A Subarea-Level Transaction Simulation Framework Supporting Parallel Paths and Energy Tagging

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***Abstract*—A methodology is proposed to improve transaction modeling for electrical systems, and associated expense estimation, by applying a transmission constraint data reduction technique and a novel transmission model formulation. A linear programming model is described, which represents parallel flows and manages transaction tagging and accounting to improve model optimality and treatment of nonlinear phenomena. The modeling framework is a large-scale approach that provides screening results to initiate detailed small-scale investigations. The methodology also supplements the flow-based transmission modeling philosophy currently under consideration by the North American Electric Reliability Council (NERC). The proposed method extends the NERC utility-level model to a subarea-level network model to improve overall transmission modeling detail and performance. In addition, the model merges an optimizing technique with the parallel path and energy tagging features into one homogeneous model.**

***Index Terms*—Power system operations, transmission modeling, parallel paths, distribution factors, energy tagging, linear programming.**

I. INTRODUCTION

THE study of the effects of transmission system parallel paths is multifaceted and affects the economies of system operation. Several enhancements to present modeling capabilities were discussed in [1], with a focus on representing the characterization of parallel path influences on network behavior. These methods called for increased data acquisition, improved load and generation characterization, and real-time information systems to support these elevated modeling data requirements—all required to implement full AC network modeling and optimal power flow (OPF) applications.

Because the nature of parallel paths typically influences a broad geographic network, significant amounts of network-specific information are required to support AC OPF applications. The communication network infrastructure required to support broad-area data dissemination is beginning to take shape, as open access same-time information systems (OASIS) and other NERC-initiated integrated security network (ISN) projects flourish. However, detailed load and generation parameters remain proprietary utility information. Because load and generation levels are estimated, linearized methods that use distribution factors remain popular over large-scale AC OPF solutions. The General Agreement on Parallel Paths (GAPP) method and the subsequent methods underway at NERC's Security Process Support System Task Force (SPSSTF) are representative of distribution factor approaches [2], [3]. The practicalities of realizing the infrastructure to support the improved methods outlined in [1] give way to simpler, linearized methods, which suggests the importance and application of the method described in [4], [5].

The NERC SPSSTF builds on the GAPP method and the concurrent GAPP experiment underway. Similar to the GAPP method, the SPSSTF proposes a transaction information system (TIS) and an interchange distribution calculator (IDC). The NERC TIS performs information management operations similar to those of the GAPP information system. Likewise,the NERC IDC is functionally equivalent to the GAPP interface participation factor matrix, which characterizes transaction flows through interconnected systems. Both methods characterize interutility (i.e., utility-to-utility or area-to-area) transactions. Although generation dispatch within a specific system affects interconnecting transmission lines in various ways, these methods focus only on interutility transactions, without regard to any subarea generation variations. The method described in [4], [5] suggests a way to include the effects of subareas in the same DC modeling paradigm used by GAPP and NERC.

This paper describes an application of a linear programming (LP) model that uses the aggregation method and example system described in [5]. The proposed model supports complete energy tagging and implements the reduced transmission constraints derived in [5] to characterize subarea-induced parallel flows. The costs of generation, network services, and transmission line usage are minimized as part of the LP objective function, subject to various system constraints described in this paper. The model can be used as a screening tool to identify system scenarios that require detailed AC analyzes. In addition, the concepts derived in this paper may be relevant to the work underway at NERC to improve the accuracy of the IDC development effort.

II. NOMENCLATURE

All parameters and variables listed below are positive values or are constrained as positive variables, except for P_l^{Line} which is a free variable on the interval $(-\infty, +\infty)$, and for γ_{ijl}, which is a parameter on the interval $[-1, 1]$.

Symbol	**Definition**
A	Set of all areas (a) in model
C_{ks}^{Gen}	Segment-specific subarea (s) generation costs

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C_l^{LH}	Segment 2 (high) net line usage cost
C_l^{LL}	Segment 1 (low) net line usage cost
C_{dl}^{LU}	Transaction- and direction-specific line (l) usage cost
C^{Total}	Total system operating costs
d	Line flow direction identifier (defined or opposite)
G_a	Area (a) generation level
G_s	Subarea (s) generation level
G_{ks}^{Max}	Maximum segment subarea (s) power generation
G_s^{Max}	Subarea (s) maximum power generation
G_{ks}^{Seg}	Segment subarea (s) power generation level
K_s	Set of all segments for piecewise generator costs
k	Segment identifier
L	Set of all interutility tie lines (l)
L_{dkl}^{Cap}	Direction- and segment-specific line (l) capacity
L_{kl}^{Loss}	Segment-specific line (l) loss factor
O_{as}^{AS}	Ownership mapping among areas(a) and subareas(s)
O_{sl}^{SL}	Ownership mapping among subareas (s) and transmission lines (l)
P_l^{Line}	Transmission line (l) real net power flow
P_s^{Load}	Subarea (s) power consumption
P_{dl}^{Loss}	Transmission line (l) net power losses
P_{dkl}^{Seg}	Transmission line (l) segment flow
Q_l^{Line}	Transmission line (l) reactive net power flow
S	Set of all subareas (s) in model
T_{mn}^{A}	Area(m)-to-area(n) energy transaction
T_{ij}^{E}	External network energy transaction (i-to-j)
T_{ij}^{S}	Subarea(i)-to-subarea(j) energy transaction
V_{mn}^{AA}	Permissible area(m)-to-area(n) contracts
γ_{ijl}	Generator shift factor for subarea energy transaction

III. MODEL OVERVIEW AND OBJECTIVES

A. Contract Path Versus Parallel Path

The contract path method and model formulations used for implementing the method are popular for a number of reasons. First, many utilities still do business via the contract path method. Second, model formulations used to apply the method result in straightforward, intuitive solutions. The complexity of physical network behavior is removed from the model details and formulation. Applications of the method have been shown in numerous LP formulations [6]–[8] that focus on representing regional real (megawatt) power flows without explicitly modeling transmission line impedance parameters.

The primary benefits of representing parallel flows are (1) the advantageous improvement of electrical transmission network modeling and (2) improvement of transmission system flow and cost accounting due to improved transaction representation. The model described in this paper represents transactions by applying generator shift factors (GSF's), γ_{ijl}, to establish individual network line flows that result from each scheduled transaction. This parallel path implementation offers improved simulation of transactions over those of conventional contract path approaches. Only real power flows are considered in the proposed model.

B. Level of Network Aggregation

There are basically two extremes of network model implementation: a regional view and a bus view. Between these two extremes, lie the GAPP and NERC models, which provide a system (utility or control area) perspective plus parallel flow transaction support. AC load flow and OPF models provide the most detailed view at the bus level. Trade-offs exist among these alternatives in terms of required data to support the network representation.

The model formulation described in this paper proposes a network view that lies between the system and bus views. For example, the matrices that characterize transactions in the GAPP and NERC approaches represent a system-to-system transaction view (G_a, T_{mn}^A). The method introduced in [4] suggests that individual buses within systems often can be clustered and represented as a collection of similar subareas, which comprise each system. The model described in this paper supports subarea-to-subarea transactions (G_s, P_s^{Load}, T_{ij}^S), where various subareas (as defined in [5]) reflect a grouping of electrically similar buses in a larger area or system. Moving the level of network aggregation closer to the bus level improves the characterization of network parallel flows.

C. Modeling External Influences

The physical network topology is influenced by internal loads and generating resources, as well as external network influences connected at the boundaries of the network topology. The model described below permits adjustments to network flows caused by external contracts outside of the network under study. External contracts affect the available network resources without affecting the LP objective function. In the proposed model formulation, GSF's are applied to external network transactions (T_{ij}^E) to represent their impact on network behavior and to avoid inaccurate modeling of transmission capability.

D. Energy Tagging

Energy tagging is an essential modeling feature designed to capture detailed energy transaction accounting. If a parallel path modeling paradigm is applied, a transaction from System A to System B affects all transmission lines on a scale of 0% to 100%. Therefore, it is important to associate the amount of power that flows through any given line with a specific transaction between the two participating systems. Energy tagging provides this useful capability.

The GAPP and NERC methods take into account these energy tags through a parallel path modeling framework. However, these models do not optimize the required generation dispatch and associated transmission usage, as the balance among system generation end loads is obtained. The model described in this paper merges the optimizing characteristic of a simplified OPF model and the parallel path representation and energy tagging features of the GAPP and NERC models into one homogeneous model. In addition, energy tagging is supported at the network subarea level, so that both area-to-area and subarea-to-subarea transactions are tagged (T_{mn}^A; T_{ij}^S; V_{mn}^{AA}, where a permissible contract between areas specifies $V_{mn}^{AA} = 1$, otherwise $V_{mn}^{AA} = 0$; and O_{as}^{AS}, where $0.0 \leq O_{as}^{AS} \leq 1.0$ designates the ownership of subarea s by area a). This feature allows the model to satisfy a general area-to-area contract by optimizing over the respective subareas to determine the most cost-effective subarea-to-subarea contract to dispatch.

E. Line Flow Representation and Loss Accounting

Net line flows represent the resulting flow on a particular transmission line after subtracting the sum of the flows in the opposite direction from the sum of the flows in the defined direction (P_l^{Line}). Net flows are important for correct establishment of line losses and associated transmission costs and are determined through the use of the energy tagging feature described above. In addition, line ownership (O_{sl}^{SL}, where $0.0 \leq O_{sl}^{SL} \leq 1.0$ designates the ownership of line l by subarea s) is supported to properly account for transmission line usage fees that apply to various transactions.

Line losses are represented as a function of net line flows. The implementation applied in this paper uses a two-segment, piecewise linear curve (P_{dkl}^{Seg}, P_{dl}^{Loss}, L_{kl}^{Loss}). A study conducted by the NERC Independent Operating Services Task Force [9] concluded that annual average loss accounting may no longer be practical in the competitive marketplace. On the other hand, the task force agreed that incremental line loss accounting is impractical and overly complex for large-scale modeling tasks. Considering the alternatives, the task force's conclusion supported hourly average line loss factors.

The model below implements this feature by using a two-segment approach, although n-segments are equally feasible as long as realistic system data are available to support the required modeling overhead. Two segments enhance loss accounting by characterizing lightly, and highly loaded transmission line loss conditions.

Second, the two-segment line loss representation supports a two-level transmission pricing methodology based on net line use. Lines operating under lightly loaded conditions require less utility intervention (e.g., ancillary services or network monitoring) than lines operating under highly loaded conditions. As a result, the model supports two cost recovery methods, available to the transmission services provider, to account for two alternative network services operating conditions (C_l^{LL}, C_l^{LH}). This feature permits transmission owners to better represent their net line usage costs (variable costs) in the formulation. After the model determines the lost energy, the energy deficit is added to the line owner's energy demand, where a separate contract to recover the losses is posted and granted to the lowest priced generator, subject to other model constraints.

Third, a fixed line usage fee is represented in the formulation. The cost of using transmission capacity is assessed as a fixed line usage cost based on the proportion of the total transaction amount (C_{dl}^{LU}). The GSF's and energy tagging features provide this additional costing mechanism, because the proportion of energy on the line and the transaction owner are known for each transaction. These costs further depend on the direction of the transaction. For example, a transaction following the predominant flow pattern can be priced higher than a contract in a direction opposite to the predominant flow. These contract-specific charges are determined independent of network service charges based on net flows. A transaction fee can be charged even though a net line flow of 0 MW requires no generation to compensate for losses. Contract-specific costs offer incentives to promote contracts that reduce transmission bottlenecks (by applying a lower cost) or penalize transmission users for contributing to bottlenecks (by assigning a higher cost). These fees are paid to the transmission line owner(s). However, this fee is set to zero if the generation provider or the energy buyer of the transaction is the transmission line owner. These costs also ensure embedded transmission and/or stranded cost recovery.

IV. Model Description

The proposed model uses a network of nodes and links to estimate spot market activities that result in real power transmission line flows. Nodes represent subarea generating resources, subarea load centers, and transmission substation points. A fictitious supernode, comprised of these subarea nodes, represents an area of the electrical system that often corresponds to a specific control area, utility, or system. Nodes are connected via links, which represent transmission lines that have transfer limitations (L_{dkl}^{Cap}), line ownership attributes, and two levels of transmission cost and loss accounting. Each node and link has a set of constraints that describe the physical aspects of an interconnected energy system.

The proposed model represents an average cost-based, deterministic formulation with enhanced network model resolution and improved transmission cost accounting. In addition to the transmission costs already described, the model's objective function includes subarea generator production costs, represented as convex, n-segment, piecewise linear cost curves (C_{ks}^{Gen}, G_{ks}^{Max}, G_{ks}^{Seg}).

Specifically,the model objective function represents the summation of all system costs, including: piecewise generation costs, transmission line ancillary service costs, and transaction-specific transmission line usage costs and is defined as

$$\begin{aligned} \mathrm{MIN}\, C^{Total} = & \\ & \sum_{s \in S} \sum_{k \in K_s} C_{ks}^{Gen} * G_{ks}^{Seg} + \\ & \sum_{l \in L} \sum_{d=0}^{1} \left[C_l^{LL} * P_{d1l}^{Seg} + C_l^{LH} * P_{d2l}^{Seg} \right] + \\ & \sum_{l \in L} \sum_{i \in S} \sum_{j \in S} \left[\begin{array}{c} (1 - O_{il}^{SL}) * T_{ij}^{S} * \gamma_{ijl} * \\ \left[C_{1l}^{LU} |^{ijl \geq 0} - C_{0l}^{LU} |^{\gamma_{ijl} < 0} \right] \end{array} \right]. \end{aligned} \tag{1}$$

In addition, several constraints are required to model physical network and equipment characteristics. For example, the relationship between subarea and area generation levels is defined as

$$G_a = \sum_{s \in S} O_{as}^{AS} * G_s \qquad \forall \quad a \in A. \tag{2}$$

Similarly, the sum of all generation segments is equal to the total subarea generation as in

$$G_s = \sum_{k \in K_s} G_{ks}^{Seg} \qquad \forall \quad s \in S. \tag{3}$$

The generation supply (dispatch) out of each subarea is directly related to the sum of all outgoing transactions. This relationship is represented as

$$G_i = \sum_{j \in S} T_{ij}^S \qquad \forall \quad i \in S. \tag{4}$$

The total subarea demand is comprised of subarea loads and subarea-owned line losses. The relationship between these demands and incoming transactions is shown by

$$\sum_{i \in S} T_{ij}^S = P_j^{Load} + \sum_{d=0}^{1} \sum_{l \in L} O_{jl}^{SL} * P_{dl}^{Loss} \qquad \forall \quad j \in S. \tag{5}$$

The transactions at the area level are determined by summing all subarea transactions. Because the valid area-to-area contracts are constrained by V_{mn}^{AA}, the relationship between all valid (where $V_{mn}^{AA} = 1$) subarea and area contracts becomes

$$T_{mn}^A = \sum_{i \in S} \sum_{j \in S} O_{mi}^{AS} * O_{nj}^{AS} * T_{ij}^S \qquad \forall \quad m, n \in A. \tag{6}$$

The power flow in all transmission lines is determined by the transactions contributing to its flow. This relationship is defined as

$$P_l^{Line} = \sum_{i \in S} \sum_{j \in S} \gamma_{ijl} * (T_{ij}^S + T_{ij}^E) \qquad \forall \quad l \in L. \tag{7}$$

The relationship between the bidirectional power flow in each transmission line and its associated directional line segments ($d = 1$ implies a “defined” flow direction) is defined as

$$P_l^{Line} = \sum_{k=1}^{2} \left[P_{1kl}^{Seg} - P_{0kl}^{Seg} \right] \qquad \forall \quad l \in L. \tag{8}$$

The last required constraint characterizes transmission line losses. The total line loss in all lines is determined by summing the individual line segment losses, as defined in

$$P_{dl}^{Loss} = \sum_{k=1}^{2} P_{dkl}^{Seg} * L_{kl}^{Loss} \qquad \forall \quad d \in \{0, 1\} \text{ and } l \in L. \tag{9}$$

To simplify the model formulation, several physical constraints are represented as variable lower and upper bounds. For example, the subarea maximum generation constraint is

$$(G_s)^{Max} = G_s^{Max} \qquad \forall s \in S. \tag{10}$$

A minimum generation constraint could be defined in a similar way as a lower bound on G_s.

The maximum generation capacity of any single cost curve segment is

$$(G_{ks}^{Seg})^{Max} = G_{ks}^{Max} \qquad \forall \quad s \in S \text{ and } k \in K_s. \tag{11}$$

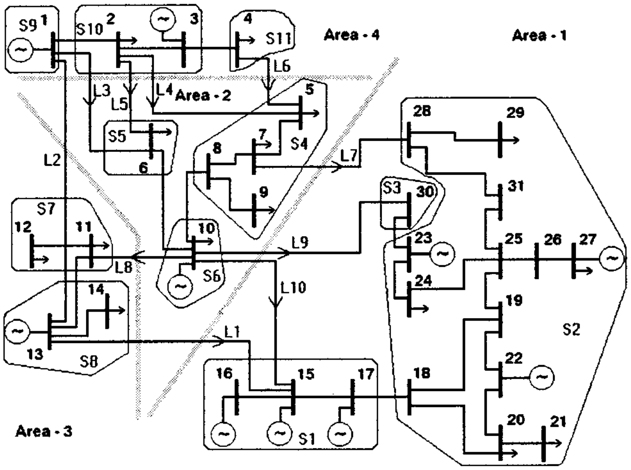

Fig. 1. Four-area system denoting subarea partitions and transmission lines.

Lastly, the per-segment maximum transfer capability is represented as

$$(P_{dkl}^{Seg})^{Max} = \frac{L_{dkl}^{Cap}}{(1 - L_{kl}^{Loss})}, \tag{12}$$

where $d \in \{0, 1\}$, $k \in \{1, 2\}$, and $l \in L$.

V. APPLICATION TO FOUR-AREA SYSTEM

In [4], a method was introduced to group individual system buses into a collection of buses defining a subarea. Various subareas were associated with an area, which corresponded to an individual utility. Subarea and area topology data are mapped to S and A, respectively. In addition, L represented the interarea transmission lines, which comprised the network topology.

An illustration showing the network areas, subareas, and transmission lines is shown in Fig. 1. For the four-area system, $|S| = 11$, $|A| = 4$, and $|L| = 10$. These sets define the four-area topology [5] used to demonstrate model validation and simulation results throughout the remainder of this paper.

A. Four-Area Interarea Model

An interarea model was constructed by using the proposed formulation. The AC load flow representation served as the basis for the interareamodel characteristics. For example, the maximum generation of each subarea was taken from the load flow model generation levels. Similarly, the value for subarea loads also was taken from the load flow model. Uniform generation, ancillary service, and line usage costs were adopted to foster en unbiased cost influence on the objective function. Likewise, line losses were uniform to eliminate influences on contract selection. The contract choice and line flows were the only remaining variables for the model to optimize. These conditions were required to cast the proposed model as a DC load flow model that used the dispatched contracts and GSF’s to determine line flows.

Recall that the model formulation uses GSF’s to characterize line flows as a function of subarea-to-subarea contracts. GSF’s represent real-power injections under DC (or linear) load flow assumptions. Likewise, the proposed model only simulates real power flows and neglects any AC (or nonlinear) behavior. Therefore, the DC limitation must be kept in mind when benchmarking model performance.

Strictly speaking, the proposed model cannot be expected to accurately model any transmission line having a significant reactive flow. Because this restriction is unrealistic in practice, a relaxed condition is adopted to permit benchmarking model performance with an AC load flow model. The evaluation used in this study examines lines, where

$$|Q_l^{Line}| \leq |P_l^{Line}| \qquad \forall \quad l \in L \tag{13}$$

to ensure that each evaluated transmission line primarily delivers real power. For the four-area system, 5 out of 10 transmission lines satisfy this requirement. These 5 lines provide the representative line-set used to compare various modeling scenarios with AC load flow results. Specifically, transmission lines 1, 4, 6, 8, and 10 (designated in Fig. 1 as L1, L4, L6, L8, L10, respectively) form the line-set used for comparing results.

As part of the initial model formulation, the interarea model represented 90 interarea GSF's. As a result, intraarea contracts did not produce any transmission line flows. The formulation was constructed under the assumption that intraarea contracts would not significantly affect interarea transmission line flows. The interarea model was run for these conditions. The five interarea-modelline flows showed a 43.3% average error when compared with the AC-simulated line flows.

B. Effect of Including Intraarea GSFs

To investigate potential modeling improvements, the interarea model was modified to include 20 additional GSF's, which represented intraarea contracts. The same generation dispatch was achieved, except for some minor contract adjustments (<8.0% change in S2 generation) caused by changes in line losses. The average error under these conditions was 11.5% for the five transmission lines when compared with the AC-simulated line flows.

C. Contract Path Case

To assess the overall performance of the two parallel path model implementations, a contract path model was constructed. The contract path case was represented by using the parallel path formulation and by adjusting all fractional GSF's to integer values, where only 1, -1, and 0 are permitted in the contract path case. Contract paths were determined by assigning direct-path transmission lines between connecting subareas. The interarea generation dispatch was forced by applying subarea contract constraints to ensure that generation levels remained consistent among the three model cases. After the adjustments were made, the model was run. The contract path formulation produced an average error of 47.3% when compared with the AC results.

VI. CONCLUSIONS AND SUMMARY

Table I summarizes the line flows for the three model cases relative to the AC load flow results. To summarize Table I, the interarea formulation produced an average error of 43.3%, the intraarea formulation produced an average of 11.5%, and the contract path formulation produced an average of 47.3% when compared with the AC load flow results.

TABLE I
COMPARISON OF MODELED LINE FLOWS RELATIVE TO AC LOAD FLOW RESULTS IN MW

Line Number	AC Load Flow	Interarea	Intraarea	Contract Path
1	-63.4	-55.3	-55.8	-44.0
4	13.0	-3.0	11.8	0.0
6	-11.2	-6.9	-14.7	-4.8
8	24.1	19.3	24.4	31.5
10	-51.1	-39.8	-53.3	-60.2
Avg. Percent Error		43.3	11.5	47.3

The interarea model was constructed under the assumption that intraarea contracts would not significantly affect interareatie lines. However,the comparison of average percent errors shows that the intraarea formulation performed best when compared with the AC load flow results. Because a large S1-to-S2 contract was scheduled, the intraarea loop-effects on Line 10 were not negligible. On the other hand, 20 additional GSF's (an increase of 22%) were required to characterize intraarea contracts. Depending on the desired model accuracy, execution time, or number of constraints, the interarea model could be preferred over the intraarea formulation. None of these factors affected model performance for the four-area system. A larger system topology and complex piecewise generation cost curves could expand the number of constraints beyond the LP-solver maximum constraint limitation. These trade-offs must be considered as a particular formulation is selected.

A decision to use the intraarea model also should be guided by the overall confidence in modeling data accuracy. The additional overhead of applying intraarea GSF's may outweigh the modeling improvements, if other model parameters represent estimated figures. Moreover, the choice of applying parallel path methods over the contract path method also should consider overall data integrity. The modeling accuracy achieved by applying parallel path methods can be compromised by data precision errors.

The intraarea formulation provided a high-end estimate of the flow in Line 6, whereas the interarea model provided a low-end estimate. Line 6 is a low-voltage transmission line that can become easily thermally limited. A conservative representation, as provided in the intraarea representation, would signal the need to conduct an AC load flow analysis to obtain an accurate flow estimate. The interarea model would continue to dispatch contracts until the line flow was in excess of the thermal line limitation. By including intraarea GSF's, the intraareamodel reduces the likelihood of underestimating the line flows on this low-voltage line. The other four lines belong to the high-voltage network and are less likely to have thermal limitations.

The contract path model also failed to estimate the Line 6 flow on the conservative side. In a similar manner, examination of Table I shows a flow of 0.0 in Line 4. In this situation, the contract path model did not determine a flow for the line, because Line 4 was not part of any active contract path. When this situation arises, large line flow errors are possible, which can cause improper generation dispatch.

In addition to these simulations, the method has demonstrated its usefulness in estimating line flows for generator siting and increased system demand scenarios [10]. In the generator siting situation, the average percent error between the proposed and AC model results was 12.3%. Another example illustrating the system impacts of a new system load showed an average error of 20.9% for the five-line set. Again, close agreement was found between proposed model results and AC load flow results.

In summary, the key concept of this modeling approach is the combination of clustering bus-level GSF's into subarea definitions (nonarbitrary network aggregation) that improve network parallel path representation. The LP model applies the clustered data to reduce the required number of transmission constraints. The model fully supports parallel path network flows and energy tagging information to improve model performance beyond the performance achieved by conventional contract path formulations. Under uniform generation and transmission cost conditions, the model results were compared with AC load flow results and showed encouraging results.

In addition, the model formulation offered several significant benefits over conventional linear formulations. First, moving the level of network aggregation closer to the [8] bus level improved the characterization of network parallel flows. Second, energy tagging was supported at the network subarea level, so that both area-to-areaand subarea-to-subarea transactions were tagged. Third, the model supported [9] accurate estimation of net line flows that enabled improved line loss and cost accounting. Depending on modeling requirements, the additional effort required to derive the parallel path formulation can provide substantial improvements over existing aggregate (area-level) formulations.

REFERENCES

[1] J.A. Kavicky and S.M. Shahidehpour, "Parallel Path Aspects of Transmission Modeling," *IEEE Transactions on Power Systems*, vol. 11, no. 3, pp. 1180–1190, 1996.

[2] "General Agreement on Parallel Paths Committee," in *Outline of the GAPP Method for Use in an Up to Two Year Experiment*. Newark, NJ: Public Service Electric & Gas Company, December 1993.

[3] North American Electric Reliability Council, , "Security Process Support System Task Force (SPSSTF),", Princeton, NJ, http://www.nerc.com/~oc/spsstf.html, March 1997.

[4] J.A. Kavicky and S.M. Shahidehpour, "Determination of Generator Siting and Contract Options Based on Interutility Tie Line Flows," *IEEE Transactions on Power Systems*, vol. 12, no. 4, pp. 1649–1653, 1997.

[5] J.A. Kavicky and S.M. Shahidehpour, "Simplifying Generator Siting and Contract Options," in *Proceedings of the American Power Conference 59th Annual Meeting*, vol. 59, April 1997.

[6] N.S. Rau and C. Necsulescu, "A Model for Energy Exchanges in Interconnected Power Systems," *IEEE Transactions on Power Systems*, vol. 4, no. 3, pp. 1147–1153, 1989.

[7] E. Vaahedi, R.J. Poirier, C. Necsulescu, and A.N. Karas, "Benefits of Economy Transactions and Wheeling in Canada," *IEEE Transactions on Power Systems*, vol. 8, no. 3, pp. 1299–1305, 1993.

[8] J.A. Kavicky and T.D. Veselka, "Modeling Regional Power Transfers," in *Proceedings of the American Power Conference 56th Annual Meeting*, vol. 56, April 1994.

[9] North American Electric Reliability Council, , "Defining Interconnected Operations Services Under Open Access,", Princeton, NJ, March 1997.

[10] J.A. Kavicky and S.M. Shahidehpour, "Characterizing and Modeling Subarea-level Energy Transactions," in *Proceedings of the American Power Conference 60th Annual Meeting*, vol. 60, April 1998.

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