

A Comparison of Two Hybrid Methods for Multi-Area Reliability Analysis

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Abstract: This paper describes and compares two hybrid algorithms which combine the advantages of the state space decomposition technique and Monte Carlo simulation to provide multi-area reliability tools which allow improved system modeling by including DC load flow constraints. The first method uses decomposition-simulation, and accommodates all generation contingencies and a limited number of tie-line contingencies. The second method involves pruning of the state space prior to simulation, and accepts all generation and tie-line contingencies. Both techniques can deal with arbitrary network configurations, and can treat arbitrary probability distributions of generation and transmission systems. The two methods are compared by using them to determine the reliability indices of 3-area, 4-area and 5-area configurations of the IEEE Reliability Test System.

1 Introduction

Present day power systems almost invariably operate under interconnected conditions. The evolution of sophisticated control methodologies has been accompanied by an increase in the complexity of interconnections and exchange policies. These and other developments foreseeable in the immediate future, such as competitive markets, non-utility generation, and open transmission access, must be accompanied by the development of more powerful multi-area tools for the planning and analysis of large and complex interconnected systems. The increasing size of systems and the increasing number of operational constraints impose exorbitant demands on these tools in terms of computational effort. This motivates development of improved tools and techniques which provide more accurate system modeling and at the same time enable analysis of large and complex systems with a reasonable amount of computational effort.

Several approaches have been proposed for reliability analysis of multi-area systems. These approaches include state space decomposition [1], stochastic and probabilistic load flows [2, 3], equivalent assistance method [4], and Monte Carlo simulation [5, 6]. The first three of these are analytical approaches, while the fourth is a statistical simulation technique. There are also hybrid techniques [7, 8, 9, 10] which combine analytical and Monte Carlo methods.

In developing multi-area reliability tools, two models have been predominantly used to represent the inter-area power flows: the capacity flow model [1] and the DC load flow model [6, 11]. Though both models are in use, there is some disagreement among users and developers regarding the appropriateness of each model. It is, however, well known that the capacity flow model fails to accommodate Kirchhoff's voltage law, whereas the DC flow model succeeds in doing so, although in a simplified form [8]. To this extent, the DC flow model may be considered to be a more accurate representation. Most analytical and hybrid approaches have used the capacity flow model [1, 7]. In most cases the DC flow model has been incorporated in Monte Carlo methods

[6, 11]. In a few instances [2, 3, 12, 13], the DC flow model has been used in analytical methods, but these have limited applicability [8]. However, the authors have developed two hybrid methods [8, 9, 10] which successfully incorporate the DC flow model and are computationally more efficient than purely analytical or purely simulation based methods. These methods are described briefly and compared in this paper.

2 System Modeling

2.1 Generation Model

Based on the capacity states and forced outage rates of units available in a given area, a discrete probability distribution function is constructed, for every area, using the *Unit Addition Algorithm* [14].

2.2 Transmission Line Model

The transmission line model can be constructed for every transmission line, in the form of a probability mass function, or a discrete probability distribution function, over all the capacity levels, including zero.

2.3 Load Model

The load model used consists of N_c (20 in this research) discrete multi-area load vectors, each associated with a probability. This model may be formed by clustering the multi-area hourly load points into N_c clusters using *nearest centroid sorting* [14, 15]. This representation not only makes the load model smaller and more manageable, but also preserves the correlation between area loads.

2.4 The State Space

For any given load scenario, the available area generations and the tie-line capacities will determine whether or not the area loads will be satisfied. We can thus define a state space as the set of all possible combinations of generation levels and tie-line capacities. In general, therefore, a system with N_a areas and N_t tie-lines will have a discrete state space of dimension $(N_a + N_t)$, each axis consisting of the area generation or tie-line capacity levels, zero levels included.

In accommodating N_c multi-area load vectors, the following device is employed. An appropriate load level is chosen for every area, to constitute the reference load level vector. For every load vector in the load model, the generation model in each area is modified. This modification consists of 'shifting' a generation model by a capacity level equal to the difference between the load level and the reference level for that area, so that the margin between any generation level in the modified model and the reference load remains the same as that between the corresponding capacity level in the original model and the vector load. These modified models are interleaved together to form what will be referred to as an integrated generation model. When the integrated generation model is used to represent the area generation in the $(N_a + N_t)$ -dimensional state space described above, the resulting state

space is referred to as the integrated state space.

The operations of decomposition, pruning and simulation described in the next section are performed on the integrated state space.

2.5 The DC Flow Model

The DC flow model [8, 6, 11] uses the linearized dependence of the real power flows on the nodal voltage angles, and seeks to minimize loss of load in the system subject to this dependence and the generating and transmission capacity limits. It is thus formulated as a linear programming problem, as given below.

$$\text{Loss of Load} = \text{Min} \sum_{i=1}^{N_a} C_i \quad (1)$$

subject to:

$$\begin{aligned} \hat{B}\theta + G + C &= D \\ G &\leq G^{max} \\ C &\leq D \\ b\hat{A}\theta &\leq F_f^{max} \\ -b\hat{A}\theta &\leq F_r^{max} \\ G, C &\geq 0 \\ \theta &\text{ unrestricted} \end{aligned}$$

where

- N_a = number of areas
- N_t = number of tie-lines
- C = N_a -vector of area load curtailments
- C_i = i -th element of C , i.e., unsatisfied demand in area i
- D = N_a -vector of net negative injections for No Load Loss Sharing (NLLS) and actual area loads for Load Loss Sharing (LLS)
- G^{max} = N_a -vector of maximum available net positive injections for NLLS and available area generation for LLS
- F_f^{max} = N_t -vector of forward flow capacities of tie-lines
- F_r^{max} = N_t -vector of reverse flow capacities of tie-lines
- G = N_a -vector of net positive injections for NLLS and actual area generation for LLS
- θ = N_a -vector of node voltage angles
- b = $N_t \times N_t$ primitive (diagonal) matrix of tie-line susceptances
- $\hat{A}$ = $N_t \times N_a$ element-node incidence matrix
- $\hat{B}$ = $N_a \times N_a$ augmented node susceptance matrix
- $= \hat{A}^T b \hat{A}$

3 Description of the Methods

3.1 Decomposition-Simulation Including DC Flow Constraints

State space decomposition [1, 7, 8] is an analytical method which recursively decomposes the system state space into disjoint sets of acceptable, unclassified, and loss of load states. This is achieved by means of partition vectors, which are determined using Eq. (1) and variants thereof [8, 9]. The reliability indices are then determined from the loss of load sets. Because this method deals with sets of states rather than individual states, it is extremely powerful. However, for the same reason, it is also necessary for the state space to be

coherent [12]. A system is said to be coherent if the failure or degradation of a component cannot in any way result in an improvement in system performance, and, likewise, the restoration of a failed component cannot in any way deteriorate the system performance. The capacity flow model does not affect the system coherence, since the flow profile does not depend on the line susceptances, and an increase in the capacity of any line can only result in an increase in the throughput capability of the entire network. The DC flow model disturbs the coherence of the state space with respect to tie-line capacity changes. This means that if the system is in an acceptable state and some tie-lines move to states with higher capacities, one or more parts of the system may have loss of load. Similarly if the system is in system loss of load state and some lines change to lower capacities, some parts which had loss of load may meet their load demands. This is because changes in capacities cause changes in line impedances, causing the network to redistribute loads.

In order to include the DC flow model in the decomposition framework, therefore, coherency must be preserved. This is achieved by assuming that the tie-line states do not fail. This is in some cases regarded as a reasonable assumption, since studies on some real systems [11] have indicated that because of the relatively low failure rates of tie-lines, it is the tie-line capacities, rather than their failure rates, which have a significant effect on the system reliability. Moreover, such an implementation, i.e., one assuming perfectly reliable tie-lines, is not entirely restrictive in terms of tie-line failures; a limited number of tie-line contingencies can be considered by using the method to compute indices for the individual contingencies, weighing each index by the probability of the corresponding contingency, and then aggregating the weighted indices.

One other problem requires to be dealt with. It has been found, as will be shown in the section, that decomposition tends to become inefficient after a point, and grows increasingly time consuming. It is therefore prudent to stop decomposition at a suitable stage and subject the rest of the state space to Monte Carlo simulation. This involves randomly sampling system states, testing them for acceptability using Eq. (1), and adding their contribution to the reliability indices. Monte Carlo simulation is also an extremely powerful method, because it affords tremendous modeling flexibility. However, simulation by itself can also be quite time consuming; in this case, though, it converges quite rapidly, since it is performed over a reduced state space. This hybrid of decomposition and simulation proves to be quite effective, and has been described and validated in [8, 9].

In general, it is difficult to accurately determine an ‘optimal mix’ of decomposition and simulation, since this ‘optimal mix’ is dependent on such parameters as system size, configuration, reserve margin, and load diversity. In practice a threshold probability p_0 is defined, such that all sets with probability larger than p_0 are subjected to decomposition, while the rest are subjected to simulation. A small value of p_0 therefore results in a large degree of decomposition, and vice versa.

3.2 Pruning and Simulation

This method consists of pruning the state space before performing Monte Carlo simulation. ‘Pruning’ refers to cutting away arbitrarily large parts of the state space, such that these parts do not contain any failure state. This is also achieved by means of partition vectors determined using Eq. (1). Monte

Carlo simulation is then performed over the remaining state space; the simulation now converges rapidly, not only because the sample space is reduced, but also because it now contains a higher proportion of failure states. The reliability indices are estimated entirely from simulation.

Since pruning also deals with sets of states, coherency must be preserved during this phase. This is done by forcing the tie-lines to remain at their maximum capacities during pruning. They are allowed to assume all states during the simulation phase. It has been shown [8, 10] that this hybrid method proves to be extremely effective, especially because tie-lines are generally highly reliable. Since all tie-line states are considered during the simulation phase, this method is inherently capable of including *all* tie-line contingencies. It is also relevant to remark that since pruning does not remove any failure state, all failure states are retained for simulation, and there is no loss of accuracy accompanying the acceleration in convergence. The method is described in detail in [8, 10].

Here, too, the mix of pruning and simulation can be controlled by defining a threshold probability p_0 , such that only sets of probability larger than p_0 are subjected to pruning, while the rest are set aside for simulation.

4 Test Cases and Results

In this section the two methods are compared, in terms of both speed and accuracy.

It is convenient to first define all the test cases which will be used for both validation and comparison of the methods. Three configurations are defined, as shown in Fig. 1. Every area in these configurations is identical to the IEEE-RTS [16], with area generation capacity 3405 MW and area peak load 3000 MW. Every inter-area tie consists of a double circuit line, each line having susceptance -60 per unit, capacity 150 MW, and failure probability 0.04. Each tie-line therefore has three states, as shown in TABLE I. Six test cases are considered, as shown in TABLE II. The first three cases ignore the tie-line failure probabilities, and assume them to be perfectly reliable. The remaining cases consider all the tie-line states given in TABLE I.

In constructing all models, for both methods, capacity and load states were rounded off to 50 MW steps. 20-cluster load models were used. In all cases, the No Load Loss Sharing (NLLS) policy was assumed: in the event of loss of load, the curtailments were allocated among the areas suffering loss of load in such a manner as to minimize the total curtailment, while ensuring that the assisting areas first met their entire area demands. Also, for these test cases no planned outage is considered, i.e., the entire year is treated as a single interval with full generation availability, except for forced outages.

Cases 1, 2 and 3 are used solely to exhibit the sensitivity of the decomposition-simulation method to different threshold

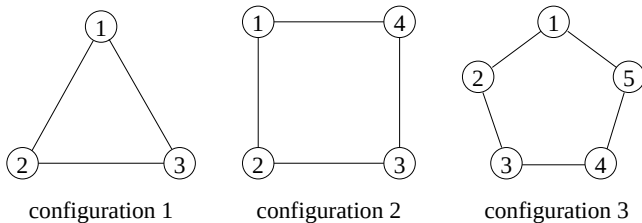


Fig. 1. Configuration of Test Cases

TABLE I. TIE-LINE STATES

CAPACITY	SUSCEPTANCE	PROBABILITY
300 MW	$-120 pu$	0.9216
150 MW	$-60 pu$	0.0768
0 MW	$0 pu$	0.0016

probabilities, and to show that there are ‘optimal’ values of p_0 (in the neighborhood of 10^{-7} for these cases) for which the method performs most efficiently. The results of these tests are shown in TABLE III. It is clear from column 6 (corresponding to complete decomposition) that it is a good idea to switch from decomposition to simulation at a certain stage, especially for large systems.

Cases 4, 5 and 6 are used to compare the two methods. The comparison is provided in TABLE IV. Now cases 4, 5 and 6 consider multiple tie-line contingencies. While the pruning and simulation method is inherently capable of considering all contingencies, the decomposition-simulation method must be used on selected tie-line contingencies. Observe that in case 4, since there are 3 tie-lines with 3 states each, there are altogether $3^3 = 27$ tie-line contingencies. Case 5 has $3^4 = 81$ contingencies, and case 6 has $3^5 = 243$ contingencies. It was therefore necessary to select tie-line contingencies for cases 5 and 6. For case 5, contingencies for upto third order were selected, i.e., failure of 0, 1, 2 or 3 circuits were considered (each tie-line consists of 2 circuits). These (31 contingencies) were found to span 99.98% of the probability space of all the tie-line contingencies. For case 6, contingencies of upto second order were selected, i.e., failure of 0, 1 or 2 circuits were considered. These (21 contingencies) were found to span 99.38% of the probability space of all the tie-line contingencies. For case 4, all 27 contingencies, spanning 100% of the probability space, were considered.

Since complete decomposition of the 3-area system is relatively fast, $p_0 = 0$ was used when applying the first method on case 4. So this result represents a completely analytical solution. In cases 5 and 6, $p_0 = 10^{-7}$ was used. In applying the pruning and simulation method, $p_0 = 10^{-7}$ was used on all cases.

It is evident from TABLE IV that the pruning and simulation method is not only capable of dealing with many more transmission contingencies than the decomposition-simulation method, but is also considerably faster. However, it must be realized that the decomposition-simulation method provides the option of determining the indices completely analytically (albeit under increased time and memory requirements) and is therefore capable of greater accuracy, while the pruning and simulation method, being essentially an estimation method, necessarily results in some amount of uncertainty. In the future, as computers become faster and memory gets cheaper and more abundant, it may be possible to apply the decomposition-simulation method to larger systems and at the same time include larger numbers of transmission contingencies.

TABLE II. TEST CASES

CASE	CONFIGURATION	TIE-LINE STATES
CASE 1	configuration 1	all ties perfectly reliable
CASE 2	configuration 2	all ties perfectly reliable
CASE 3	configuration 3	all ties perfectly reliable
CASE 4	configuration 1	tie-lines as in TABLE I
CASE 5	configuration 2	tie-lines as in TABLE I
CASE 6	configuration 3	tie-lines as in TABLE I

TABLE III. SENSITIVITY OF DECOMPOSITION-SIMULATION TO THRESHOLD PROBABILITY

CASE	CPU time ¹ (h:mm:ss) for different threshold probabilities (p_0)					Optimal p_0^*
	$p_0 = 10^{-5}$	$p_0 = 10^{-6}$	$p_0 = 10^{-7}$	$p_0 = 10^{-8}$	$p_0 = 0.0$	
CASE 1	0 : 00 : 25	0 : 00 : 25	0 : 00 : 15	0 : 00 : 20	0 : 00 : 20	10^{-7}
CASE 2	0 : 01 : 20	0 : 00 : 45	0 : 01 : 10	0 : 03 : 10	0 : 41 : 35	10^{-6}
CASE 3	0 : 04 : 25	0 : 02 : 45	0 : 02 : 40	0 : 05 : 35	23 : 47 : 00	10^{-7}

TABLE IV. COMPARISON OF THE TWO METHODS

CASE	Decomposition-Simulation					Pruning & Simulation				
	LOLE (h/year)		EUE (MWh/year)		CPU time ¹ (h:mm:ss)	LOLE (h/year)		EUE (MWh/year)		CPU time ¹ (h:mm:ss)
	SYSTEM	AREA	SYSTEM	AREA		SYSTEM	AREA	SYSTEM	AREA	
CASE 4	1.869	0.743	321.4	107.1	0 : 03 : 00	1.816	0.736	319.5	106.5	0 : 00 : 04
CASE 5	1.574	0.441	242.2	60.6	0 : 48 : 23	1.548	0.434	234.1	58.5	0 : 00 : 20
CASE 6	1.731	0.372	233.9	46.8	1 : 00 : 26	1.750	0.384	243.6	48.7	0 : 00 : 45

cies. Both methods therefore have their relative merits.

5 Conclusion

This paper has presented and compared two hybrid methods for reliability evaluation of multi-area systems — the decomposition simulation method and the pruning and simulation method. These methods incorporate improved network modeling by including DC flow constraints, and at the same time effectively solve the problem of noncoherence which accompanies the inclusion of these constraints in analytical frameworks which deal with sets of system states. These methods are extremely effective, and possess the following features.

1. Both methods can handle arbitrary network configurations and arbitrary probability distributions of generation and transmission systems.
2. Both methods consider generation contingencies of all orders. The first method can consider a limited number of transmission contingencies, while the second considers all transmission contingencies.
3. Both methods provide improved network modeling by including DC flow constraints.
4. Both methods are computationally more efficient than purely analytical or purely Monte Carlo simulation.

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¹On a DEC Alpha 2100 – 4/275