Coordinated Multilateral Trades for Electric Power Networks

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Abstract

Recent moves to open up electric power transmission networks to foster generation competition and customer choice have touched off a debate over how the transmission system should be restructured in order to meet the goal. The opposing sides of this debate are now commonly represented by the bilateral model and the poolco model. Both models resort to conventional centralized operation in dealing with the shared resources of an integrated transmission network. The conventional operating paradigm was developed in a different era for electric utilities operated as regulated monopolies. A new operating paradigm is needed for a restructured industry that encourages efficient competition and at the same time maintains necessary coordination to guarantee a high standard of reliability. We propose a new operating paradigm in which the decision mechanisms regarding economics and reliability (security) of system operation are separated. Economic decision is carried out by private multilateral trades among generators and consumers. The function of reliability is coordinated through the power system operator who provides publicly accessible data based on which generators and consumers can determine profitable trades that meet the secure transmission loading limits. We prove that any sequence of such coordinated private multilateral trades, each of which benefits all parties to the trade, leads to efficient operations, i.e., maximizes social welfare. The coordinated multilateral trading model achieves all the benefits of a centralized pool operation without the visible hand of a pool operator in economic decisions. It is also shown that the coordinated multilateral trading model can coexist with the traditional model and provides non-discriminatory service to both utility customers and direct-access customers.

1 Introduction

Recently, regulated industries such as telecommunications, trucking, airline and gas have experienced major changes resulting from reduced regulation and increased competition. The electric utility industry is the last major regulated monopoly to undergo change. The traditional regulated monopoly is justified only in an environment in which (1) economy of scale exists in the industry, and (2) the pace and magnitude of technological advancement remains moderate and predictable. As social acceptance and financial viability of large generators have declined and possibilities for innovations in electrical, as well as supporting information technologies, have soared, the continued monopolization of the electric utility industry becomes untenable.

These recent moves to open up the electric power industry demonstrate the new general agreement on three principles: (1) pressure for greater competition should continue; (2) consumer choice should be enhanced; and (3) access to transmission services should be arranged in ways necessary to accommodate consumer choice and supply competition. These new competitive pressures and emerging market forces exert an increasing influence over the future structure of the industry.

When the CPUC issued its proposal promising direct access and open competition by the year 2002, it touched off a debate over how the transmission system should be restructured in order to meet that goal. The opposing sides of this debate are now commonly represented as the *bilateral model* and the *poolco model.*[1]

The bilateral model is based on the principle that free market competition is a route to economic efficiency. In this model suppliers and consumers independently arrange trades, setting by themselves the amount of generation and consumption and the corresponding financial terms, with no involvement or interference by the power system operator (PSO).[2] Economic incentives will lead generators to find the best-paying customers and consumers to find the cheapest generators. So long as consumers or generators do not have significant market power, these trades will lead to short term economic efficiency. Perhaps even more important in the long run, generators and other providers will find it profitable to support innovations that consumers want. However, the bilateral model faces a fundamental problem which detracts considerably from its ability to promote free market competition.

First, the lack of coordination among the independent trades can lead to a violation of transmission network constraints. The network constraints arise from loading limits on transmission equipment and from the requirement that the network be operated in a secure state.[3] Coordination is necessary because physical laws dictate how power goes from the generators to the consumers in a transmission network. Individual generator has very limited control over transmission loading on a particular facility.

Faced with the need for coordination of trades to ensure system safety and power balance, bilateral model advocates resort to the traditional model. They propose to grant the PSO the authority to determine the safe level of generation (if the aggregate of individual trades is not safe). But with the introduction of this centralized authority, the bilateral model is metamorphosed into poolco---the model to which it was originally counterposed.

We believe that any restructuring model, no matter how noble its goal, if its proper functioning relies on external enforcement, rather than internal economic incentives, is in danger of being derailed in practice. The two approaches that arose from the CPUC proposal -- the bilateral model and the poolco model -- were fundamentally flawed in that they assumed the operating paradigm as a given constraint and then attempt to construct a market around it. The current operating paradigm, however, developed in a different era for a different industry structure, namely, the regulated monopoly. There is no inherent incentive in the traditional operating paradigm to promote competition; it was never design to do so. Because both the bilateral model and the poolco model embrace the traditional paradigm, both models require regulation in order to force the PSO to perform its duties. Therefore, it is not surprising that both models result in significant gain in the requirement for regulation, contrary to the original intent.

We take a completely different approach. We propose to develop a new operating paradigm that is compatible with the competitive market structure. The crowning achievement of the traditional operating paradigm is its seamless coordination of transmission operation. Coordination does not require centralization. Coordination among various parties has two dimensions: information structure and decision-making authority.[4] In the traditional operating paradigm, both the information structure and decision-making are centralized. We have examined alternative information and decision-making structures for a new operating paradigm to achieve the same level of seamless coordination and have developed a model which we call it the Coordinated Multilateral Trading model. We have solved the fundamental problem, namely ensuring system reliability/security, that weakened the bilateral model. Moreover, our model will achieve the same economic efficiency as the poolco model ideally achieves. But the PSO has no visible hand in the economic decisions. Efficiency is attained through the invisible hand of the market. The proposed model does not require explicit description of cost/benefit functions as other models do-such requirement in an economic system can lead to welfare loss. Therefore the coordinated multilateral trading model will achieve higher economic efficiency.

2 Requirements for a New Operating Paradigm

2.1 Coordination

For the transmission system to properly support "shared" services such as maintaining security and providing transmission losses, coordination among all parties is required. It is a gross simplification to equate coordination with centralization. As a matter of fact, an examination of coordination should focus on ways to distribute information (who knows what) and control (who does what) for all parties: generators, consumers, system operator, regulator, etc., to achieve the goals. In the traditional paradigm, both information structure and decision-making

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[1] Several articles in the Electricity Journal, September 1994, articulate both sides of the debate very well. Poolco model is largely based on the system being implemented in England and Wales, a detailed description of the basic structure of the system can be found in: White, A., "The electricity industry in England and Wales," James Capel & Co., Feb. 1990. For conceptual foundation of poolco, see Hogan, W. W., "Contract networks for electric power transmission," *J. Regulatory Economics*, vol. 4, 1992, pp. 211-242, Ruff, L., "Stop wheeling and start dealing: resolving the transmission dilemma," *The Electricity journal*, June 1994, pp. 24-43. Bilateral model has been implemented in Norway, see: Moen, J., "Electric utility regulation, structure and competition. Experiences from the Norwegian electric supply industry," *Norwegian Water Resources and Energy Administration*, Aug. 1994. A critical appraisal of both models can be found in: Wu, F. F., P. Varaiya, P. Spiller, and S. Oren, "Folk theorems on transmission open access: proofs and counterexamples," *POWER report* PWP-23, U of Calif Energy Insti., Oct 1994, and Oren, S. S., P. T. Spiller, P. Varaiya, and F. F. Wu, "Nodal prices and transmission rights: a critical appraisal," *The Electricity Journal*, vol. 8, April 1995, pp. 14-23. There are variations in different bilateral and poolco proposals, we consider the basic models here.

[2] The term PSO used here is rather general, it represents the organization with facilities to carry out the necessary functions.

[3] There is also need to coordinate the use of other shared resources, e.g., back-up generators.

[4] These concepts are borrowed from the theory of coordination. Coordination theory studies the specification of the "rules of the game" by which the decisions of various agents can be coordinated in order to achieve a common goal.

authority are centralized to achieve the three main operating objectives: power balance, security/reliability, and economy. As we move toward increased competition, the way in which the traditional paradigm relies on centralized authority may not be necessary or desirable to attain coordination. It is possible to reach the same level of coordination through different information and decision-making structures. With this objective in mind, we seek to (i) separate each objective (power balance, security/reliability, and economy) and (ii) design information and decision mechanisms for each objective. We can then evaluate the alternative operating paradigm in terms of economic efficiency, reliability and implementability.[5] The goal is to find a new operating paradigm which achieves at least the same economic efficiency and the same level of reliability as the centralized paradigm does, and hopefully more, and which is reliable and implementable using existing computer, communication and control (3C) infrastructure.

2.2 Separating security and economy

As competition is introduced in generation, thus breaking up the monopoly, we believe that the decision-making for efficiency and reliability can and should be decentralized and it can be done with a proper information structure. First of all, it is helpful to analyze security and economic generation separately by examining the differences in decision-making and information structure requirements for the two functions.

In analyzing the task of economy, we must remember the goal of a market based economy. In a free market, decision-making authority should be decentralized and decisions should be made by participating suppliers and consumers. The information structure in a free market should facilitate economic efficiency. Furthermore, the information structure should not result in a situation in which there is market dominance or anti-competitive gaming opportunity. To achieve that, it is necessary to keep the cost/benefit information completely private.

The security of the transmission system is a shared responsibility among all generators and consumers. With today's technology, there is a delay in communication and control that makes it impossible or undesirable to mitigate a security violation after it occurs. Therefore, in system operation, the security concerns must be incorporated while economic decisions are being made. This is consistent with the principle of current practice in which security is treated as an operating constraint in economic decisions. The challenge, however, is to determine the degree of centralization and decentralization in the decision-making process and to design an information structure such that sufficient information can be made available to all potential trades to assess security feasibility and economic viability. Moreover, for fair competition, public information should be shared and transparent, i.e., the method by which the data is obtained and security constraints are calculated must be obvious and readily reproducible by anyone.

2.3 Requirement summary

We propose a new operating paradigm which allows suppliers and consumers primarily to seek profit on their own, while the PSO guarantees security. Only when security is threatened, does the PSO intervene to make a decision on curtailment. Participants collaborate in the responsibility for maintaining security with the help of information provided by PSO. For the purpose of maintaining security, the PSO passes on information to the generators and loads based on which the generators and loads structure their trades so as not to cause security problems. Because maintaining security is a community effort, all security information is open to the public.

Suppliers and consumers themselves carry out the economic function, making the decisions concerning the price and amount at which to buy and sell. The pricing information relied upon by participants for their economic decisions is all private. Since all trades are independently arranged, methods to calculate and allocate transmission losses are required.

Ultimately, the goal of this new paradigm is to: (1) organize arrangements so as to achieve economic efficiency; and (2) encourage search for alternatives and innovations for any function that requires a centralized duty.

3 Coordinated Multilateral Trading Model

A multilateral trade is a trade involving two or more parties in which the sum of generation minus the sum of consumption losses is equal to its share of losses. The party that arranges the trade is called a broker. The broker may be a generator or consumer involved in the trade but may also be an unrelated third party. A multilateral trade is a generalization of a bilateral trade. But, as will be shown later, in order to relieve congestion or to ensure security of operation, it is *essential* to have coordinated trades involving three or more parties.

3.1 Optimal Dispatch

Consider a power network consisting of $(n + 1)$ nodes or buses operating in sinusoidal steady-state. The voltage phasor at bus i is denoted

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[5] Several alternative information structures have been proposed: Kaye, R. J., F. F. Wu, P. Varaiya, "Pricing for system security," IEEE PES Winter Meeting, New York, Jan. 1992. Baldick, R., R. J. Kaye, and F. F. Wu, "Electricity tariffs under imperfect knowledge of participant benefits," IEEE Tran. Power Systems, vol. 7, 1992, pp. 1471-1480.

$$V_i e^{j\theta_i} \quad i = 0, 1, \ldots, n \tag{1}$$

An arbitrary bus, say bus 0, is chosen as the reference bus for the voltage phasor angles, i.e., $\theta_0 = 0$. Let us assume that the voltages V_i are kept constant by adjusting reactive powers at the buses and we focus on real power flows. The real power flow balance at each bus is expressed by the (real) power balance equation[6]

$$f_i(\theta) = q_i \quad i = 0, 1, \ldots, n \tag{2}$$

where $\theta = (\theta_1, \ldots, \theta_n)^T$, q_i is the net power injection at bus i. We adopt the sign convention that q_i is positive (negative) if there is net generation (consumption) at bus i. The vector $\boldsymbol{q} = \begin{bmatrix} q_0, q_1, \ldots q_n \end{bmatrix}^T$, the array of all nodal injections, is called an injection vector.

The (real) power flow through any transmission line (or transformer) can be expressed as a function of θ. Indeed, the power flow through a set of lines or between two regions can always be expressed as a function of θ. Let the line flow limit on line i or the transfer limit between two regions be denoted by l_i; then the transmission loading constraints are

$$g_k(\theta) \le l_k \quad k = 1, 2, \ldots, L \tag{3}$$

where L is the total number of such constraints.

Let $c_i(q_i)$ be the cost function if bus i is a net generation bus, $q_i > 0$, and let $c_i(q_i)$ be the negative of the consumer benefit function if bus i is a net consumption or load bus, $q_i < 0$. We assume that the functions c_i are convex and strictly increasing.

The optimal dispatch problem is to maximize total consumer benefit and to minimize total generation cost such that the power flows are balanced and the line flow constraints are satisfied. If consumer benefit is treated as negative cost, then the problem becomes

$$\min \; c(\boldsymbol{q}) = \sum_{i=0}^{n} c_i(q_i) \tag{4}$$

subject to

$$\boldsymbol{f}(\theta) = \boldsymbol{q} \tag{5}$$

$$\boldsymbol{g}(\theta) \le \boldsymbol{l} \tag{6}$$

The Kuhn-Tucker optimality conditions for the above nonlinear programming problem (4)-(6) are:

$$\frac{\partial c}{\partial \boldsymbol{q}} = \boldsymbol{p} \tag{7}$$

$$\boldsymbol{p}^T \frac{\partial \boldsymbol{f}}{\partial \theta} + \mu^T \frac{\partial \boldsymbol{g}}{\partial \theta} = 0 \tag{8}$$

$$\begin{cases} \mu_k (g_k(\theta) - l_k) = 0 \\ \mu_k \ge 0 \end{cases} \tag{9}$$

The optimal dispatch problem (4)-(6) stated here is the standard welfare maximization problem in economic theory. It is also a generalization of the standard optimal power flow (OPF) problem in power systems analysis, with consumer benefit included.

We now make two simplifying assumptions. The first is to assume that the lines are lossless and the second is to assume that the linear approximation of the line flows (2) and (3) is valid. We will revisit and relax these two assumptions in Sec. 8.5 and Sec. 8.6, respectively. It should be pointed out that linear approximations are often used in power flow analysis. The approximations are fairly good for real power flows.

Under the linearity assumption, the power flow equations (2) and (3) can be written as:

$$\langle \boldsymbol{f}_i, \theta \rangle = q_i \quad i = 0, 1, \ldots, n \tag{10}$$

$$\langle \boldsymbol{g}_k, \theta \rangle \le l_k \quad k = 1, 2, \ldots, L \tag{11}$$

where the inner product of two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, $\langle \boldsymbol{a}, \boldsymbol{b} \rangle$, is defined as $\boldsymbol{a}^T\boldsymbol{b}$.

In this case, the optimal dispatch problem becomes:

$$\min \; c(\boldsymbol{q}) \tag{12}$$

subject to

$$\langle \boldsymbol{f}_0, \theta \rangle = q_0 \tag{13}$$

$$\boldsymbol{F}\theta = \bar{\boldsymbol{q}} \tag{14}$$

$$\langle \boldsymbol{g}_k, \theta \rangle \le l_k \quad k = 1, 2, \ldots, L \tag{15}$$

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[6] Let the reciprocal of the impedance between line km be $y_{km} = 1/z_{km} = g_{km} - jb_{km}$. Then the k-th equation is

$$\begin{aligned} f_k(\theta) &= \sum_m g_{km} V_k^2 + \sum_m -g_{km} V_k V_m \cos(\theta_k - \theta_m) \\ &\quad + \sum_m b_{km} V_k V_m \sin(\theta_k - \theta_m) \\ &= q_k \end{aligned} \tag{1}$$

. See textbooks such as Bergen, A. R. *Power Systems Analysis*. Prentice-Hall, 1986, and Wood, A. J., and B. F. Wollenberg. *Power Generation, Control, and Operation*. New York: John Wiley and Sons, 1984.

where $\bar{\boldsymbol{q}} = (q_1, \ldots, q_n)^T$ and $\boldsymbol{F} = \begin{bmatrix} -f_1^T- \\ \vdots \\ -f_n^T- \end{bmatrix}$. Note that $\boldsymbol{F}$ is invertible. Problem (12)-(15) is a convex programming problem with linear constraints. Therefore, $\boldsymbol{q}^*$ is optimal if and only if it satisfies (7)-(9):

$$\frac{\partial c}{\partial \boldsymbol{q}}(\boldsymbol{q}^*) = \boldsymbol{p}^* \tag{16}$$

$$p_0^* \boldsymbol{f}_0^T + (\bar{\boldsymbol{p}}^*)^T \boldsymbol{F} + \sum_{k=1}^{L} \mu_k \boldsymbol{g}_k^T = 0 \tag{17}$$

$$\begin{cases} \mu_k(<g_k, \theta> - l_k) = 0 \\ \mu_k \geq 0 \end{cases} \tag{18}$$

Using the standard terminology of nonlinear programming, any $\boldsymbol{q}$ satisfying (10)-(11), or (13)-(15) is said to be feasible. The set of feasible $\boldsymbol{q}$, denoted by S, is a convex set in a (n+1)-dimensional space. Assume that S has interior, the boundary of S is denoted by ∂S.

3.2 Feasible Trades

We shall define multilateral trades. A bilateral trade between a generator at node i and a consumer at node j for α MW to be generated at node i and α MW to be delivered at node j is represented by an injection vector $\boldsymbol{q}$ whose ith component is α and jth component is (-α) In general, a trade may involve multiple parties and will be called a multilateral trade.

Definition A multilateral trade is represented by an injection vector $\boldsymbol{q}[k]$ such that $\sum_{i=0}^{n} q_i[k] = 0$, where k is used to index a set of multilateral trades. The set of all multilateral trades in the system results in an injection vector $\boldsymbol{q} = \sum_k \boldsymbol{q}[k]$. A multilateral trade $\boldsymbol{q}[k]$ is said to be curtailed if $\boldsymbol{q}[k]$ is replaced by $\gamma_k \boldsymbol{q}[k]$, $0 \leq \gamma_k \leq 1$.

Definition Suppose that $\boldsymbol{q} \in \partial S$, i.e., eqs. (10)-(11) are satisfied and

$$<\boldsymbol{g}_k, \theta> = l_k \quad \text{for } k = k_1, k_2, \ldots, k_m \text{ and} \tag{19}$$

$$<\boldsymbol{g}_k, \theta> < l_k \quad \text{otherwise}$$

A (multilateral) trade $\Delta\boldsymbol{q} = (\Delta q_0, \Delta\bar{q})$ is a *feasible-direction* (FD) trade at $\boldsymbol{q}$, if

$$<\boldsymbol{n}_k, \Delta\bar{\boldsymbol{q}}> \leq 0 \quad \text{for } k = k_1, k_2, \ldots, k_m \tag{20}$$

where

$$\boldsymbol{n}_k = \boldsymbol{F}^{-T} \boldsymbol{g}_k \tag{21}$$

and **F** is defined in eq. (14).

Remark. The physical meaning of the vector ***n*k** defined in eq. (21) is the following: the i-th element of ***n*k** is equal to the amount of MW flows on line k if 1 MW is injected into the i-th node of the network (and taken out at the reference node). To see this, we first express the i-th element of ***n*k**, (***n*k**)**i**, using a vector ***e*i**, whose elements are all zeros except the i-th element which is equal to 1. We have (***n*k**)**i** = $<\boldsymbol{n}_k, \boldsymbol{e}_i> = <g_k, \bar{\theta}>$ where $F\bar{\theta} = \boldsymbol{e}_i$. The second inner product implies that (***n*k**)**i** is the amount of power flow through line k when the operating point is at $\bar{\theta}$, the solution of the power flow equations when the power injected to the network is ***e*i**, i.e., one unit power injected into node i. The inner product $<\boldsymbol{n}_k, \Delta\bar{\boldsymbol{q}}>$ is thus the net amount of power flow on line k as a result of the trade $\Delta\boldsymbol{q}$. The requirement for a trade to be in the feasible direction (Eq.(20)) is that the trade should result in reducing the net power flowing through the congested line. We shall refer to the vector ***n*k** as the Loading Sensitivity Vector corresponding to line k. Those who are familiar with optimization theory will recognize ***n*k** as the normal vector to the manifold (affine subspace, in the linear case) defined by the constraints $<\boldsymbol{g}_k, \theta> = l_k$.

We now state two key results.

Lemma 4. Let $\boldsymbol{q} \in S$ and $\boldsymbol{q} \neq \boldsymbol{q}^*$. There exists a FD trade $\Delta\boldsymbol{q}$ at $\boldsymbol{q}$ that reduces the total cost, i.e., $c(\boldsymbol{q} + \Delta\boldsymbol{q}) < c(\boldsymbol{q})$.

Lemma 5 For a FD trade $\Delta\boldsymbol{q}$ at $\boldsymbol{q} \in S$ that reduces the total cost, $c(\boldsymbol{q} + \Delta\boldsymbol{q}) < c(\boldsymbol{q})$, there is profit to be made in arranging such a trade.

It is possible that a profitable trade between participants can result in overload of another transmission limit besides the original congestion. If the trade potentially overloads an additional transfer limit, the PSO must solve a set of equations similar to those concerning the original transmission congestion to ensure that the additional transfer limit is not overloaded. In other words, the PSO must curtail the trade to insure that this transfer limit is not overloaded and then broadcast the Loading vector corresponding to this constraint. The PSO thus sends to participants two vectors: a Loading vector for the original transmission congestion and a Loading vector for the additional congestion. With these two vectors, participants can negotiate trades that are profitable while not resulting in overload for either the original congested transmission or the additional transfer limit. In the general case, if several of transmission transfers are congested, the PSO can produce Loading vector, one for each transfer limit and participants can use these vectors to ensure that their trade does not overload any of them.

3.3 Coordinated Multilateral Trading Process

Now we are ready to state the proposed multilateral trading process.

Coordinated Multilateral Trading Process

Step 1. (Initialization)

Brokers arrange trades $\boldsymbol{q}[k]$. Let $\boldsymbol{q}^0 = \sum_k \boldsymbol{q}[k]$.

Step 2. (Curtailment)

If $\boldsymbol{q0}$ is not feasible, the power system operator (PSO) curtails the trades to a point where the resulting injections $\boldsymbol{q}$ are feasible.

Step 3. (Announcement)

If lines $k_1, \ldots, k_m$ are congested at $\boldsymbol{q}$, the system operator announces the Loading vectors, $\boldsymbol{n}_k$, $k = k_1, \ldots, k_m$.

Step 4. (Trading)

If a profitable trade in the feasible direction is found, a broker arranges it. The broker uses $\boldsymbol{nk}$ to determine whether a trade is in the feasible direction. If no profitable trade is found, go to Step 6.

Step 5. (Feasibility)

If the trade is infeasible, let the power system operator curtail the trade and go to Step 3. If the trade is feasible, let PSO fulfill it and go to Step 4.

Step 6. (Termination)

Stop.

We are going to show that the coordinated multilateral trading process converges to the optimal solution under the assumption that all participants make reasonable decisions. By that we mean whenever there is a worthwhile profitable trade, the participants will carry it out. More precisely, let us call a trade $\Delta\boldsymbol{q}$ with profit less than ε, i.e., $(c(\boldsymbol{q}) - c(\boldsymbol{q}+\Delta\boldsymbol{q})) < \varepsilon$, an ε-unworthy trade and one with profit greater than ε, $(c(\boldsymbol{q}) - c(\boldsymbol{q}+\Delta\boldsymbol{q})) \geq \varepsilon$, an ε-worthy trade. We assume that (i) For any $\varepsilon > 0$ (sufficiently small), any ε-unworthy trade in the feasible direction will not be arranged and any ε-worthy trade will eventually be identified and arranged. (ii) Once a worthy profitable trade is identified, the parties involved are willing to carry it out. The following theorem asserts that the coordinated multilateral trading process converges to the solution of the optimal dispatch under such assumptions.

Theorem 1. Under the assumptions that all participants make reasonable decisions (assumptions (i) and (ii) above), the Coordinated Multilateral Trading Process converges to the solution of the optimal dispatch $\boldsymbol{q}^*$.

In fact, the coordinated multilateral trading model achieves better economic efficiency if the cost and benefit functions can not be explicitly written down as functions of generation or consumption as required for any centralized economic dispatch. In such a case, there is potential welfare loss for the centralized dispatch model, but not in the coordinated multilateral model. Thus the coordinated multilateral trading model is superior to any scheme that relies on centralized dispatch both on grounds of incentive compatibility and information efficiency.[7]

3.4 Trading Arrangement

We now elaborate the trading arrangement process between the generators and the consumers, with the help of a broker. The decision-making by a broker to find a profitable trade $\Delta\boldsymbol{q}$ in the feasible direction can be formulated analytically as an optimization problem. Let I be the index set of the generators and loads engaged in the trade $\Delta\boldsymbol{q}$ arranged by the broker, i.e., $I = \{i; \Delta q_i \neq 0\}$. The objective of the broker is to maximize the net profit of the trade, or to maximize the total cost reduction $\sum c_i(q_i) - c_i(q_i + \Delta q_i)$, subject to the constraints that (i) the amount of generation and load balances out, and (ii) the loading constraints (feasible direction) set by the PSO is observed. Mathematically, it can be written as

$$\min \sum_{i \in I} c_i(q_i + \Delta q_i) - c_i(q_i) \qquad (22)$$

subject to

$$\sum_{i = I} \Delta q_i = 0 \qquad (23)$$

$$\sum_{i = I} (\boldsymbol{n}_k)_i \Delta q_i \leq 0, \qquad k \in K = \{k_1, k_2, \ldots k_m\} \qquad (24)$$

The optimization problem formulated above (22)-(24) is a version of the transmission constrained economic dispatch (TCED). If the cost function is quadratic, the resulting TCED is a simple quadratic programming problem for which efficient solution algorithms exist. The optimality conditions for the optimization problem stated above are:

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[7] See literature.......

$$\frac{dc_i}{dq_i}(q_i + \Delta q_i) = \lambda + \sum_{k \in K} \mu_k (\boldsymbol{n}_k)_i \qquad i \in I, i \neq 0 \quad (25)$$

$$\frac{dc_0}{dq_0}(q_0 + \Delta q_0) = \lambda \qquad i \in I, i = 0 \quad (26)$$

where λ and μ are the Lagrange multipliers of Eqs. (23)and (24), respectively. Several immediate conclusions follow from the above results, which are stated below as assertions.

Assertion 1. If (i) the optimal solution occurs at a point involving only those constraints in K and (ii) the additional trade involves all participants, i.e., $I = \{0, 1, 2, ..., n\}$, then the solution to the TCED is precisely the solution of the optimal dispatch and the marginal cost at the buses correspond to the optimal solution. The value of the optimal marginal cost at bus i relative to the marginal cost at the slack bus 0 is equal to

$$\frac{dc_i}{dq_i} - \frac{dc_0}{dq_0} = \sum_{k \in K} \mu_k (\boldsymbol{n}_k)_i \quad (27)$$

Proof: Combining Eqs. (35) and (26) we obtain Eq. (27). Comparing Eq. (27) with the optimality condition Eqs. (17) and (18), ignoring losses, the assertion follows.

A very important conclusion that can be drawn from the above formulation is on the number of parties necessary to construct a profitable trade in the feasible direction. It is stated below.

Assertion 2. If there is only one transmission congestion. i.e, m=1, a trilateral trade may be necessary in order to construct a profitable trade in the feasible direction.

Proof: At the optimal solution of the TCED, Eqs. (23)-(26) must all be satisfied. If the trade involves only two parties, Eqs (33)-(24) become two equations with two unknowns. If there is a solution, it may not satisfy Eqs. (35)-(26). Therefore, a trilateral trade may be necessary.

Of course, if more parties are involved, the better solution the chance a profitable can be found. The extreme case is that every generator and load is involved in the trading, which is precisely the arrangement of today's integrated utility arrangement, the problem formulated above then becomes the so-called transmission-constrained economic dispatch in today's advanced control centers.

Consider the case with only one transmission congestion, further guidelines for finding a feasible trilateral trade can be derived. For a trilateral trade involving, say generator 1, generator 2, and consumer 3, such that $\Delta q_1 + \Delta q_2 = \Delta q_3$. We want to derive guidelines for a broker to spot profitable trades that are feasible. The transmission system security constraint derived from the Loading vector (**n1**, **n2**, **n3**,...) can be rewritten as:

$$\frac{\Delta q_1}{\Delta q_2} \leq \frac{n_2 - n_3}{n_3 - n_1} \quad (28)$$

For a profitable trade to exist, the marginal benefit of additional MW for consumer 3 must be higher than the marginal cost of one of the generators, say generator 1, i.e., $MC_3 > MC_1$., where $MC_i = \frac{dc_i}{dq_i}(q_i)$. Suppose that generator 1 is also serving as the broker. If $n_3 \geq n_1$, $(n_1 - n_3)\Delta q_1 \leq 0$ for any amount of Δq_1 MW. As the trade from node 1 to node 3 helps relieve the congestion, any profitable trade can be carried out and there is no need to solicit the participation of another generator. A more interesting situation is when $n_3 < n_1$. Assertion 3 below follows immediately upon examining the signs in Eq. (28).

Assertion 3. Suppose $MC_3 > MC_1$ and $n_3 < n_1$, hence profitable bilateral trade between generator 1 and consumer 3 is not feasible. The broker should look for a generator, say generator 2, that satisfies either of the following conditions for possible trades that are profitable. (i) $n_3 > n_2$), generator 2 to generate. (ii) $n_3 < n_2$, generator 2 to back down.

In the special case of a single transmission congestion, the amount of generation and consumption in a trilateral trade can be determined if the cost benefit functions are explicit. Assertion 4 states the result.

Assertion 4. For a trilateral trade with one transmission congestion, the optimal trade $(\Delta q_1, \Delta q_2, \Delta q_3)$, is the solution of the equations:

$$\Delta q_1 + \Delta q_2 = \Delta q_3 \quad (29)$$

$$\frac{\Delta q_1}{\Delta q_2} = \frac{n_2 - n_3}{n_3 - n_1} \quad (30)$$

$$\frac{n_2\left(\frac{dc_1}{dq_1}(q_1 + \Delta q_1)\right) - n_1\left(\frac{dc_2}{dq_2}(q_2 + \Delta q_2)\right)}{n_2 - n_1} = \frac{n_3\left(\frac{dc_1}{dq_1}(q_1 + \Delta q_1)\right) - n_1\left(\frac{dc_3}{dq_3}(q_3 + \Delta q_3)\right)}{n_3 - n_1} \quad (31)$$

4 Conclusion

As the electric power industry moves into an era of supply competition and consumer choice, a new operating paradigm for the transmission network connecting suppliers and consumers is needed. The new operating paradigm must be compatible with the economic principles of the new era. The two alternative transmission restructuring proposals, bilateral model and poolco model, adhering to the old operating paradigm developed for regulated monopolies, are trying to sculpture the foot to fit the shoe. They restructure the wrong end of the problem! The proposed changes are unnecessary, unworkable, and undesirable. We have designed a new operating paradigm in which coordinated private multilateral trades, each of which benefits all parties to the trade, lead to overall welfare maximization. The proposed coordinated multilateral trading model achieves better economic efficiency because there is no need to provide the power system operator or anybody else the individual's explicit cost and benefit function. All cost/benefit information are private and they are used only for the purpose of negotiating contracts between willing parties. The same level of service reliability and system security as in today's centralized operation can be achieved in the proposed model through proper design of the information structure. All generators and consumers have open-access to the transmission network as long as the parties observe their fair share of responsibility for the shared resource of the transmission network. Non-discriminatory transmission service is offered to everyone, whether part of a coalition or not. The proposed model can readily be implemented with existing communications, computing and control infrastructure.

Thus the proposed model achieves short term efficiency. The separation within our model between the technical security and loss allocation functions carried out by the PSO and the financial transactions carried out in the free market, leads to great flexibility. First, consumers and generators can create arbitrarily differentiated commodities of electric power (based, for example, on reliability, interuptibility, etc.) in order to take advantage of diversity in consumer choice and generation technology. Second, over time, even the limited functions of the PSO, can be provided by alternatives. Thus, for example, allocated losses can be provided by independent generators, as can back-up generation. Thus the proposed model provides incentives for long term innovation. The poolco and bilateral models, by installing the centralized PSO at the core of their proposals, preclude the possibility of such innovation. Moreover, the latter models require a permanent regulatory body that is even more sophisticated, resourceful, and vigilant than it is today. The coordinated multilateral trading model, by contrast, envisions a steady reduction in the need for regulation.

At the equilibrium operating point under coordinated multilateral trading model, the marginal cost (price) at each node of the network will be equal to what a central dispatch authority would determine[8] if true cost/benefit functions can be, and are in fact, provided. The coordinated multilateral trading model thus attains all the advantages of optimal nodal pricing. The optimal nodal prices send correct economic signals to the generators and consumers in the system to encourage efficient competition in generation, as well as efficient transmission expansion. As a result of transmission congestion, the marginal cost of generation at some locations will be lower than the marginal price the consumers are willing to pay at some other locations. That gives incentives for generators, consumers or brokers to engage in network upgrading or expansion to facilitate more profitable trading. The incentives are shared by all the generators and consumers affected by the congestion and the incentive for network enhancement is not limited to the congested line.

A vibrant financial market facilitates competition.[9] It has been proposed to establish locational (nodal) electricity forward markets throughout the network. Such markets will facilitate the development of optimal nodal pricing. The coordinated multilateral trading model is compatible with such nodal markets. One important consequence of having nodal forward markets is that they help hedging the price difference between the supplier and the consumer due to transmission congestion.

Advances in 3C technologies have moved the security function in operation from using simple guidelines on transfer limit set by off-line computer simulations to real-time assessment.[10] On-line steady-state security assessment software have been introduced and used in some advanced energy management systems. It uses on-line load flow or optimal power flow to examine the consequence of potential disturbances, with all the loading and meteorological data available, rather than working with off-line postulated conditions. Significant research has been accomplished in recent years in furthering the security assessment into system dynamic responses to disturbances. Deployment of on-line steady-state and dynamic security assessments can greatly enhance effective utiliza-

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[8] Optimal nodal pricing is discussed in: Schweppe, F. C., R. D. Tabors and R. E. Bohn, *Electricity Spot Pricing*, Kluwer Academic Press, 1988.

[9] See Outhred, H., and R. J. Kaye, "The nodal auction model for implementing competition in a bulk electricity industry," U of New South Wales Report DEPE 941012, Oct. 1994 and also Oren, S. S., P. T. Spiller, P. Varaiya, and F. F. Wu, "Nodal prices and transmission rights: a critical appraisal," *The Electricity Journal*, vol. 8, April 1995, pp. 14-23.

[10] See for example Wu, F. F., "Analysis techniques for power system security assessment and optimization: research needs and emerging tools," *Proc. Wksp on Power System Security Assessment*, Iowa State University, April 1988. Direct methods for transient stability have been proposed as a tool for on-line dynamic security assessment, see: Fouad, A. A., and V. Vittal, *Power System Transient Stability Analysis Using the Transient Energy Function Method*, Prentice-Hall, 1992, and also: Varaiya, P., R. L. Chen, and F. F. Wu, "Direct methods for transient stability analysis of power systems: recent results," *Proc. of the IEEE*, vol. 73, 1985, pp. 1703-1715.

tion of existing transmission capacity. Coordinated multilateral trading model is compatible with such technological development. We believe feasibility conditions under on-line security assessment scenarios can be developed.

In this paper, we focus on how to operate the system to achieve economically efficient generation and consumption in a network where the integrity of the network operation has to be maintained. The network is treated as a shared resource used by the parties connected to it. The owner of the network and the operator of the network provide a service to the generators and consumers using the network and should be compensated. The compensation issue, or the transmission pricing issue, has not been addressed. The merchandising surplus in the coordinated multilateral trading model, i.e., the difference between the total benefit for consumers and the total cost for generators in the whole network, represent the profit made by the participants and should be used to compensate the transmission network owner and operator. This is a subject of further research.