

A Global Decomposition Algorithm for Reliability Constrained Generation Planning and Placement

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Abstract-- This paper presents a method of deciding the best placement of additional generation for long term generation adequacy planning in multi-area power systems. The approach uses evaluation of the prospective scenarios of additional generation, and tie-lines. Maximum number of additional generators in each area will be determined from the cost with respect to overall budget constraint. The selection criterion is based on improvement in system reliability after unit additions. The reliability indices of different generation combinations will be evaluated utilizing global decomposition approach. Instead of making direct comparison after global decomposition is performed, this paper proposes an algorithm that combines comparison and decomposition phase for better computational efficiency. The best combination will yield maximum reliability with acceptable cost.

Index Terms—Global decomposition, generation planning, reliability, multi-area power systems.

I. INTRODUCTION

In power systems restructuring environment, Independent Power Producers (IPPs) individually invest in generation expansion. IPPs and ISOs may wish to obtain the optimal location that yields a favorable trade off between system reliability and cost. Therefore, the need for determining generation in each area, which will improve system reliability, is assuming an increased importance.

At present, the generation requirement is calculated by simulation and ad hoc methods. As an example, Independent System Operator--New England (ISO-NE) utilizes Multi-Area Reliability Simulation Program (MARS) for this calculation [1]. A recent study of long term generation adequacy in a multi-area power system is thoroughly analyzed and reported by Rau and Zeng [1]. An optimization procedure along with MARS is proposed to determine an excess or deficient amount of generation in each area. One of the contributions of this paper is to show the relationship between risk level of each area and load changes.

However, the method requires iterations between optimization and risk calculation which is obtained from many runs of MARS. In a single MARS run, the outage of

each component in the system is simulated chronologically by Monte Carlo sampling which may require a long history to produce converged results.

Decomposition, originally proposed in [7], is an efficient reliability evaluation technique. The basic concept of this approach is to classify the system state space into three sets; acceptable sets (*A* sets), unacceptable sets (*L* sets), and unclassified sets (*U* sets) while the reliability indices are calculated concurrently. Improved versions of decomposition for including load and planned outages in a computationally efficient manner are described in [2, 4-6].

This paper develops a comparison algorithm for selecting the best generation combination utilizing global decomposition method for reliability index calculation. Scenario analysis is proposed to determine the best generation combination. The comparison is made concurrently with global decomposition process to improve computational efficiency and reduce memory required. In the following section, system modeling is presented. Scenario analysis and global decomposition are then described in more detail. The comparison algorithm is proposed next and applied to a 12-area system. Concluding remarks are then given in the last section.

II. SYSTEM MODELING

Power system network is generally comprised of generation, transmission lines, and load. The system is partitioned into several areas geographically where each area contains various generation units, transmission lines in the area, load and tie lines that connect different areas. In this analysis, it is assumed that tie-line equivalent parameters are given. The following presents detailed modeling of each unit namely area generation, area load and tie lines. Then, a power flow model is presented.

A. Area Generation Model

The failure rate, mean repair time and capacity of each generating unit are assumed to be provided. Discrete probability distribution function for generation in each area is constructed based on unit parameters assuming two-stage Markov process shown in Fig. 1.

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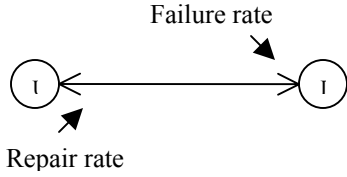


Fig. 1. Two-stage Markov Process

The distribution function is constructed utilizing unit addition algorithm approach. The probability table, which contains levels of state capacity including zero and their corresponding probabilities, is represented by (1).

$$\bar{p}_i = \Pr(\bar{c}_i) \quad (1)$$

where

\bar{c}_i is capacity vector of area i

\bar{p}_i is probability vector of area i

For computational efficiency, the generation capacity will be rounded off to a fixed increment so that only minimum capacity state and number of states in each area are stored. States with very small probability will be ignored.

B. Area Load Model

To preserve a correlation between area loads, area peak loads are represented in a vector form of (2).

$$\bar{L} = (L_1, L_2, \dots, L_N) \quad (2)$$

where

\bar{L} is load vector

L_i is peak load in area i

N is number of areas in the system

C. Tie Line Model

Tie-line parameters are its capacity, forced outage rate and repair rate. Discrete probability distribution of tie-line capacity between areas is constructed based on the given parameters assuming two-stage Markov process, up and down states. Like area generation model, the distribution function is constructed utilizing unit addition algorithm approach.

The Tie-line model is represented by (3), which contains the connection areas (from area, to area), its capacity and its corresponding probability (4).

$$\bar{t}_{ij} = (\bar{f}_{ij}, \bar{b}_{ij}) \quad (3)$$

$$\bar{p}_{ij}^t = \Pr(\bar{t}_{ij}) \quad (4)$$

where

\bar{t}_{ij} is tie-line capacity vector from area i to area j

\bar{f}_{ij} is tie-line capacity vector from area i to area j in forward direction

\bar{b}_{ij} is tie-line capacity vector from area i to area j in backward direction

\bar{p}_{ij}^t is probability vector of tie-line capacity from area i to area j

D. Power Flow Model

The system is transformed into a network capacity flow model as shown in Fig. 2. Each node in the network represents an area and each arc connecting between nodes represents tie

line capacity in multi-area power systems. Artificial source and sink nodes are created to represent area generation and load. An area generation arc connects source node to its area while an area load arc connects its area to sink node. Every arc in the network is associated with capacity states and corresponding probabilities.

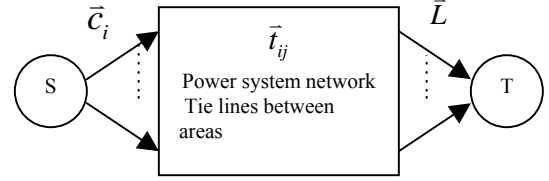


Fig. 2. Power System Network: Capacity Flow Model

III. SCENARIO ANALYSIS

Prospective generation locations in the system are pre-selected by an expert. These candidate locations create various possible generation combinations, each of which yields different system reliability and cost. The generation combinations with acceptable costs are analyzed and the selection for the best location is based on system reliability, system loss of load probability in this case, with additional generation.

Scenario analysis examines all possible generation combinations with global decomposition as a reliability evaluation tool. The advantage of this tool is that a reliability index of any combination can be extracted after a single decomposition. A comparison is made to determine the best generation location.

Instead of making a comparison after the global decomposition is complete, this paper proposes a comparison algorithm that works interactively with each step of decomposition to gain computational efficiency. In the following, system state space representation is presented. Next, global decomposition approach is explained in more details. Then, a comparison algorithm is presented.

A. State Space Representation

The system state space consists of generation states of each area and inter-area tie line states. It is defined as equation (5).

$$S = \begin{bmatrix} M_1 & M_2 & \dots & M_N \\ m_1 & m_2 & \dots & m_N \end{bmatrix} \quad (5)$$

where

M_k is maximum state of arc k .

m_k is minimum state of arc k .

N is number of arcs in the network

A system state, x , can assume any value between its minimum and maximum state as shown in (6).

$$x = [x_1 \quad x_2 \quad \dots \quad x_N] \quad (6)$$

where $m_k \leq x_k \leq M_k$

x_k is state of arc k .

B. Global Decomposition Approach

The maximum possible number of additional generators in each area is included in the state space before performing global decomposition. The additional generation in each area

is rounded off to the closest integral multiple of the fixed increment used in generation model construction. For a particular scenario, the omitted generators are assigned zero probability of the up state. In this manner, decomposition needs to be performed only once and the probability for all possible scenarios can be extracted from it. Global decomposition approach analytically partitions the state space into the following three different sets of states.

1. Sets of acceptable states (A sets): The success states that all area loads are satisfied.
2. Sets of unacceptable states (L sets): The failure states or Loss of load states that some area loads are not satisfied.
3. Set of unclassified states (U sets): The states that have not been classified into A or L sets.

The state space is initially categorized as U sets and then further decomposed into A sets, L sets, and U sets. The process of partitioning the state space into A and L sets involves determining maximum flow in the network. The maximum flow from artificial source to sink node is found in order to classify system loss of load state. Ford-Fulkerson algorithm is implemented with breadth-first search for finding existing flow in the system. At the beginning of the decomposition, state space (S set, as in (5)) is the first U set, unclassified set.

At every step of decomposition, one A set, N L sets and N U sets are generated from one U set. The A sets will be deleted to minimize memory usage since the goal of this evaluation is to extract all L sets for system loss of load probability computation. The U sets have to be kept and partitioned further into A , U and L sets. After global decomposition is performed, the state space will be completely partitioned into various L sets. Probability of each set is calculated from (7).

$$\Pr(X) = \prod_{k=1}^N \sum_{m_k^x \leq x_k \leq M_k^x} p_{x_k} \quad (7)$$

where

X is any set

x_k is state of arc k

p_{x_k} is probability of state x_k of arc k

M_k^x is maximum state of arc k in set X

m_k^x is minimum state of arc k in set X

N is the number of arcs in the network

System loss of load probability of each combination can be computed from the summation of probability over all L sets by assigning zero probability to the omitted states because of the absence of generators in the combination under consideration.

The concept of global decomposition is based on the fact that decomposition depends only on the state capacities and not the state probabilities. In this application, the problem is to select the best generation combination in the system that will yield the maximum reliability. The state space contains maximum possible number of additional generators in each area. The sets obtained from this state space are valid for all scenarios. Probability of each scenario can then be evaluated by allowing zero probability for some omitted states because of the non-inclusion of certain generators

C. Comparison Algorithm

A straightforward approach for comparison is to compute system loss of load probability of each combination after complete global decomposition and then make comparison. This paper proposes an algorithm that compares and cuts off some low performance generation combinations at each stage of decomposition. The proposed algorithm will compute probability of A sets, and L sets of all possible combinations at each stage of decomposition. If the probability of A sets of combination i is greater than combination j , then, the following comparison will be made.

$$(1 - P_A^i) < P_L^j \quad (8)$$

where

P_A^i is probability of A sets from combination i

P_L^j is probability of L sets from combination j

Equation (8) implies that maximum system loss of load probability of combination i is smaller than current (partial) system loss of load probability of combination j . This means that even if the resulting U sets of combination i were all loss of load sets, system loss of load probability from combination i will still be smaller than that from combination j . At each stage of decomposition, a comparison will be made and low performance combination will be deleted from the possible solution list. The procedure may not require complete global decomposition process. It can be stopped when the possible solution list has only one combination or for all possible solutions, probability of unclassified sets is less than an epsilon.

The steps of the algorithm are outlined below.

Step 0 Initialization

- System state space is the first U set.
- Possible solution list \leftarrow every combination i .

Step 1 Decomposition and Evaluation

- Partition U sets into A and L sets
- Compute and update P_A^i and P_L^i for every combination i .
- Find $P_A^{\max} = \max_{\forall i} P_A^i$

Step 2 Comparison

- If $P_L^i > (1 - P_A^{\max})$, delete combination i from possible solution list.

Step 3 Stopping criterion

- Stop if
 - number of combination is 1, or,
 - For all i , $P_U^i = 1 - P_A^i - P_L^i < \varepsilon$
- Otherwise, create U sets and go to step 1.

This method improves computational efficiency and reduces memory usage for storing U sets and L sets. At each stage of decomposition, A and L sets will be deleted after probability evaluation. Probability of all possible scenarios is evaluated and a comparison in (8) is made to delete some solutions. When some low performance solution is cut off, number of possible solutions that need to be evaluated will be smaller at each iteration.

IV. IMPLEMENTATION TO TWELVE-AREA SYSTEM

The 12-area power system [3] is shown in Fig. 3. It is assumed that the budget is \$150 million and the additional generators have capacity of 50 MW each. TABLE I shows area generation and loads as well as availability and cost per generator in prospective areas which are areas 1 to 5, and 9 to 12. Maximum number of unit additions allowed in each area is three units, which are included in the state space before performing global decomposition. Total number of scenarios is 165, i.e., 165 combinations of generators are to be analyzed. Probability distribution table for generation and tie-lines are developed with a capacity increment of 50 MW. System probability of loss of load before additional generation is 0.02639.

TABLE I
GENERATION AND LOAD PARAMETERS

Area j	Load (MW)	Generation (MW)	FOR of additional units	Cost per unit (\$m)
1	1400	2550	0.05	50
2	8000	23600	0.05	50
3	4800	15100	0.05	50
4	1200	3100	0.05	50
5	300	100	0.05	50
6	0	550	-	-
7	0	3500	-	-
8	0	400	-	-
9	1000	2100	0.05	50
10	1200	3100	0.05	50
11	1550	4150	0.05	50
12	1300	900	0.05	50

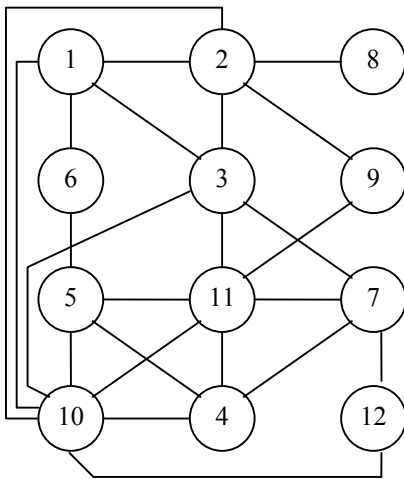


Fig. 3. Twelve-Area Test System

The optimal solution provided by the algorithm is to locate all three generators in area 12. Loss of load probability after additional generation is 0.00762. TABLE II shows number of possible scenarios to be evaluated and number of omitted scenarios at each stage of decomposition. The algorithm starts cutting off some scenarios at decomposition stage 15. These possible scenarios are deleted after a comparison in equation (8) is made. The number of possible scenarios (combinations of area generators) that need to be evaluated is smaller. This

improves computational efficiency since number of L sets created in later decomposition is often large.

TABLE II
NUMBER OF POSSIBLE AND OMITTED SCENARIOS AT EACH DECOMPOSITION STAGE

Decomposition Stage	Number of possible scenarios	Number of omitted scenarios
1-14	165	0
15	165	36
16	129	84
18	45	36
19	9	8

Since the goal of this study is to select the best generation location, there is no need to perform complete decomposition. If a comparison is made after performing global decomposition, more stages of decomposition need to be conducted. The proposed algorithm terminates after 19 stages of decomposition, which helps in reducing computational time and memory usage for storing U and L sets

V. CONCLUSION

An algorithm for long term generation adequacy planning is described in this paper utilizing global decomposition as a reliability evaluation tool. Scenario analysis is applied for the selection of the best solution. The direct approach is to perform one global decomposition, calculate system loss of load probability of all possible combinations, and then make a comparison for the best solution. However, the direct comparison after global decomposition requires high memory usage for all L sets.

The proposed method performs solution comparison and decomposition concurrently to improve computational efficiency. This method requires less memory usage since the L sets from each stage of decomposition can be deleted after evaluation. The comparison in (7) also helps reduce number of possible solutions at each stage of decomposition. Therefore, the number of evaluations and comparisons is smaller at a given stage of decomposition. Global decomposition need not be completed once the solution is found

VI. REFERENCES

- [1] N. S. Rau and F. Zeng, "Adequacy and Responsibility of Locational Generation and Transmission – Optimization Procedure", IEEE trans. on Power systems, vol. 19, no. 4, November 2004, pp. 2093-2101.
- [2] Z. Deng and C. Singh, "A New Approach to Reliability Evaluation of Interconnected Power Systems Including Planned Outages and Frequency Calculations", IEEE trans. on Power Systems, vol. 7, no. 2, pp. 734-743, May 1992.
- [3] S. Sung, "Multi-Area Power System Reliability Modeling", Ph. D. Dissertation, Texas A&M University, College Station, Texas, May 1992.
- [4] C. Singh and Z. Deng, "A New Algorithm for Multi-Area Reliability Evaluation – Simultaneous Decomposition—Simulation Approach", Electric Power System Research, vol. 21, 1991, pp. 129-136.
- [5] A. Lago-Gonzalez and C. Singh, "The Extended Decomposition Simulation Approach for Multi-Area Reliability Calculations", IEEE trans. on Power Systems, vol. 5, no. 3, August 1990, pp. 1024-1031.
- [6] C. Singh and A. Lago-Gonzalez, "Improved Algorithm for Multi-Area Reliability Evaluation Using the Decomposition-Simulation Approach", IEEE trans. on Power Systems, vol. 4, no. 1, February 1989, pp. 321-328.

- [7] P. Doulliez, E. Jamouille, "Transportation Networks with Random Arc Capacities", *Reveu Francaise d'Automatique, Informatique et Recherche Operationelle*, Vol 3, pp 45-66, 1972.