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Congestion Management System Methods: Comparison on the 118 Bus System

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Abstract

The paper discusses the optimality conditions pertaining to the implementation of the cluster-based congestion management systems (CMSs). In particular we are interested in two cluster-based CMSs; zonal pricing method and congestion cluster pricing method. The methods differ in the criteria used for aggregating the nodes into clusters.

The implementation of the cluster-based CMS has widely recognized advantages and disadvantages compared to the implementation of the bus-based CMS, i.e. the nodal pricing method. The advantages are related to the beneficial direct access and customer choices by providing transparent information to system users involved in bilateral transactions. The uniform prices within clusters simplify the computation of financial risks in bilateral transactions arising from the spatial differentiation in generation in the presence of transmission congestion. The disadvantages are related to the unfavorable increase in cost of dispatched generators in short term. The short term dispatch is suboptimal due to two factors: (1) the cost from the cluster-wide prices in inter-cluster pricing and (2) the cost from the uplift charges in intra-cluster pricing. In order to maximize the beneficial effect while minimizing the unfavorable impact, the cluster boundaries need to be defined such that the power flows at the congestion interfaces are unaffected by any transactions between two buses within a cluster. We show that this can be accomplished with less difficulties when using congestion cluster pricing method than using zonal pricing method. A numerical example is given to illustrate the proposition.

Keywords

Energy Market, Congestion Management Systems (CMS), Nodal Pricing Method, Zonal Pricing Method, Congestion Cluster Pricing Method, Congestion Distribution Factors (CDFs), Spot Market, Bilateral Transactions, Transmission Charge, Efficiency (Short Term and Long Term)

I. Introduction

In the electric power industry the maximization of short term efficiency has been accomplished through a strict regulation on the operation of the existing generation and transmission resources under the vertically integrated utility structure. From the regulator's perspective it is a relatively simple task to put an optimal regulation regime in place for overseeing the operation since the short term efficiency is quantifiable by measuring the system-wide generation cost in meeting the given load at each hour. The maximization of long term efficiency, however, has not yet been obtained despite the rigid regulation on the planning by the utility. This is mainly due to the difficulties in making judicious investment decisions under uncertainties through a centralized decision making process. As a result there is no optimal regulation regime defined for overseeing the planning as the long term efficiency is not easily quantifiable.

The competition and market mechanism are introduced to improve on this long term inefficiency. The well designed market structure replaces the strict regulation regime and achieves the system-wide efficiency in both long term and short term not through an explicit coordination by a single utility but rather through decentralized decision making processes of many entities. These entities are driven by economic incentives and financial risks. By placing the proper incentives and risks in the form of profit to suitable entities, the prudent operation and planning result benefiting the overall system.

It is important to recognize that there is a considerable difference in choosing a regulatory regime and designing a market structure. In designing a market structure, the objective is not the explicit optimization of short term and long term efficiencies as in choosing a regulatory regime but is rather the best accommodation of physical/financial transactions that lead to optimization of these efficiencies.

The trade in spot markets are frequently linked to the short term efficiency since the timely utilization of existing resources translates to the immediate reduction in cost. The bilateral transactions, on the other hand, are often associated with the long term efficiency. This is the result of the information on utilization of resources over a sustained period of time revealed through bilateral transactions, which has a considerable impact on investment decisions. The bilateral transactions also allow for direct access of customers by suppliers and for product choices by customers, which is directly related to the technology and infrastructure of the suppliers.[1]

Unlike other commodities, the peculiar characteristics of the power system make it difficult to design a market that admits straightforward execution of bilateral transactions. These characteristics include but not limited to the strict requirement for near real time balancing of supply and demand, the non-storability of electricity in an economical way, the lack of controllability in power flows throughout the transmission grid, and the existence of multiple generation (and up to certain degree transmission) technologies. When parts of the grid hit the physical transfer limits referred to as the transmission congestion, some generators need to be constrained off and some constrained on in order to relieve the congestion. This process of choosing which generators to dispatch in the presence of congestion is called, the congestion management system (CMS).[2] The CMS plays a considerable role in operating the energy market since it limits certain system users from participating in the market. For example, if a supplier involved in a bilateral transaction is selected as the generator to be constrained off, this bilateral transaction needs to be curtailed despite the adequacy in generation by the supplier.

Currently there are two schools of thoughts in implementing market-based CMS. They are bus-based CMS and cluster-based CMS. In bus-based CMS, each node in the system network receives a particular nodal price based on supplier's willingness to produce so that the quantity produced is limited by this price. The nodal pricing method is an example of bus-based CMS.[3] In the cluster-based CMS, the nodes belonging to a same cluster receives a single cluster-wide price. The zonal pricing method and the congestion cluster pricing methods are the examples of cluster-based CMS. The methods differ in the criteria used for aggregating the nodes into clusters.[4]

The implementation of the cluster-based CMS has widely recognized advantages and disadvantages compared to the implementation of the bus-based CMS. The advantages are related to providing transparent information regarding congestion status to system users involved in bilateral transactions. The uniform prices within clusters simplify the computation of financial risks in bilateral transactions arising from the limitation on generation in the presence of transmission congestion. The disadvantages are related to the unfavorable increase in cost of dispatched generators in short term. The short term dispatch is suboptimal due to two factors: (1) the cost from the cluster-wide prices in inter-cluster pricing and (2) the cost from the uplift charges in intra-cluster pricing.

The paper is organized as follows:

Section II provides the mathematical background on implementation of various CMSs. In the section we point out the suboptimality of generation dispatch under the cluster-based CMS compared to the dispatch under the bus-based CMS strictly on the short term measured in terms of total generation cost of meeting the load. A detailed comparison of the zonal pricing method and the congestion cluster pricing method is given in Section III. Some optimality conditions on the long term are stated for choosing the congestion cluster pricing method over the zonal pricing method. Section IV presents the numerical examples to illustrate the proposition, and Section V summarizes the conclusions of the paper.

II. Congestion Management Systems

The implementation of the nodal pricing method, the zonal pricing method and the congestion cluster pricing method can be posed as optimization problems.[1] For simplicity, we make the following two assumptions. First, the formulation of the problems are performed under the DC power flow assumption. The DC power flow equations in matrix notation are written as:

$$\mathbf{B}\delta = \mathbf{Q_{G_i}} - \mathbf{Q_{D_i}} \tag{1}$$

where

δ	: the voltage angle vector
Q_{G_i}	: the real power generation vector for buses G_i
Q_{D_i}	: the real power load vector for buses D_i

Then the flow vectors for lines can be computed as

$$\mathbf{F_l} = \mathbf{H}\delta \tag{2}$$

where $\mathbf{H}$ is the linearized flow matrix for the system.

Second, the generation cost of supplier G_i, C_{G_i}, is assumed to be quadratic function of the output given by,

$$C_{G_i}(Q_{G_i}) = a_{G_i} Q_{G_i}^2 \tag{3}$$

[1]The major part of the section is a summary of the results presented in [4].

where

Q_{G_i} : the dispatched generation amount at node G_i

C_{G_i} : the total cost of generation at node G_i expressed in terms of Q_{G_i}

This implies that under the perfectly competitive market condition, the optimal production decision for the given price is to generate based on the marginal cost given by,

$$\begin{aligned} MC_{G_i} &= \frac{dC_{G_i}}{dQ_{G_i}} \\ &= 2a_{G_i}Q_{G_i} \end{aligned} \tag{4}$$

A. Bus-based Congestion Management Systems

A.1 Nodal Pricing Method

The nodal pricing method is based on the computation of location marginal price at each individual node in the system developed in [3]. The optimization problem to be solved in order to determine the location marginal prices is given by

$$\min_{Q_{G_i}} \sum_{G_i} C_{G_i}(Q_{G_i}) \tag{5}$$

subject to the load flow constraint, i.e., total generation is equal to system load,

$$\sum_{G_i} Q_{G_i} = \sum_{D_i} Q_{D_i} \qquad : \lambda \tag{6}$$

the transmission line flow limit constraints, i.e., the power flow on line l is within the maximum rating of the line,

$$|F_l| = \left| \sum_{G_i} H_{lG_i} Q_{G_i} - \sum_{D_i} H_{lD_i} Q_{D_i} \right| \leq F_l^{max} \quad : \mu_l \tag{7}$$

and the generation limit constraints, i.e., the dispatch amount at node G_i is within the maximum rating of the corresponding generator

$$0 \leq Q_{G_i} \leq Q_{Gi}^{max} \qquad : \eta_{G_i} \tag{8}$$

The solution to the optimization problem (5) is then given by

$$\begin{aligned} \rho_i &= \frac{dC_{G_i}}{dQ_{G_i}} + \eta_{G_i} \\ &= \lambda + \textstyle\sum_l \mu_l H_{lG_i} \end{aligned} \tag{9}$$

where $\mu_l \neq 0$ if and only if $|F_l| = F_l^{max}$ and

$$Q_{G_i} = \begin{cases} Q_{G_i}^{max} & \rho_{G_i} \geq p_{G_i}^{max} \\ \frac{\rho_i}{2a_{G_i}} & 0 \leq \rho_{G_i} \leq p_{G_i}^{max} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

where $p_{G_i}^{max} = 2a_{G_i} Q_{G_i}^{max}$.

B. Cluster-based Congestion Management System

The practical implementation of the cluster-based CMS consists of two steps: (1) aggregation of individual nodes into clusters and (2) computation of cluster-wide prices.

Under both the zonal pricing method and the congestion cluster pricing method, the cluster-wide prices are computed in the same way. Suppose the nodes $G_i, G_{i+1}, \cdots, G_{i+k}$ are in the cluster z_j. Then the new generation cost associated with the cluster z_j is given by

$$C_{z_j}(Q_{z_j}) = f_{z_j}(Q_{G_i}, Q_{G_{i+1}}, \cdots, Q_{G_{i+k}}) \tag{11}$$

where f_{z_j} is the monotonically increasing nonlinear function representing the least cost combination of Q_{G_i}'s in z_j for producing Q_{z_j}. The marginal cost of zone z_j, MC_{z_j}, can be used in order to compute $f_{z_j}(\cdot)$ where

$$MC_{z_j} = \begin{cases} \left(\frac{1}{2a_l} + \frac{1}{2a_{l+1}} + \cdots + \frac{1}{2a_{l+s}}\right)^{-1} Q_{z_j} & Q_{z_j} \in R_{I_1} \\ \left(\frac{1}{2a_m} + \frac{1}{2a_{m+1}} + \cdots + \frac{1}{2a_{m+t}}\right)^{-1} Q_{z_j} & Q_{z_j} \in R_{I_2} \\ \cdot & \\ \cdot & \\ \cdot & \\ \left(\frac{1}{2a_n} + \frac{1}{2a_{n+1}} + \cdots + \frac{1}{2a_{n+u}}\right)^{-1} Q_{z_j} & Q_{z_j} \in R_{I_k} \end{cases} \tag{12}$$

where R_{I_i}'s define the region of operating condition in cluster j with q number of generators are still below the generation limits. a_r's represent the coefficient of associated marginal cost of those generators below their generation limits.

With $C_{z_j}(Q_{z_j})$, the cluster-wide prices are computed by solving the optimization problem given as

$$\min_{Q_{z_j}} \sum_{z_j} C_{z_j}(Q_{z_j}) \tag{13}$$

subject to the load flow constraint, i.e., total generation is equal to system load,

$$\sum_{z_j} Q_{z_j} = \sum_{D_i} Q_{D_i} \qquad : \lambda \tag{14}$$

the congestion interface flow limit constraints, i.e., the power flow on any line l *along only the congestion interfaces* is within the maximum rating of the line,

$$|F_l| = \left| \sum_{z_i} H_{lz_i} Q_{z_i} - \sum_{D_i} H_{lD_i} Q_{D_i} \right| \leq F_l^{max} \quad : \mu_l \tag{15}$$

and the generation limit constraints, i.e., the dispatch amount in cluster z_j is within the sum of maximum rating of the corresponding generators within the cluster

$$0 \leq Q_{z_j} \leq \sum_{G_i \in z_j} Q_{G_i}^{max} \qquad : \eta_{z_j} \tag{16}$$

The computation of H_{lz_i} yields

$$H_{lz_i} = \frac{dF_l}{dQ_{G_i}} \frac{\partial Q_{G_i}}{\partial Q_{z_j}} + \frac{dF_l}{dQ_{G_{i+1}}} \frac{\partial Q_{G_{i+1}}}{\partial Q_{z_j}} + \cdots + \frac{dF_l}{dQ_{G_{i+k}}} \frac{\partial Q_{G_{i+k}}}{\partial Q_{z_j}} \tag{17}$$

with

$$\frac{dF_l}{dQ_{G_i}} = H_{lG_i} \tag{18}$$

and with

$$Q_{G_i} = \frac{1}{2a_i} \left(\frac{1}{2a_i} + \frac{1}{2a_{i+1}} + \cdots + \frac{1}{2a_{i+k}} \right)^{-1} Q_{z_j} \tag{19}$$

if $Q_{G_i} \in R_{I_i}$.

The solution to the optimization problem eq:znopf then given by

$$\rho_{z_i} = \lambda + \sum_l \mu_l H_{lz_i} \tag{20}$$

where $\mu_l \neq 0$ if and only if $|F_l| = F_l^{max}$ and

$$Q_{G_i} = \begin{cases} Q_{G_i}^{max} & \rho_{z_i, G_i \in z_i} \geq p_{G_i}^{max} \\ \frac{\rho_{z_i}}{2a_{G_i}} & 0 \leq \rho_{z_i, G_i \in z_i} \leq p_{G_i}^{max} \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

where $p_{G_i}^{max} = 2a_{G_i} Q_{G_i}^{max}$.

III. Optimality Conditions for Cluster-based CMS

The optimality of the nodal pricing method is ensured since the locational marginal price in Eq. (9) represents the marginal valuation of net benefits at that node thereby providing the correct generation incentive with respect to allocating the limited transmission capacities to the most cost-effective suppliers. The total generation cost is minimized as a result in meeting the given load subject to the transmission constraints. Under the nodal pricing method, however, the participants entering into bilateral contracts need to assess the transmission congestion related risks between every nodes since the prices can vary significantly from one node to another even when they are geographically contiguous. Given that the large systems such as New England are composed of over 2000 buses [5], the risk assessment is quite intensive computationally. Thus, the market structure under nodal pricing method is not very accommodating in terms of implementing bilateral transactions as conjectured earlier.

The prices under the cluster-based CMS do not vary from one node to another unless they belong to separate clusters. Assuming that the system is divided into less than 100 clusters, this is a drastic reduction in complexity in terms of assessing the transmission congestion related risks when entering into bilateral contracts compared to under the nodal pricing method. Thus, the market structure under the cluster-based CMS is much more accommodating to the bilateral transactions.

The reduction in complexity, however, comes at the cost of suboptimality of the solution in Eq. (20) relative to in Eq. (9). This is due to the aggregation step in which the sensitivity of the power flow on lines along congestion interfaces with respect to the injection is computed on the cluster basis within the region. Intuitively the increase in total generation cost is the result of decrease in flexibility of selecting injections for relieving congestion since the choices are now limited to the number of clusters from the number of nodes. Thus, the step in aggregation becomes significant. For this reasons it is interesting to compare the zonal pricing method to the congestion cluster pricing method since the methods differ in the criteria for aggregating individual nodes into clusters.

A. Zonal pricing

Under zonal pricing method, the nodes are aggregated into zones based on price differentials in locational marginal prices. It is worthwhile bringing to attention that in order to implement zonal pricing, the optimization problem (5) needs to be solved first since the locational marginal prices are required for defining zones. From the solution (9), the nodes, G_i and G_j are put into the same zone if $\rho_{G_i} \approx \rho_{G_j}$. The criteria of defining $\approx$ depend on the number of zones allowed and on the judgment of system operator. For example, for the large number of zones allowed $G_i \in z_k$ if

$$\frac{|\rho_{G_i} - \rho_{z_k}|}{\rho_{z_i}} \leq 2\% \tag{22}$$

whereas for the small number of zones

$$\frac{|\rho_{G_i} - \rho_{z_k}|}{\rho_{z_k}} \leq 5\% \tag{23}$$

where ρ_{z_k} is the average of ρ_{G_i}'s.

B. Congestion-cluster pricing

In congestion-cluster pricing method the nodes are aggregated into congestion clusters based on their relative impacts of injection on congested transmission lines. The key to the method is the novel approach recently proposed in [6] used to compute the sensitivity measures of injections.

Contrast to the zonal pricing method where the locational marginal prices are the prerequisite for the implementation, the knowledge of likely congested transmission lines are required for the congestion cluster pricing method. This can be done by again solving the optimization problem (5) and identifying the congested lines after substituting the solution in Eq. (10) into the load flow equations in Eq. (1). However, in many cases the experienced system operator often knows the potentially congested transmission lines within the system in which case initially solving the optimization problem (5) is not required.

Once the potentially congested transmission lines are identified, the system operator computes so-called *congestion distribution factors* (CDFs) which measure the effects of injection at each node on those transmission lines. The magnitude of CDF defines the sensitivity of the flow in transmission line of interest for a given injection. The sign denotes if the injection will increase or relieve the congestion.

Assuming that the potentially congested transmission lines match the result of solving the the optimization problem (5), due to Eq. (17) the resulting clusters z_k's are equivalent to consisting of nodes, G_i and G_j if $H_{lG_i} \approx H_{lG_j}$[2] for l's where $\mu_l \neq 0$ in Eq. (9). The criteria of

[2]It is not correct to use the notation H_{lG_i} to denote the CDFs but there is little harm in the abuse of notation (for the simple purpose of this paper without introducing further complications) since CDFs can be regarded as the distribution factors that are independent of the choice of slack bus.

defining $\approx$ again depend on the number of congestion clusters allowed and on the judgment of system operator. For example, for the large number of congestion clusters allowed $G_i \in z_k$ if

$$\frac{|H_{lG_i} - H_{lz_k}|}{H_{lz_k}} \leq 2\% \tag{24}$$

whereas for the small number of zones

$$\frac{|H_{lG_i} - H_{lz_k}|}{H_{lz_k}} \leq 5\% \tag{25}$$

where H_{lz_k} is the average of H_{lG_i}'s.

C. Optimality under Multiple Line Congestion

Suppose there is one potentially congested transmission line in the system after solving the optimization problem (5)[3], and the number of clusters allowed is limited to x for implementing cluster-based CMS.

Under the congestion cluster pricing method, then, the system operator adjusts the threshold τ_{cc} such that the number of resulting clusters defined by

$$\frac{|H_{lG_i} - H_{lz_k}|}{H_{lz_k}} \leq \tau_{cc}\% \tag{26}$$

is less than or equal to x.

Similarly under the zonal pricing method, the system operator adjusts the threshold τ_z for dividing the system into zones until the number of zones defined by

$$\frac{|\rho_{G_i} - \rho_{z_k}|}{\rho_{z_i}} \leq \tau_z\% \tag{27}$$

is less than or equal to x.

Even though the congestion cluster pricing method and the zonal pricing method use different criteria, it is observed that the resulting clusters and zones are very similar when only a single potentially congested line is present.[4] Depending on the choice of H_{lz_k} or ρ_{z_k}

[3]For the purpose of comparison we assume the potentially congested transmission lines are determined by solving the optimization problem (5) even under the congestion cluster pricing method. However, it should be noted that in real life application the system operator is more likely to rely on the historical pattern of congestion for identifying these transmission lines without resorting to solving (5), which is another advantage of employing the congestion cluster pricing method over the zonal pricing method.

respectively, the degree of the suboptimality can vary, but the empirical results also show that this effect is minimal compared to the effect of choice in x and of choice in τ_{cc} or τ_z.

In the case of more than one potentially congested transmission lines, however, the resulting clusters under the congestion cluster pricing method and the zones under the zonal pricing method may significantly divergent from each other. Under the congestion cluster pricing method, the system operator defines the clusters by looking at the congestion on transmission lines one at a time. For each potentially congested line l_α, the nodes are aggregated into congestion clusters based on Ineq. (26) as follows:

$$\frac{|H_{l_\alpha G_i} - H_{lz_k}|}{H_{lz_k}} \leq \tau_{cc,\alpha}\% \tag{28}$$

where $\alpha = 1, 2, \cdots, \#$ of potentially congested lines. Once the clusters are defined for each transmission lines, these clusters are superposed on top of one another and new cluster boundaries defined by taking the intersections of the clusters defined initially. The number of resulting clusters can be quite large since the number of intersections grows at worst by the multiple of congested transmission lines and the number of clusters defined for each line. In order to maintain the number of clusters to less than or equal to x, some intersection may have to be re-combined as well as adjusting H_{lz_k} and τ_{cc}. When the intersections are required to be re-combined, the degree of suboptimality of the cluster-based CMS needs to be examined since it may have a large effect.

As indicated earlier the suboptimality is due to two factors: (1) the cost from the cluster-wide prices in inter-cluster pricing and (2) the cost from the uplift charges in intra-cluster pricing. Of these two factors, the cost from the uplift charges has a greater impact from the perspective of the short term as well as long term efficiencies since it increases the total generation cost and *directly affects the implementation of bilateral transactions*. Given that the cluster-based CMS is to allow for transparent information to system users, the cluster boundaries need to be defined such that the power flows at the congestion interfaces are unaffected by any transactions between two buses within a cluster. In case there is an intra-cluster congestion, this is no longer true and some bilateral transactions within the system may be required to be curtailed. Therefore, the effect of bilateral transactions within clusters should be considered meticulously when defining congestion clusters by adjusting H_{lz_k} and τ_{cc} at the initial division steps for each line as well as at the re-combination steps by ensuring the injection and withdrawal within the cluster has minimal effect of power flows on transmission lines on congestion interfaces.

Under the zonal pricing method the system operator defines the zones considering only the collective effect of potentially congested lines irrespective of the distinct effect of each line. Thus, there is little difference in the way the zones are determined in the presence of congestion on a single transmission line or on multiple lines. This is a consequence of using the criteria of similar locational marginal prices for aggregating nodes into zones. As evidenced in Eq. (9) the individual effect of H_{lG_i} is only apparent in ρ_i in the form of $\sum_l \mu_l H_{lG_i}$. Therefore, there may be cases where two nodes having very different sensitivities of injection on the power flows through the congested transmission lines are placed in the same zone if the individual effects are cancelled out in the computation of locational marginal prices. This is a highly undesired consequence as even though these two nodes are placed in the same zone, the bilateral transactions between these two nodes have a large impact on transmission congestion. The resulting zonal division is especially suboptimal compared to the congestion cluster pricing methods for the reasons explained earlier.

IV. Example

The concepts described in the previous sections are illustrated through the 118 bus (power flow test case) system shown in Figure 1. The zonal pricing method and the congestion cluster pricing methods are applied to the system and are compared in the presence of multiple potentially congested transmission lines.

First, we assign some appropriate system characteristics to the generators, loads and transmission lines. The characteristics include the cost function of the form given in Eq. (3) and generation limit of $Q_{G_i} \in [0, \infty)$ assigned to each generator, inelastic demand assigned to each load, and line impedance[4] and transfer limits assigned to each transmission line. Then, the optimization problem (5) is solved in order to compute the locational marginal prices and to identify the congestion interfaces. Three lines between buses 15 and 17, between buses 65 and 68, and between buses 94 and 100 are identified as reaching the limits of 10MW, 40MW and 40MW respectively. Finally, based on the locational marginal prices and the CDFs (computed for each of the three lines), zonal boundaries and cluster boundaries are

[4]The line capacitance and resistance are neglected under the DC load flow assumptions.

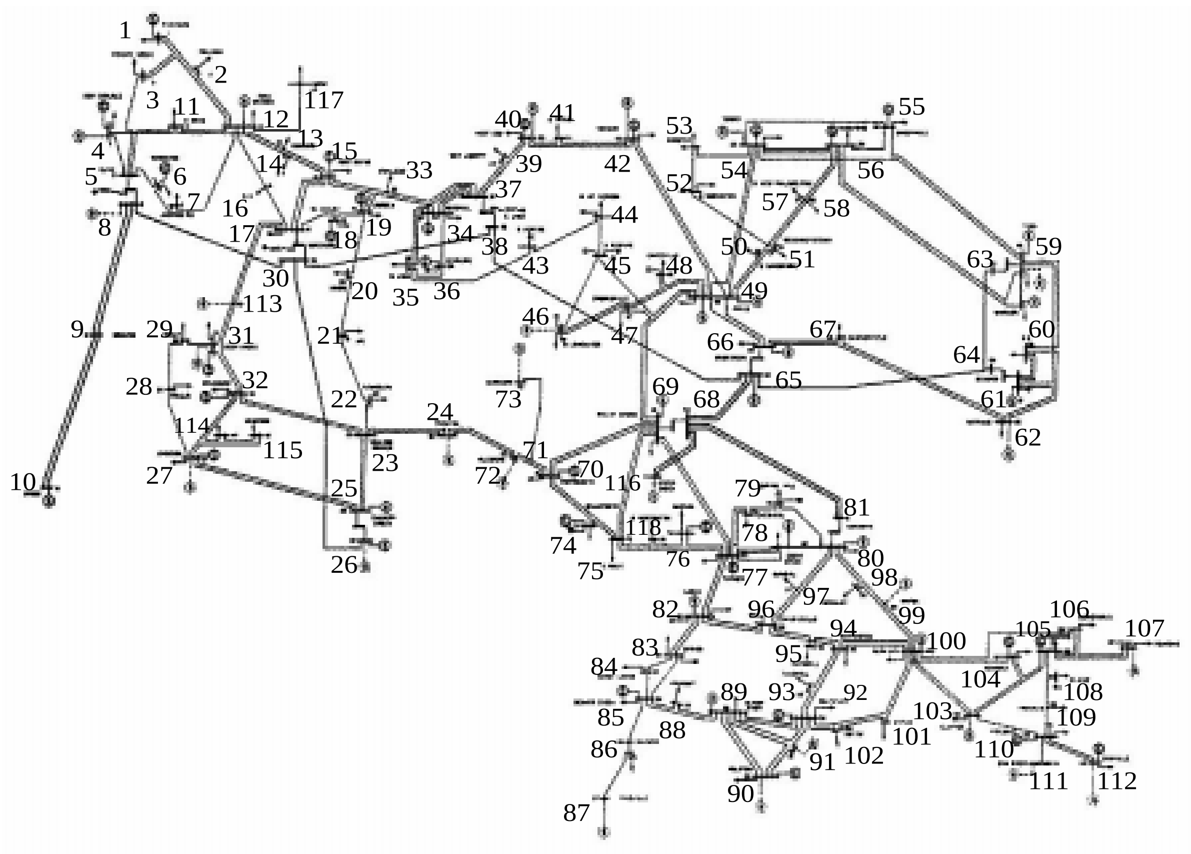

Fig. 1. One line diagram of 118 bus (power flow test case) system

determined by applying the criteria defined for the zonal pricing method and the congestion cluster pricing method respectively. There is an imposed limit on number of allowed zones and clusters to be less than or equal to 25.

Table I shows the zonal division based on similar locational marginal prices. The difference in locational marginal prices among the nodes within the same zone is restricted to be within 5% of one another.

Table II presents the congestion cluster division based on similar CDFs. For each constrained line, clusters are formed by aggregating nodes with CDFs that are similar in magnitude and have the same polarity/sign (either negative or positive depending on the convention of direction in power flows). By aggregating nodes having the differences in CDFs within 5% of one another into the same congestion clusters, 12 to 15 clusters are identified for each congested transmission line. By superposing these cluster boundaries 31 clusters are defined

Zone	1	2	3	4	5
Buses	1-3	4,5	8-10	11,12, 117	6,7,16
Zone	6	7	8	9	10
Buses	17,113	27-32,114,115	30	18	13,14,19,20,33
Zone	11	12	13	14	15
Buses	21,22	23-26,72	34-43	44-48	49-67
Zone	16	17	18	19	20
Buses	68-71,73-76,79-81,116,118	82-92	93-96	97	77,78
Zone	21	22	23	24	
Buses	98,99	100,103-112	101,102	15	

TABLE I

Division under the zonal pricing method

Cluster	1	2	3	4	5
Buses	1-7,11,12,16,117	8-10,30	17,113	27-29,31,32,114,115	25,26
Cluster	6	7	8	9	10
Buses	18	13-15	33	19	20-22
Cluster	11	12	13	14	15
Buses	23, 24	71-73	34-37,39-41,43	42,44-50	69,74-76,118
Cluster	16	17	18	19	20
Buses	68,116	38,64,65	51-58	59-63,66,67	79-81
Cluster	21	22	23	24	25
Buses	77,78	93-97	100-112	82-92	98,99

TABLE II

Division under the congestion cluster pricing method by taking the intersections. Some of these clusters are then recombined so that the number of clusters at the end is equal to 25 (the limit on number of allowed clusters). The clusters recombination process is justified by constraining the recombined clusters to have little effect on total generation cost before and after the process. The resulting total generation cost of meeting the load is given in Table III.

Method	Total Cost of Generation ($)
Nodal	37,122
Congestion cluster	37,125
Zonal	37,127

TABLE III

Total generation cost of meeting the load

This constraint on limiting the change in total cost of generation in recombination process is also equivalent to requiring little change in power flows through transmission lines before and after the process. Since the flows on lines are preserved through the recombination process, the effect of bilateral transactions within a cluster on congested transmission lines remain unaffected as desired. This is a key advantage of congestion cluster pricing method over the zonal pricing as evidenced by examining the affiliation of bus 116 under these two methods. Under the zonal pricing method bus 116 belongs in the same zone as buses 70-75. However, any bilateral transactions between 116 and any one of buses 70 through 75 results in 14% of transfer passing through one of three constrained lines, transmission line between buses 65 and 68. Under the congestion cluster pricing method the bus 116 is correctly identified belonging to the separate cluster from buses 70 through 75. When the constraint on transmission line between buses 94 and 100 is relaxed, the bus 116 is correctly identified as belonging to a different zone under the zonal pricing. This indicates that the congestion on the transmission line between buses 94 and 100 offsets the effect of injection at bus 116 on the power flows through the other congested transmission lines when only the locational marginal prices are considered. Suppose there is a bilateral transaction of 200MW between buses 116 and 75. Table IV shows the resulting total generation cost for given system load (3,668MW in spot market and 200MW through bilateral transaction) and transmission charge imposed on this bilateral transaction. Given that the total load in spot

Method	Total Gen. Cost ($)	Trans. Charge on Bilateral 116-75 ($)
Nodal	37,188	105
Congestion cluster	37,191	106
Zonal	37,192	0

TABLE IV

Total Costs with Bilateral Transaction

market is only 3,668MW, the transmission charge levied on the bilateral transaction of $105 computed through the nodal pricing method is quite high compared to the total transmission revenue of $1,380. This is because the transaction causes a large increase in transmission congestion on line between buses 65 and 68 as described earlier. The transmission charge of $106 computed by the congestion cluster pricing method correctly identifies the contribution of this transaction on transmission congestion. However, the transmission charge on the same bilateral transaction is $0 through the zonal pricing method since the buses 116 and 75 belong to the same zone, thus resulting in an enormous inefficiency.

It is also evidenced that the congestion cluster pricing method seems to fare better against the zonal pricing method in terms of the total cost of generation, deviation of generation dispatch from the nodal pricing method although this may be related more to having one more cluster than under the zonal pricing method.

V. Conclusion

As the deregulation of electric power industry spreads throughout the U.S., it is more and more evident that the appropriate CMS must accompany the market design in order to truly achieve the goal of deregulation: the improvement in long term efficiency. The cluster-based CMSs may be desirable relative to the other existing CMSs since they are much more accommodating to implementing bilateral transactions by providing transparent information on status of transmission (system) congestion. Plus, the uniform prices within clusters simplify the computation of financial risks in bilateral transactions arising from the limitation on generation in the presence of transmission congestion.

However, the implementation of cluster-based CMSs requires a meticulous consideration as it may greatly reduce the suboptimality inherent to the cluster-based CMSs compared to the bus-based CMS strictly on the short term measured in terms of total generation cost of meeting the load.

Among various cluster-based CMSs the paper examine, in details, the zonal pricing method and the congestion cluster pricing method which differ in the criteria used for aggregating the nodes into clusters. Although the implementation of the zonal pricing method is relatively easier than the congestion cluster pricing method as they are several more involved steps are required in defining congestion clusters than determining zones, there are several advantages associated with the congestion cluster pricing method that makes the method much more attractive. The advantages include but are not limited to (1) no requirement on solving the optimization problem linked with the nodal pricing method in case the potentially congested transmission lines can be identified based on historical data, (2) reduction in deviation of generation dispatch from the nodal pricing method and most importantly (3) accuracy in identifying congestion interfaces so that the risk of bilateral transactions associated with the transmission congestion can be evaluated with higher certainty.

In the presence of the multiple potentially congested lines, the initial division of the system into congestion clusters can lead to a large number of clusters by taking intersection of clusters connected with each congested transmission lines. Under such case combining the zonal pricing method and the congestion cluster pricing method may result in a efficient division of the system. Plus, the formulation developed in the paper is limited to static setting. In order to account for the dynamics of the system, the formulation needs to be generalized for the longer term analysis.

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