 4–14
Line 16–21	(0.03)	Line 16–24
Line 21–22	(0.02)	Line 16–24

Table 3. Bid function of the generator bus

Bus number	Bus type	Load[MW]	Bid function[$/Mwh]
30	Gen.	0	8
31	Gen./Load	10	7
32	Gen.	0	7
33	Gen.	0	8
34	Gen.	0	8
35	Gen.	0	6
36	Gen.	0	6
37	Gen.	0	7
38	Gen.	0	8
39	Gen./Load	1100	8

5.1 Zone creation through congestion distribution factors

First, the flowgates must be designated considering the contingency with high probability and high impact on the network.

The designated flowgates are Lines 4–4 and 16–24 from the line contingency analysis. The threshold for zone clustering is defined as the difference in 20% of CDFs. Table 4 and Fig. 2 show the clustering result. The concrete process of zone creation is presented in Appendix 7.1.

Table 4. Clustering results for each contingency case

Area	Bus
A	2,3,4,17,18,25,26,27,28,29, 30.37.38
B	1,39
C	5,9
D	6,7,8,31
E	10,11,12,13,32
F	14,15,16,19,20,33,34
G	22,23,24,35,36
H	21

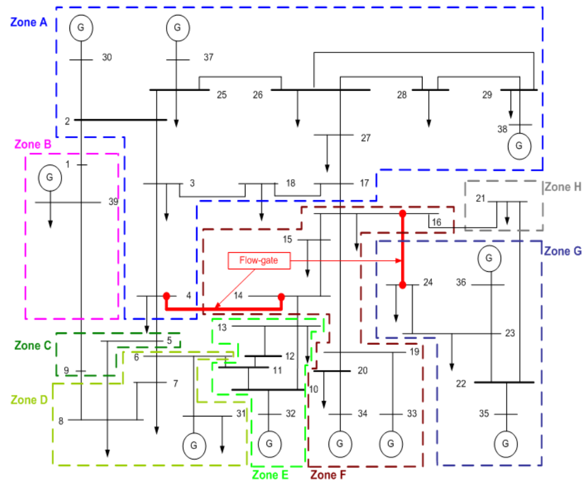

Fig. 2. System clustering of the IEEE 39-bus system

5.2 Information exchange in normal condition

PTDF information and line congestion cost are also necessary to decide the market activities of MPs.

PTDF with respect to Flowgate in the normal condition is presented in Table 15 in Appendix 7.2. For a more convenient publication of this information, PTDF should be simplified with respect to zone by averaging the PTDF of the same zone. It is more useful for MPs than the PTDF in terms of each bus. Table 7 shows the zone-based PTDF in the normal condition. For example, the zone-based PTDF value of Zone A is calculated by averaging the PTDF of the bus included in Zone A, utilizing the value referred to in Tables 4 and 12.

Table 5. Zone-based PTDF in the normal condition

Line	A	B	C	D
4–14	-0.019	0.001	0.004	-0.019
16–24	0	0	0	0
Line	E	F	G	H
4–14	-0.228	-0.241	-0.191	-0.191
16–24	0	0	-0.516	-0.173

Next, the line congestion cost can be determined by solving the OPF with the probability of line outage. This information can be used in the long-term market for a decentralized decision. The probabilities of an occurring congestion at Lines 4–14 and 16–24 are assumed to be 0.15 and 0.05, respectively, as shown in Table 2. Table 6 shows the weighted average costs considering the probability of congestion. Expectedly, MPs can take their economic judgment to maximize their profit or minimize their cost using this information.

Table 6. Congestion cost in the normal condition [$/MWh]

Congestion line	μ_l
Line 4–14	0.305
Line 16–24	0.050

Table 7 shows which generator is more effective, considering the transmission cost from the viewpoint of the load at bus 39. In this table, the generators' bid cost is used for energy cost, and the congested line cost and PTDF information are applied for transmission cost, as shown in Eqs. (7) and (8). Only the congestion cost is considered in calculating transmission cost because it will be a dominant component in using the transmission network. The sum of energy cost and transmission cost is expressed as the total cost, as shown in Eq. (9).

- Energy Cost [\$]=Load [MWh] × Generators' Bid Cost [\$/MWh] (7)
- Transmission Cost [\$]=PTDF × Load [MWh] × Congested Line Cost [\$/MWh] (8)
- Total Cost [\$]=Energy Cost [\$] + Transmission Cost [\$] (9)

From the calculation in Table 7, it would be desirable for the load at bus 39 to make a long-term contract with the generator at bus 35 or bus 36. In a normal condition system, security can be supported in spite of MPs' economic action, as all the contracts do not violate line constraints, especially flowgates 4–14, as shown in Fig. 3. Line flow in this flowgate is 0.70 [pu] in the normal condition. Eventually, system reliability and market efficiency can be achieved in the normal state.

Table 7. Energy cost and transmission cost at bus 39 in the normal condition

Bus	Zone	Energy Cost [\$]	Transmission Cost [\$]	Total Cost [\$]
30	A	7040	5.18	7045.18
31	D	6160	5.21	6165.21
32	E	6160	61.11	6221.11
33	F	7040	64.62	7104.62
34	F	7040	64.62	7104.62
35	G	5280	74.00	5354.00
36	G	5280	74.00	5354.00
37	A	6160	5.18	6165.18
38	A	7040	5.18	7045.18
39	B	7040	0.36	7040.36

5.3 Information exchange in a line contingency condition

If the unplanned outage occurred in Line 16–17, the ISO should issue the PTDF information and the estimated line cost through the OPF. For the MPs' transaction, zone-based PTDF data are recalculated in Table 8, which is derived from Table 16 in Section 7.2.

Table 8. Zone-based PTDF in Line 16–17 in the outage condition

Line	A	B	C	D
4–14	0.106	0.0180	-0.057	-0.107
16–24	0	0	0	0
Line	E	F	G	H
4–14	-0.349	-0.613	-0.613	-0.613
16–24	0	0	-0.516	-0.173

Table 9 shows the congested line cost after upgrading. Here, the probability of contingency at Line 16–17 is applied to one. Owing to the outage in Line 16–17, Line 4–14 will be congested, leading to the sharp cost increase in Line 4–14. Eventually, the information on congestion cost can be used to reflect reliability in the market operation.

Table 9. Congestion cost after line 16–17 outage [\$/MWh]

Congestion line	μ_l
Line 4–14	2.033
Line 16–24	0

Similar to the earlier case, MPs can adjust their contracts again from the upgraded information, congested line cost, and PTDF. The ISO will expect the line congestion to be managed by MPs' reaction from the given congested line cost.

Loads can recalculate their energy-buying cost based on the changed information. Table 10 shows the result of energy cost and transmission cost from the load at bus 39 after the Line 16–17 outage.

Table 10. Energy cost and transmission cost at bus 39 in the line 16–17 outage

Bus	Zone	Energy cost [\$]	Transmission cost [\$]	Total cost [\$]
30	A	7040	190.32	7230.32
31	D	6160	191.86	6351.86
32	E	6160	624.12	6784.12
33	F	7040	1096.13	8136.13
34	F	7040	1096.13	8136.13
35	G	5280	1096.13	6376.13
36	G	5280	1096.13	6376.13
37	A	6160	190.32	6350.32
38	A	7040	190.32	7230.32
39	B	7040	32.20	7072.20

Although the generator at bus 35 or bus 36 still has an economic merit in the line contingency condition, the load at bus 39 would be better for a long-term contract with the generator at bus 37 instead of the generator at bus 35 or bus 36. If this decentralized scheme through cost information is possible, the ISO can enable MPs to assume economic behaviors. At the same time, it can ensure system reliability by restraining the transactions at the congested line, as shown in Fig. 3.

Fig. 3 illustrates the line flow at the congested Line 4–14 in each case; i.e., case in the normal condition, case after

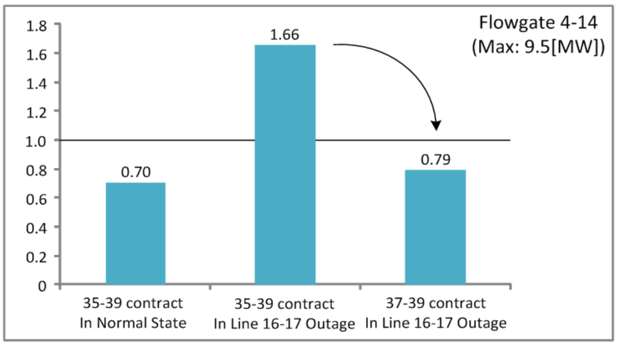

Fig. 3. Flowgate flow

Line 16–17 outage, and case after bilateral contract between the load at bus 39 and the generator at bus 37. In this figure, if the load at bus 39 keeps the contract with the generator at bus 35, then the flow limit at Line 4–14 will be violated. However, if it changes a contract for its profit through the information exchange, it can decrease the congested line flow and exert good influence on system reliability.

In the end, cost information can help accomplish system reliability and market efficiency in the market environment through the decentralized decision by MPs.

6. Conclusions

The current study shows that congestion management can be achieved by a decentralized approach based on the given information, especially congestion cost. It also reveals commonly available information about system conditions to communicate simultaneously with numerous MPs. The given congestion cost information leads MPs to select voluntarily the efficient behavior to minimize their costs and the reliable behavior to control the congestion. When there is congestion in the network, MPs respond to it and act in a way that improves system reliability with an appropriate response.

Ultimately, the study can be extended to the fundamental market mechanism and information exchange, which is a very important factor in the market architecture. Practical research on the design of information exchange is required to support the implementation from the proposed approach.

7. Appendix

7.1 System clustering process

This section describes the system clustering process of the IEEE 39-bus system explained in Section 5.1.

The IEEE 39-bus system can be divided into several zones based on the CDF. The threshold for zone creation is defined as 20% in terms of the biggest element of the CDF vectors. To create the zone as in the proposed method, N-1 line contingency analysis should be performed respectively. First, the flowgate must be designated, considering the contingency with high probability and high impact on the network. Line contingencies considered in this case are Lines 16–17, 16–21, and 21–22. The flowgates are Lines 4–14 and 16–24, as indicated in Table 2.

<u>Case 1) In the Case of Line 4–14 Congestion due to Line 16–17 Contingency</u>

Table 11 shows ① $D_{bus4}^{line4-14}$ and ② $D_{bus14}^{line4-14}$ vectors determined from (2) and (3), which are PTDFs based on bus 4 and bus 14, respectively, where Line 4–14 is connected.

Table 11 also indicates the CDF vector determined from (4) by averaging the vector from ① $D_{bus4}^{line4-14}$ and ② $D_{bus14}^{line4-14}$. Eventually, the system is divided into six zones, as shown in Fig. 4.

Table 11. D Vector and CDF in line 16–17 contingency

D \ Bus	1	2	3	4	5	6	7
①	-0.109	-0.049	-0.031	0	-0.223	-0.265	-0.244
②	0.649	0.708	0.727	0.757	0.535	0.492	0.514
CDF	0.270	0.330	0.348	0.379	0.156	0.114	0.135
8	9	10	11	12	13	14	15
-0.233	-0.181	-0.493	-0.420	-0.493	-0.567	-0.757	-0.757
0.524	0.577	0	0	0	0	0	0.709
0.146	0.198	-0.247	-0.210	-0.247	-0.284	-0.379	-0.024
16	17	18	19	20	21	22	23
-0.757	-0.035	-0.033	-0.757	-0.757	-0.757	-0.757	-0.757
0	0.722	0.724	0	0	0	0	0
-0.379	0.344	0.346	-0.379	-0.379	-0.379	-0.379	-0.379
24	25	26	27	28	29	30	31
-0.757	-0.048	-0.041	-0.038	-0.041	-0.041	-0.049	-0.265
0	0.709	0.716	0.719	0.716	0.716	0.708	0.492
-0.379	0.331	0.338	0.341	0.338	0.338	0.330	0.114
32	33	34	35	36	37	38	39
-0.493	-0.757	-0.757	-0.757	-0.757	-0.048	-0.041	-0.145
0.264	0	0	0	0	0.709	0.716	0.613
-0.115	-0.379	-0.379	-0.379	-0.379	0.331	0.338	0.234

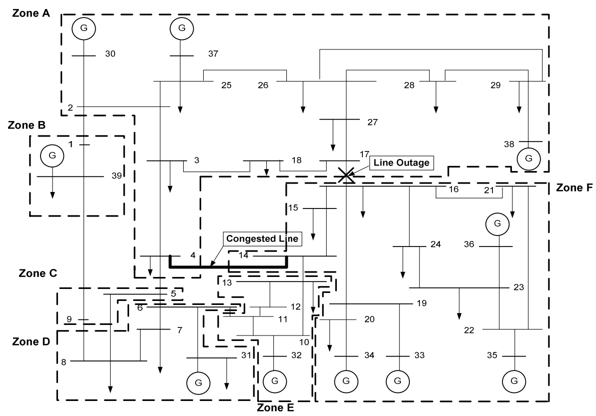

Fig. 4. Zone clustering in Case 1

Case 2) In the Case of Line 16–24 Congestion due to Line 16–21 Contingency

Table 12 shows ③ $D_{bus16}^{line16-24}$ and ④ $D_{bus24}^{line16-24}$ vectors determined from (2) and (3), which are PTDFs based on bus 16 and bus 24, respectively, where Line 16–24 is connected.

Table 12 also indicates the CDF vector determined from (4) by averaging the vector from ③ $D_{bus16}^{line16-24}$ and ④ $D_{bus24}^{line16-24}$. Eventually, the system is divided into two zones, as shown in Fig. 5.

Table 12. D vector and CDF in line 16–21 contingency

D \ Bus	1	2	3	4	5	6	7
③	0	0	0	0	0	0	0
④	1	1	1	1	1	1	1
CDF	0.5	0.5	0.5	0.5	0.5	0.5	0.5
8	9	10	11	12	13	14	15
0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16	17	18	19	20	21	22	23
0	0	0	0	0	-1	-1	-1
1	1	1	1	1	0	0	0
0.5	0.5	0.5	0.5	0.5	-0.5	-0.5	-0.5
24	25	26	27	28	29	30	31
-1	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1
-0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
32	33	34	35	36	37	38	39
0	0	0	-1	-1	0	0	0
1	1	1	0	0	1	1	1
0.5	0.5	0.5	-0.5	-0.5	0.5	0.5	0.5

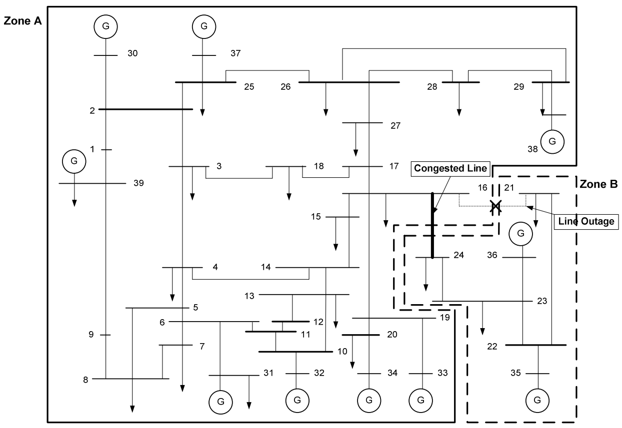

Fig. 5. Zone clustering in Case 2

Case 3) In the Case of Line 16–24 Congestion due to Line 21–22 Contingency

Table 13 shows the ⑤ $D_{bus16}^{line16-24}$ and ⑥ $D_{bus24}^{line16-24}$ vectors determined from (2) and (3), which are PTDFs based on bus 16 and bus 24, respectively, where Line 21–22 is connected.

Table 13 also indicates the CDF vector determined from (4) by averaging the vector from ⑤ $D_{bus16}^{line16-24}$ and ⑥ $D_{bus24}^{line16-24}$. Eventually, the system is divided into two zones, as shown in Fig. 6.

Table 13. D vector and CDF in line 21–22 contingency

D \ Bus	1	2	3	4	5	6	7
⑤	0	0	0	0	0	0	0
⑥	1	1	1	1	1	1	1
CDF	0.5	0.5	0.5	0.5	0.5	0.5	0.5
8	9	10	11	12	13	14	15
0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16	17	18	19	20	21	22	23
0	0	0	0	0	0	-1	-1
1	1	1	1	1	1	0	0
0.5	0.5	0.5	0.5	0.5	0.5	-0.5	-0.5
24	25	26	27	28	29	30	31
-1	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1
-0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
32	33	34	35	36	37	38	39
0	0	0	-1	-1	0	0	0
1	1	1	0	0	1	1	1
0.5	0.5	0.5	-0.5	-0.5	0.5	0.5	0.5

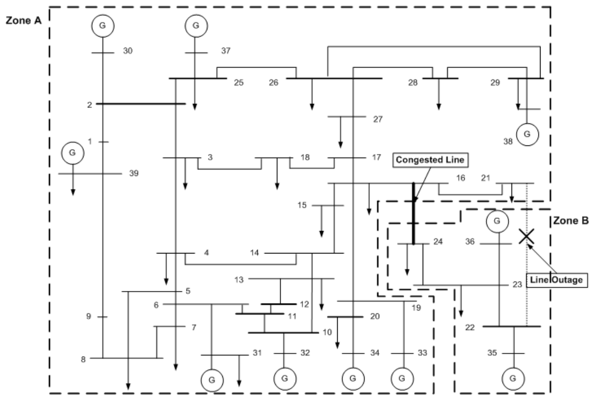

Fig. 6. Zone clustering in Case 3

Case 4) Juxtapose each case

Table 14 shows the clustering results for every contingency case. Finally, the system can be divided into eight zones by juxtaposing each case, as shown in Table 3 and Fig. 2.

Table 14. Clustering results for each contingency Case

<table>
<tr><th colspan="2">Case 1)</th><th colspan="2">Case 2)</th><th colspan="2">Case 3)</th></tr>
<tr><th>Area</th><th>Bus</th><th>Area</th><th>Bus</th><th>Area</th><th>Bus</th></tr>
<tr><td>A</td><td>2,3,4,17,18,25, 2627,28,29,30, 37,38</td><td rowspan="5">A</td><td rowspan="5">1,2,3,4,5,6,7,8,9, 10,11,12,13,14, 15,16,17,18,19, 20,25,26,27,28, 29,30,31,32,33, 34,37,38,39</td><td rowspan="5">A</td><td rowspan="5">1,2,3,4,5,6,7,8,9, 1011,12,13, 4,15,16,17,18,19, 201,25,26,27,28, 29,30,31,32,33, 34,37,38,39,21</td></tr>
<tr><td>B</td><td>1,39</td></tr>
<tr><td>C</td><td>5,9</td></tr>
<tr><td>D</td><td>6,7,8,31</td></tr>
<tr><td>E</td><td>10,11,12,13,32</td></tr>
<tr><td>F</td><td>14,15,16,19,20, 21,22,23,24, 33,34,35,36</td><td>B</td><td>21,22,23,24,35, 36</td><td>B</td><td>22,23,24,35,36</td></tr>
</table>

7.2 PTDF with respect to the flowgate

This section organizes the PTDF information with respect to flowgate in normal condition, and in Line 16–17 outage condition. Each PTDF is shown in Table 15 and Table 16, respectively.

Table 15. PTDF with respect to the flowgate in the normal condition (reference: 39-bus)

Line \ Bus	1	2	3	4	5	6	7
4-14	0.003	0.007	0.034	0.219	0.010	-0.029	-0.014
16-24	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	9	10	11	12	13	14	15
-0.007	-0.003	-0.228	-0.163	-0.228	-0.292	-0.458	-0.272
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	17	18	19	20	21	22	23
-0.191	-0.115	-0.058	-0.191	-0.191	-0.191	-0.191	-0.191
0.000	0.000	0.000	0.000	0.000	-0.173	-0.353	-0.476
24	25	26	27	28	29	30	31
-0.191	-0.007	-0.061	-0.086	-0.061	-0.061	0.007	-0.029
-0.924	0.000	0.000	0.000	0.000	0.000	0.000	0.000
32	33	34	35	36	37	38	39
-0.228	-0.191	-0.191	-0.191	-0.191	-0.007	-0.061	0.000
0.000	0.000	0.000	-0.353	-0.476	0.000	0.000	0.000

Table 16. PTDF with respect to the flowgate in line 16–17 line outage (reference: 39-bus)

Line \ Bus	1	2	3	4	5	6	7
4-14	0.036	0.095	0.114	0.145	-0.078	-0.121	-0.099
16-24	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	9	10	11	12	13	14	15
-0.088	-0.036	-0.349	-0.275	-0.349	-0.422	-0.613	-0.613
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	17	18	19	20	21	22	23
-0.613	0.110	0.111	-0.613	-0.613	-0.613	-0.613	-0.613
0.000	0.000	0.000	0.000	0.000	-0.173	-0.353	-0.476
24	25	26	27	28	29	30	31
-0.613	0.097	0.103	0.106	0.103	0.103	0.095	-0.121
-0.924	0.000	0.000	0.000	0.000	0.000	0.000	0.000
32	33	34	35	36	37	38	39
-0.349	-0.613	-0.613	-0.613	-0.613	0.097	0.103	0.000
0.000	0.000	0.000	-0.353	-0.476	0.000	0.000	0.000

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