ANL/DIS/CP-95814

CHARACTERIZING AND MODELING SUBAREA-LEVEL ENERGY TRANSACTIONS

James A. Kavicky
Energy Systems Engineer
Argonne National Laboratory
Argonne, IL

and

S.M. Shahidehpour
Dean of the Graduate College
Illinois Institute of Technology
Chicago, IL

ABSTRACT

This paper describes the application of an electrical network characterization method to an optimization model that is designed to simulate subarea-level energy transactions. The network characterization method determines subarea clusters of system buses that electrically respond to perturbations in a very similar manner. The method produces a reduced number of transmission constraints and preserves parallel path representations. The least-cost, linear programming (LP) formulation takes advantage of data reduction techniques to simplify model transmission constraints, while supporting parallel path system characteristics and energy tagging of subarea transactions. An overview of the proposed method describes the problem domain and key model features. The paper then presents two model applications that illustrate generator siting and line overload screening analyses.

1. INTRODUCTION

The representation of the effects of parallel paths on network behavior is extremely important as the unbundling of transmission services accelerates. However, the additional modeling complexity required to represent these effects does increase the number of necessary transmission constraints. The approach introduced in [1] and applied in [2] demonstrates the application of a clustering method to aggregate the effects of individual generator shift factors (GSFs), while preserving their associated parallel path characteristics. These papers describe how the technique is applied to generator siting and contract option applications to reduce transmission modeling complexity and suggest it can be used as a screening method to identify the need for detailed system studies.

The process applied in [1, 2] is summarized as follows. GSFs are determined for all interutility tie lines that interconnect adjacent systems (assumed to be utilities). By observing interutility tie line sensitivities associated with various cases, buses having similar GSF responses are grouped together. The similarities of various GSFs provide the criteria used to cluster the buses. The end result is a reduced number of representative cases based on the GSF performance derived from the typical system topology used in the study. The method avoids ad hoc methods of determining representative areas by using methods to naturally cluster system buses into subareas that electrically respond to perturbations in a very similar manner (within some tolerable error margin).

Linearized methods that use distribution factors (e.g., GSFs) are illustrated by the General Agreement on Parallel Paths (GAPP) method and the recent initiatives underway at the North American Electric Reliability Council's (NERC's) Security Process Support System Task Force [3, 4]. 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 dispatch variations. The network characterization method described above suggests a way to include the effects of subarea generation influences in the same DC modeling paradigm used by GAPP and NERC.

This paper describes an application of an LP model that uses the network aggregation method described above. The model supports complete energy tagging and implements the reduced transmission constraints to characterize subarea-induced parallel flows. The model is shown to be an effective screening tool that successfully identifies system scenarios requiring detailed AC analyses. The proposed approach considerably reduces the effort and time required to evaluate network generation and load alternatives.

2. MODEL OVERVIEW AND DESCRIPTION

The proposed optimization model provides three primary benefits over existing aggregate LP model formulations. The model presented in this paper:

- Includes a parallel path network representation
- Improves the level of network aggregation
- Provides transaction energy tagging.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

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 GSFs 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.

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 perspective plus parallel flow transaction support. In addition, the model described in this paper supports subarea-to-subarea transactions, where various subareas 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.

Energy tagging is an essential modeling feature designed to capture detailed energy transaction accounting. 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. In addition, energy tagging is supported at the network subarea level, so that both area-to-area and subarea-to-subarea transactions are tagged. 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.

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, load centers, and transmission substation points. A fictitious supernode represents an area of the electrical system that often corresponds to a specific control area, utility, or system. Nodes also serve as load centers that consume energy. Nodes are connected via links that represent transmission transfer limitations, line ownership, and two levels of transmission costs and losses. Each node and link have a set of constraints that describe the physical aspects of an interconnected energy system. Model features are summarized in the following list:

- Cost-based generation dispatch
- Subarea- and area-level network perspective
- Area ownership of network subareas
- Spot transactions at the area and subarea levels
- Firm transactions at the area and subarea levels
- Firm transactions exerted by systems outside the study area
- GSFs to determine fractional line flows caused by individual transactions
- Complete energy tagging and accounting of all flows caused by all transactions
- Transmission line flows represented as net flows
- Directional transfer limits on transmission lines
- Two-level line losses calculated on the basis of net line flows
- Two-level ancillary service cost calculated on the basis of net line flows
- Transaction- and direction-specific line usage cost
- Transmission line ownership to represent direct and wheeled line usage
- Line losses represented as an additional line owner demand
- Minimum and maximum interarea and intersubarea transfer constraints
- Minimum and maximum area and subarea generation constraints.

The model objective function is summarized in

$$\begin{aligned}\text{Total costs} = \; & \sum \text{Generation costs} \; + \\ & \sum \text{Transmission line ancillary services operating costs} \; + \\ & \sum \text{Transmission line contract-specific costs.}\end{aligned} \tag{1}$$

where the objective function is subject to the following constraints governing the conservation of:

- Subarea and area generation levels
- Subarea and area transactions
- Outgoing subarea transactions and generation levels
- Incoming subarea transactions and demands and/or line losses
- Transactions and associated line flows
- Line and line segment flows
- Line and line segment losses.

The first cost component represented in the objective function is generator production costs, which are represented as flat generation costs in \$/MWh. The application of piecewise linear cost curves is a simple extension to the existing formulation, which would allow costs to vary as a function of generation level.

The second cost factor accounts for network-based ancillary service costs that are paid to the transmission line owner. Collected revenue can be used to offset self-generated power costs or energy purchases required to compensate for accrued transmission losses.

The third factor represented in the objective function is the contract-specific costs of line usage. These costs are paid to the transmission line owner as a fixed fee proportional to the transaction amount. This fee is set to zero if the generation provider or the energy buyer of the transaction is the transmission line owner.

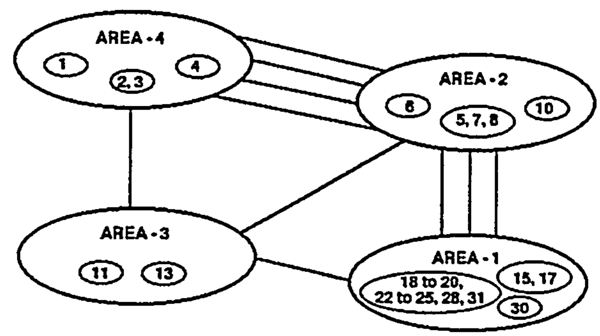

Figure 2. Four-Area, 11-Subarea Partitioned System

3. APPLICATION TO FOUR-AREA SYSTEM

The four-area interconnected system diagram (introduced in [1]) is shown in Figure 1 for reference. After the clustering method is applied and a series of numerical evaluations is performed (as described in [2]), the subarea clusters produced are shown in Figure 2. The area, subarea, and transmission line definitions derived by the aggregation method are applied to the model formulation. Figure 3 shows the system one-line diagram for the four-area system and shows the subarea partitions and the subarea and transmission line identification labels.

Several test models were constructed by using the proposed four-area system. The four-area AC load flow representation provided several required model parameters. 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 an unbiased cost influence on the objective function. Likewise, line losses were assumed to be 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 GSFs to determine line flows.

To summarize the three test cases, 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.

The interarea model was constructed under the assumption that intraarea contracts would not significantly affect interarea tie lines. However, the results show that the intraarea formulation performed best when compared with the AC load flow results. Depending on the desired model accuracy, execution time, or number of constraints, the interarea model could be preferred over the intraarea formulation to reduce the number of required contracts and transmission constraints.

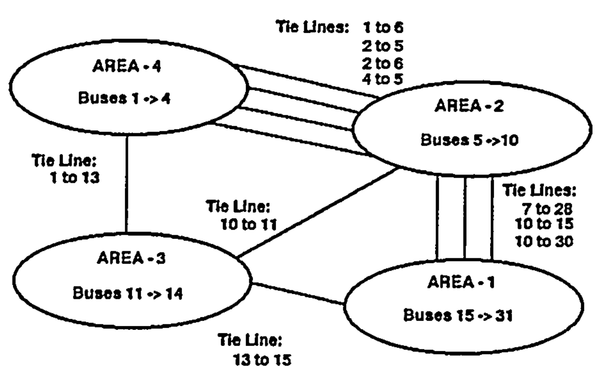

Figure 1. Four-Area System

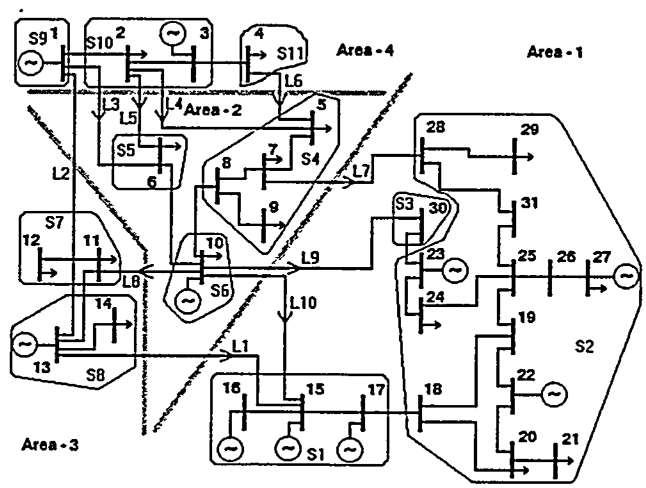

Figure 3. Four-Area One-Line Diagram Denoting Subarea Partitions and Transmission Lines

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 GSFs may not be worthwhile, 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. These trade-offs must be considered as a particular formulation is selected.

4. MODEL APPLICATIONS

After examining the general performance and application of these three modeling approaches, this section describes how the model can be used to screen generation siting alternatives and detect potential line overload conditions. The intraarea formulation is used as the base-case model throughout the remainder of this paper, because its performance was best when compared to AC load flow results. In the following examples, simulation results are compared with AC load flow model results.

4.1 Generator Siting Example

Area 1 has aging equipment at Bus 15 (see Figure 3) and needs to reduce its exports on Lines 1 and 10 (L1 and L10, respectively) to prolong equipment life. Area 1 system planners would like to achieve an approximate 30% flow reduction at Bus 15, which supports Lines 1 and 10. This modification is supported also by recent transmission system reliability concerns within Area 2. System planners feel that the desired outcome can be realized by siting 20 MW of generation in either Area 3 or Area 4. All areas are supportive of the project and are willing to cooperate with Area 1 planners.

The model is used to estimate the line flows, assuming that the generation is placed within Area 4 at Subarea 10 (S10). The model for the Alternative 1 siting option is constructed by increasing the maximum generation capability at S10 by 20 MW. The simulation is conducted, and a cost savings of $105 is estimated for each hour of operation. The line flows are reduced as desired by the planning department when compared with the base case.

A second alternative, Alternative 2, is constructed by siting 20 MW of generation at Area 3, Subarea 8 (S8). The base case is modified by allocating an additional 20 MW of generation at S8. The simulation is executed and produces an hourly cost savings of $70. Again, the desired transmission line reductions are realized.

Because the embedded, fixed, and variable generation costs are identical for constructing the facility at either site, Alternative 1 was chosen to realize the largest cost savings between the two proposed alternatives. The system planners at Area 4 then used an AC load flow model to investigate which bus within Subarea 10 (S10) provided the desired network outcome for Area 1's request. Although the load flow results between Bus 2 and Bus 3 were basically similar, the planners would have found that siting the generator at Bus 2 substantially improved the concerns about reliability at Area 2.

This example demonstrates that the model can be used to assist the generator siting selection process. The model suggested an alternative based on avoided costs. But, with what accuracy did the model compare with AC load flow techniques?

Examination of Alternative 1 line flow results shows an average percent error for the line flows (including Lines 1 and 10) of 18.3%. The load flow model was constructed with an additional 20-MW generator located at Bus 3.

Alternative 2 line flow results show an average error for the line flows of 12.3%. In this case, the load flow model was constructed with an additional 20-MW generator located at Bus 13.

The model determined that the least-cost alternative was Alternative 1. However, S10 has two buses aggregated. Alternative 1A simulated the generator placed at Bus 3. A second load flow model, Alternative 1B, was constructed to simulate a generator located at Bus 2. The average percent error comparison among Alternatives 1 (S10), 1A (Bus 3 AC load flow), and 1B (Bus 2 AC load flow) is tabulated in Table 1.

Table 1. Average Percent Error for Alternatives 1A and 1B Compared with that of Alternatives 1 and 1A

Alternative number	Average percent error with respect to Alternative 1	Average percent error with respect to Alternative 1A
1A	18.3	---
1B	12.1	7.3

Table 1 shows that the Bus 2 load flow results (Alternative 1B) agree with the S10 model simulation (Alternative 1) with an average error of 12.1%. Also notice that the two load flow solutions (Alternatives 1A and 1B) have an average error of 7.3%. This error margin is below the user-specified transaction participation threshold (TPT) of 8.0% that was allowed while constructing the subarea partitions. Interactions among areas below the TPT value can be regarded as insignificant in some applications. For example, a transfer from Area 1 to 2 may only produce a 5% change in flow between Areas 1 and 3. The transaction through Area 3 can be ignored by choosing a TPT ≥ 5%, if modeling requirements justify this relaxed condition. Again, close agreement was found between proposed model results and AC load flow results for these generator siting alternative cases.

4.2 Line Overload Example

An example of line overload is presented in this section. Suppose a new business, located in Subarea 7, plans on being ready for full production in six months. The company will require 30 MW of firm generation. Excess generation in Subarea 6 is available to serve the load increase. Will any of the lines become overloaded when this business opens?

The new load model was constructed by increasing the Subarea 7 load by 30 MW. The simulation was run and identified Line 8 as having a 75.4% increase in flow over the base-case amount. Area 3 system planners were concerned about the increased line flow, because Line 8 is already 50% loaded. An AC load flow was used to confirm these findings.

The new load model and AC load flow results were compared and showed an average error of 20.9%. Although the model signaled an overloaded condition on Line 8, the actual AC flow did increase by 37.0% over the base-case value of 50%. Such an increase should be considered as a potential problem, especially if meeting the thermal limit is possible.

5. CONCLUSIONS

An LP model is presented, which applies a clustering technique to GSFs. The model fully supports parallel path network flows and energy tagging information, thereby improving model performance beyond that achieved by conventional contract path formulations. To demonstrate modeling performance, scenarios are used to simulate generation siting and overloaded transmission line conditions. The results from this model are compared with those from AC load flow models. The results are encouraging.

The study shows that neglecting intraarea contract GSFs significantly reduces the effectiveness of the parallel path model. By including intraarea GSFs, the average error is 11.5% between results of the proposed model and the AC model. A contract path simulation shows an average of 47.3% agreement with AC load flow results. In several situations, the contract path model does not properly represent line flows for the generation dispatch, which supports the criticism against the contract path formulation.

In addition to these simulations, the method demonstrates its usefulness in estimating line flows for generator siting and increased system demand scenarios. In the generator siting situation, the average error between the proposed and AC model results is 12.3%. Another example illustrating the system impacts of a new system load shows an average error of 20.9%. Again, close agreement is found in line flow patterns between proposed model results and AC load flow results.

The proposed model formulation offers several significant benefits over conventional formulations. First, moving the level of network aggregation closer to the bus level improves the characterization of network parallel flows. Second, energy tagging is supported at the network subarea level, so that both area-to-area and subarea-to-subarea transactions can be tagged. Third, the model supports accurate estimation of net line flows that enable 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 formulations.

6. ACKNOWLEDGEMENTS

This manuscript has been authored by a contractor of the U.S. Government under contract no. W-31-109-ENG-38. Parts of this work have been directly funded by the U.S. Department of Energy, Office of Fossil Energy.

7. REFERENCES

[1] Kavicky, J.A., 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.

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

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

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