# A RELIABILITY ASSESSMENT METHODOLOGY FOR DISTRIBUTION SYSTEMS WITH DISTRIBUTED GENERATION

A Thesis

by

SUCHISMITA SUJAYA DUTTAGUPTA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Electrical Engineering

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# ABSTRACT

A Reliability Assessment Methodology for

Distribution Systems with Distributed Generation. (May 2006)

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Reliability assessment is of primary importance in designing and planning distribution systems that operate in an economic manner with minimal interruption of customer loads. With the advances in renewable energy sources, Distributed Generation (DG), is forecasted to increase in distribution networks. The study of reliability evaluation of such networks is a relatively new area. This research presents a new methodology that can be used to analyze the reliability of such distribution systems and can be applied in preliminary planning studies for such systems. The method uses a sequential Monte Carlo simulation of the distribution system's stochastic model to generate the operating behavior and combines that with a path augmenting Max flow algorithm to evaluate the load status for each state change of operation in the system. Overall system and load point reliability indices such as hourly loss of load, frequency of loss of load and expected energy unserved can be computed using this technique. On addition of DG in standby mode of operation at specific locations in the network, the reliability indices can be compared for different scenarios and strategies for placement of DG and their capacities can be determined using this methodology.

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# CHAPTER I

# INTRODUCTION

## A. Introduction

The goal of a power system is to supply electricity to its customers in an economical and reliable manner. It is important to plan and maintain reliable power systems because cost of interruptions and power outages can have severe economic impact on the utility and its customers. At present, the deregulated electric power utilities are being restructured and operated as distinct generation, transmission and distribution companies and the responsibility of maintaining reliability of the overall power system is shared by all involved companies instead of by a single electric utility [1].

With recent advances in technology, use of distributed generation (DG) in the power distribution system is increasing. Incorporating DG into the power system poses numerous challenges in terms of interconnection, protection coordination and voltage regulation. Increased reliability and reduced cost are the primary incentives of adding DG to a power network.

This thesis presents a new methodology to simulate the operation of a power distribution system with DG and to compute the reliability indices and statistics. The proposed method uses a sequential Monte Carlo simulation of the power system's stochastic model in combination with a path augmenting Max Flow algorithm. Thorough assessment of reliability and operating strategy of a distribution network can be performed using this developed technique for preliminary reliability planning studies.

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The journal model is *IEEE Transactions on Automatic Control.*

B. Distribution System Reliability

A power system consists of a generation, transmission and a distribution system. Traditionally, reliability analysis and evaluation techniques at the distribution level have been far less developed than at the generation level since distribution outages are more localized and less costly than generation or transmission level outages. However, analysis of customer outage data of utilities has shown that the largest individual contribution for unavailability of supply comes from distribution system failure [2].

Distribution systems are typically of radial configuration or meshed configuration that are operated as radial systems. Unidirectional energy flows from the supply point to the customer load points through distribution lines, cables and bus bars connected in series. The component reliability indices include failure rates and repair times.

C. Distributed Generation

The Public Utilities Regulatory Policy Act (PURPA) allowed independent non-utility power producers to generate and sell electricity in 1978. Distributed generation is small modular generation of capacity ranging from few kilowatts to 10MW. With advances in fuel cells and renewable energy sources, increase of DG is projected.

DG may be connected at the generation substation, at any point in a distribution feeder or at customer load points. Renewable energy sources include hydro, wind powered and photovoltaic generation. Other DG sources include fuel cells and micro turbines. DG may be synchronous or induction generator.

DG operating in parallel to the utility presents numerous protection and coordination problems since there are multiple sources of generation in the network and bi-directional flow of energy. In particular, the operation of overcurrent protection devices such as fuses, reclosers and relays coordinated for radial networks are considerably affected. This is a topic of active research due to high incentives and benefits derived from addition of DG in the distribution system.

DG is mostly used for standby or backup power in the event of utility supply interruption. Other applications include peak shaving, independent generation, net metering, voltage support, combined heat and power etc. In the standby mode of operation, DG improves the system adequacy index. In the peak shaving mode, DG improves system reliability by reducing feeder loading and lowering energy costs in high demand periods.

### D. Literature Review

This section gives a detailed overview of the research papers in the area of reliability assessment of power distribution systems with distributed generation. Reference [3] presented a method for reliability evaluation that took into account the fluctuating nature of energy produced by renewable energy sources such as wind and solar power generators. The authors assigned the conventional or continuous fuel source units to one subsystem and the fluctuating units to several other subsystems and for each subsystem developed a generation system model. The effect of fluctuating energy was included by modifying the generation system model of the unconventional unit. The frequency of capacity deficiency and loss of load expectation for the hour concerned was calculated by combining the generation system models, where each subsystem was treated as a multi-state unit. A discrete state algorithm was used for this method. Further, the method of cumulants was also applied to combine the subsystems to produce hourly loss of load expectation.

The authors [3] observed that the proposed methods gave significantly different results from the traditional methods at high penetration of the fluctuating units, while results obtained using the method of cumulants and those using the recursive algorithm were similar at high penetrations of the fluctuating units.

Reference [4] developed a similar methodology to evaluate loss of load expectation and unserved energy and also improved the computational efficiency. In the proposed approach, the authors correlated the hourly load to the output of the unconventional units and assigned them to specific states using the clustering algorithm. The mean values of the output of the unconventional units, the load and the probability of each cluster were obtained by dividing the number of clusters by the total number of observations. The authors combined all the subsystems to compute the reliability indices for each cluster. A case study was conducted to validate the proposed approach. The authors observed that the computation time was reduced significantly when the clustering approach was used.

Reference [5] presented a time sequential simulation to evaluate the reliability of a distribution system with wind turbine generators (WTG). The power output of the WTG at a specific hour was expressed as a function of the wind speed at that hour, and the rated power of the unit. The authors developed a six-state model for the WTG to consider the joint effects of both the wind speed and forced outage of the WTG. A two-state model represented other components of the distribution system such as transformers etc.

The authors [5] noted the reliability impact on an individual load point to be dependent on the location of the load point in the network, the switching topology and the load level. The various parameters of the WTG such as the cut-in speed, the cut-off speed and the rated wind speed were seen to affect the reliability performance as well. In conclusion, the authors note that by selecting the optimal number of WTG units and by matching the WTG with specific wind sites, the reliability of a distribution system could be greatly enhanced.

Reference [6] listed the positive impacts of DG to the distribution network such as reactive power compensation to achieve voltage control, reduction of power losses, regulation and load power consumption tracking to support frequency regulation, spinning reserve to support generation outages and improvement in reliability through backup generation.

A commercial software tool [6] was used to analyze specific DG applications to a distribution system. DG backup generator was modeled as a transfer switch and was treated as a voltage source. In an alternate scheme, the authors modeled the DG as a negative load that injects power into the system, independent of the system voltage. According to the authors, when a fault occurred, system reliability could be improved in the case where presence of DG reduced load transfer requirements. The test system analyzed consisted of a feeder with DG and four other feeders connected to the first through normally open tie points. The simulation results showed that for a certain capacity of DG, adjacent feeders experienced improvement of reliability index with previously blocked operations now functional since DG reduced loading. However, the authors observed that when the DG capacity exceeded a certain value, backfeed occurred resulting in overloading of the feeder and degradation of reliability.

Reference [7] presented an optimal siting and sizing method for placing DG in a distribution system, which was used to improve the system reliability. The authors determined the optimal siting by performing sensitivity analysis of power flow equations. The sizing methodology specific to the generation penetration level and other loading conditions was solved as a security constrained optimization problem.

Further, a genetic algorithm [7] was applied to determine optimal recloser placements in the DG populated distribution system. An objective function that minimized the composite reliability index expressed as a certain combination of the System Average Interruption Duration (SAIDI) and System Average Interruption Frequency

(SAIFI) indices was developed by the authors to solve for optimal recloser positions. A test feeder was used to verify this algorithm. The composite reliability index was determined for each zone. Based on the results, the authors noted significant reduction in the reliability indices based on the optimal recloser placements in the network.

Reference [8] presented a probabilistic reliability model that balanced demand for lower customer rates with improved reliability for a distribution system with DG. The objective of the paper was to determine the DG equivalence to a distribution facility with comparable reliability and load requirements. According to the authors, DG installation in the area was a better solution since the capital cost for the additional feeder could be avoided, the independent power producers would receive distribution capacity deferral credit and adding DG to the area would also provide voltage control for the network.

A commercial reliability assessment software [8] was used to compare the two proposals by computing SAIDI, SAIFI, load/energy curtailed, cost of outage and cost of interruption. To determine the DG equivalence to the distribution facility, the reliability index Expected Energy Not Served (EENS), was used. The authors observed that adding the third feeder significantly reduced the EENS.

Reference [9] developed a Monte Carlo based method for the adequacy assessment of a distribution system with DG. The total output power of all the working DG was treated as a random process attributed to the random nature of the DG duty cycle, its failure rates and restoration times. A two state model was used to represent the DG operation.

The authors [9] performed a case study on a distribution system supplied from a 3100MW, 132/33 kV substation and customer controlled DG with a system peak load of 2850 MW. Based on the results, the authors concluded that the system could not provide adequate energy and there was a need for increased system capacity. Hence, DG units were added in parallel to the existing substation. Monte Carlo simulation was performed for a large number of sample years to determine the unsupplied load per year. The authors found this value to drop significantly. The authors concluded that DG could enhance the distribution system capacity in the event of expected demand growth.

Reference [10] used an hourly reliability worth assessment of a distribution system to determine the optimal operating scheme for DG. Two modes of DG operation were studied viz. the peak shaving mode and the standby mode. According to the authors, in order to determine the optimal strategy for the DG operation, the reliability worth should be balanced with the cost of power through a suitable combination of the two operating modes. A six-state Markov model was used for the DG operating in the peak shaving and the standby modes.

The authors [10] performed a sequential Monte Carlo simulation of the system for reliability analysis. Using interruption cost data, the paper evaluated the expected annual average interruption cost at specific load points. To determine the optimal operating strategy for the DG, the authors developed an objective function. This function expressed the difference of the combined costs (utility power cost, DG operating cost and expected hourly interruption costs) for the peak shaving mode and the standby modes. The authors sought to minimize this objective function. An urban distribution system connected to bus 2 of the RBTS was modified to include a DG for the case studies. Based on the results, the authors observed that the total operating cost using hourly reliability worth was lower than the operating cost using the annual average operating cost. Hence, the authors concluded that the hourly interruption cost was an important reliability index for the optimal operation of the DG.

For state evaluation of the distribution network, most of these studies used load flow programs to evaluate the load demand status corresponding to a particular system state. The methodology developed in this research uses the Ford-Fulkerson algorithm to determine the flows in the network and evaluate the load demand status for every state of the system operation. On addition of DG to the network, reliability assessment and comparison can be done with this technique using easily available failure/repair statistics of components and load characteristics. Extensive line data and interconnection specifications required in load flow programs are not needed. For preliminary planning studies, this technique offers an efficient and thorough evaluation of the system reliability.

## E. Outline of Thesis

The contents of this thesis are organized into six chapters. Following the chapter on introduction, chapter II gives a brief overview of a typical distribution system similar to the network to be used later for case study analyses. Also, the main indices to be used in this research for assessing the reliability of the distribution system with DG have been discussed.

Chapter III details the simulation methodology for this research. Background information is provided on Monte Carlo simulation theory. The sequential and sampling simulation methods are compared. The need for a flow augmentation algorithm for calculating the maximum flows in a distribution network is discussed with an example case. This is followed by the description of the Labeling routine and the Ford Fulkerson algorithm for finding the maximum flows in a network. The last section of this chapter describes the implementation procedure for the Monte Carlo-Max Flow modules and the various performance enhancements that have been incorporated.

Chapter IV gives the system model characterization for a small sample system used to validate the developed methodology described in chapter III. First, an analytical method that uses Markov models and state space to evaluate the system reliability is described with results. This is followed by the results obtained using the methodology developed in this research. The last section describes the distribution systems to be used for the reliability analysis, the probability distributions used for the Monte Carlo method and a time varying system load model.

Chapter V analyzes the system reliability and individual load point reliability for various cases of the two sample distribution networks; Bus 2 RBTS and Bus 4 RBTS networks described in chapter IV. Different magnitudes of system supply constitutes each case. Within each case, the orginal network's reliability is compared with the networks when DG is added to them. A total of eighteen cases are presented, nine for each distribution network.

Finally, chapter VI presents the conclusions for this research.

# CHAPTER II

## RELIABILITY EVALUATION OF A DISTRIBUTION NETWORK

### A. Overview of a distribution network

Power systems consist of generation, transmission and distribution networks. After stepping down the voltage from transmission levels, distribution systems distribute the power received from the supply points to customer facilities. Distribution systems are typically of radial configuration where unidirectional energy flows from the supply points to the loads through distribution feeders.

Figure 1 shows an example of a basic radial distribution system. F1 and F2 are the two distribution feeders. F1 consists of distribution lines 1 through 11 connected radially to load points LP1 through LP7. F2 consists of distribution lines 12 through 21 feeding load points LP8 through LP13. In radial networks, outage of a supply point, distribution line, distribution transformer or any other component connected in series will result in loss of all loads downstream of the outage. In such situations, reliability of the network can be improved by adding distributed generators that offer an alternate point of supply to loads connected directly or indirectly by reducing the overall loading of the distribution feeders.

### B. Adequacy vs. Security

Reliability of a system can be either categorized as system adequacy or as system security. Adequacy is associated with the ability of the system to satisfy the load demand in the event of planned or unplanned outages. Inadequacy could result from insufficient generation capacity or inability of transmission or distribution networks to transfer the energy to the customer load points [11]. System security is associated

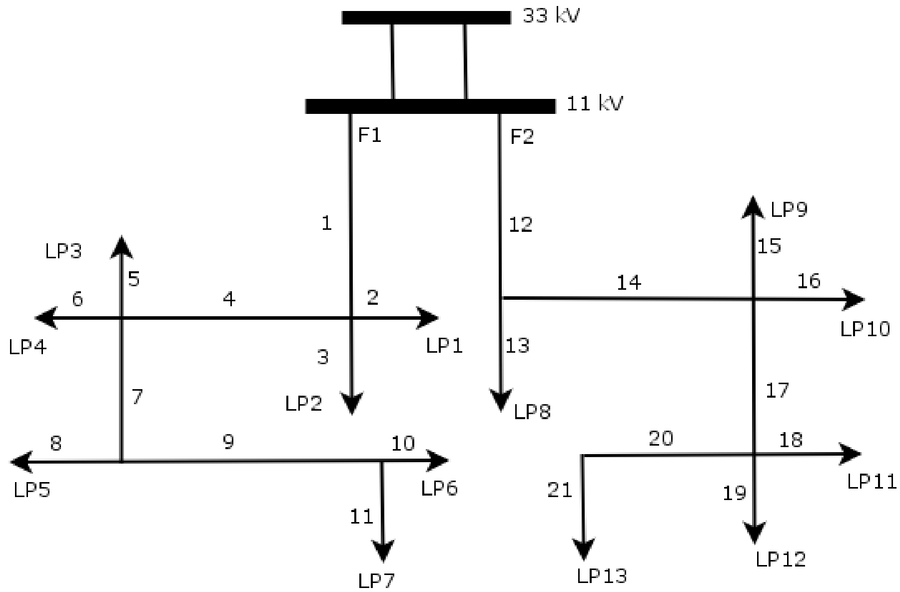


Fig. 1. Sample Distribution Network

with the network response to dynamic and transient failures caused from faults and other disturbances, which could result in widespread cascading outages and loss of stability [11]. This research will focus on the adequacy-based reliability of a power network.

### C. Comparison of Indices

Further, the adequacy indices can be categorized as deterministic and probabilistic indices. Probabilistic indices are better assessment tools than deterministic indices because they can incorporate the inherent uncertainties associated with system reliability and evaluate all the parameters that affect reliability instead of merely reflecting pre-determined conditions that may or may not influence the real operation of the power network [12].

## D. Probabilistic Indices

The reliability of a power system is expressed in terms of reliability indices. Following are the commonly used probabilistic indices in power system reliability evaluation.

### 1. Hourly Loss of Load Expectation

Hourly Loss of Load Expectation (HLOLE) is the expected number of hours per year when there will be insufficient capacity and load demand will exceed capacity. Unit for HLOLE is hrs/yr.

### 2. Loss of Load Frequency

Frequency of Loss of Load (FLOL) is the expected number of times in a year when an event of insufficient capacity occurs. FLOL is expressed in events/year.

### 3. Expected Unserved Energy

Expected Unserved Energy (EUE) is the expected amount of energy not supplied due to capacity deficiency in the period of observation. Unit for EUE is MWhr/yr.

These indices may be computed as a single value for the entire distribution network or individually for each load point in the network. The loss of load expectation index gives the number of hours of capacity deficiency but does not give information on the magnitude of that deficiency or the amount of energy that was unsupplied [12]. The EUE index includes both the duration as well as the magnitude of the deficiency.

# CHAPTER III

# SIMULATION METHODOLOGY

## A. Monte Carlo Simulation Theory

The Monte Carlo method is a stochastic simulation of the operation of a network. The failure and repair histories of components are simulated using random variables with probability distributions of the component states, which mimic the random behavior of the system operation such as component failures etc. The main objective of the simulation is to generate the expected or average value of various component and system reliability indices [11].

The benefit of Monte Carlo technique over analytical evaluation techniques is that for large-scale systems, analytical techniques become progressively more complicated and unsuitable for assessing system reliability. Analytical techniques often require contingency enumeration of a large number of states before they can be reduced. Monte Carlo techniques avoid this problem by sampling a representative set of system states.

### 1. Sequential and Sampling Simulations

There are two main approaches for Monte Carlo methods in power system reliability studies viz. the sequential and sampling techniques. The sampling technique randomly samples the probability distribution of component states to evaluate the system state. The sequential technique chronologically simulates component state transitions to evaluate the system state. In this research, the sequential Monte Carlo technique is used since it is difficult to evaluate the frequency index using the sampling approach.

The sequential Monte Carlo technique may be performed using the Fixed Time Interval (synchronous timing) method by advancing time in fixed steps or by using the Next Event (asynchronous timing) method by advancing to the occurrence of the next event. The Fixed Time Interval method is inefficient in practice since most of the simulated intervals may contain no event or change.

a. Next Event Method

This method simulates a system over time as a sequence of discrete events. Unlike the Fixed Time Interval method, this method only evaluates the system state when a component state changes. Thus the simulation is event-driven, not time driven. This is essentially a Discrete Event view of the system over time. Reliability indices are calculated using both the number and duration of system states simulated.

B. Flow Criterion in Power Network

The Monte Carlo technique is used to generate the artificial history of failure and repair of the components in power system studies. For a network, a specific state of the system components corresponds to specific states for the load points. In other words, supply outage or distribution line outage may cause loss of load at some or all load points. If there is surplus generation, some amount of generation outage may not necessarily cause loss of load. Hence, every state change in Monte Carlo of any system component requires an evaluation of the status of load demand satisfaction.

Monte Carlo techniques are well-suited for simulating a system as a stochastic model. However, for reliability studies, a stochastic model by itself cannot provide much information about the amount of power flowing through specific points in the network. Furthermore, the calculation of the amount of power flowing through a

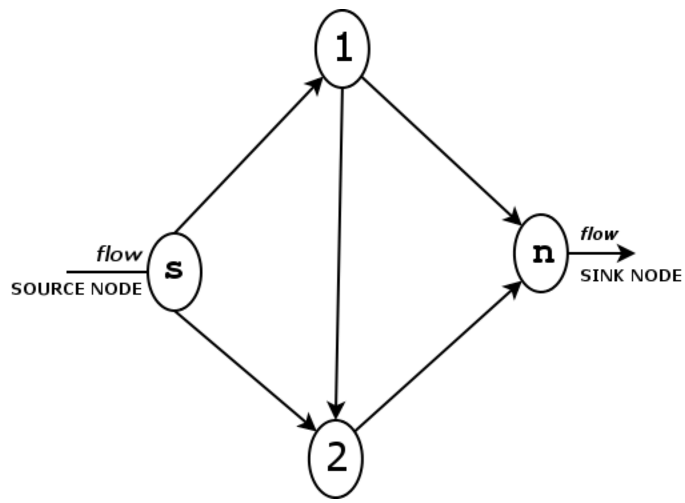


Fig. 2. Flow Graph

network, given capacities of generators, lines, and loads is not trivial.

One technique is to represent a power system as a directed acyclic graph. Each edge represents a generator, transmission line, or load. Associated with each generator or transmission line edge is a maximum capacity of power flow. Similarly, each load edge has an associated demand capacity. Vertices represent interconnection points between two lines, generators, etc. For modeling purposes, source and sink vertices are added to the graph. Figure 2 gives a basic flow graph representation. The source vertex contains only outgoing edges. Likewise, a sink vertex contains only incoming edges. Thus by definition, all vertices are reachable from the source vertex and the sink vertex is reachable from all other vertices. The network flow is the sum of flow of all edges leaving the source and is equivalent to sum of flow into the sink node.

Using this model, the problem can be formulated as follows. Given such a graph, to find the maximum power flow between the source and sink nodes. Such a flow corresponds to the maximum utilization of generation capacity. Consider an intuitive approach that consideres all possible paths from the source to the sink and increases the flow on that path by the maximum possible amount. Consider as an example,

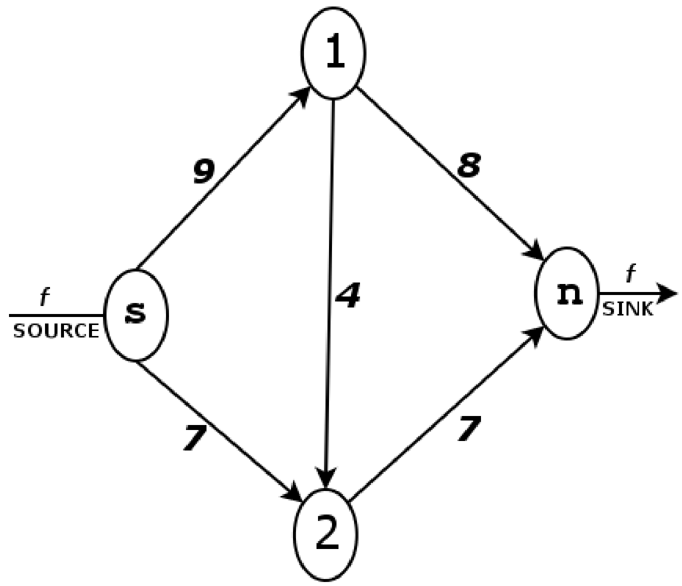


Fig. 3. Flow 1

the following basic scenario for demonstration of this. The flow network in Figure 3 gives certain capacity values for each arc traversing from the source to sink node through transition nodes 1 and 2.

Initial flows from all the arcs are zero. The first index in the parenthesis gives the actual flow value while the second index gives the capacity of the arc. The magnitude of flow in one possible path going from source-node 1-node 2-sink is the minimum of the two arc capacities as shown in Figure 4. Hence, Figure 5 shows one possible flow augmentation path from the source to sink has capacity equal to the minimum capacity arc, which in this case is node 1-node 2 of capacity 4.

Figure 6 gives the updated flow magnitude of 3 in the network. Further, utilizing the unused capacity of source-node 1 arc with the check of minimum value criterion, a second augmentation path is traced by source-node 1-sink as given in Figure 7. Arc source-node 1 has flow equal to capacity and the total flow in the network is updated to 9 as shown in Figure 8.

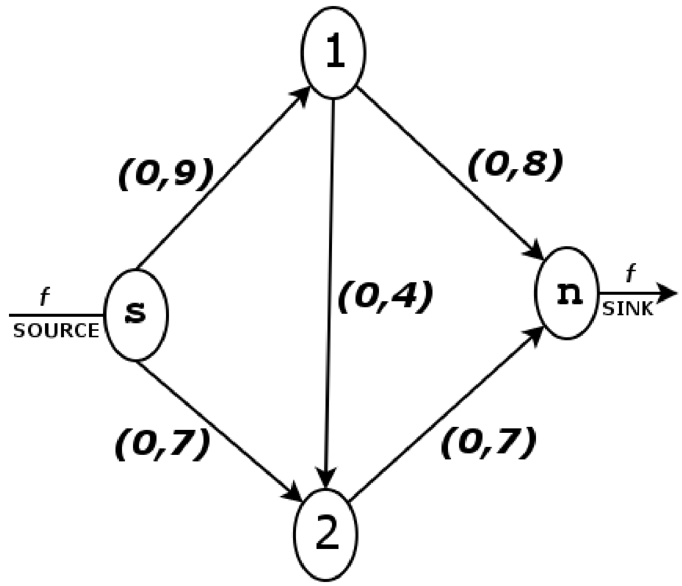


Fig. 4. Flow 2

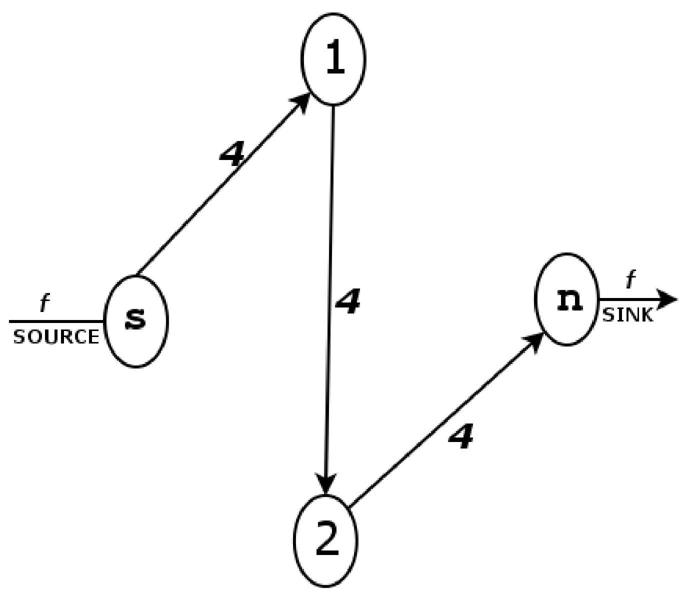


Fig. 5. Flow 3

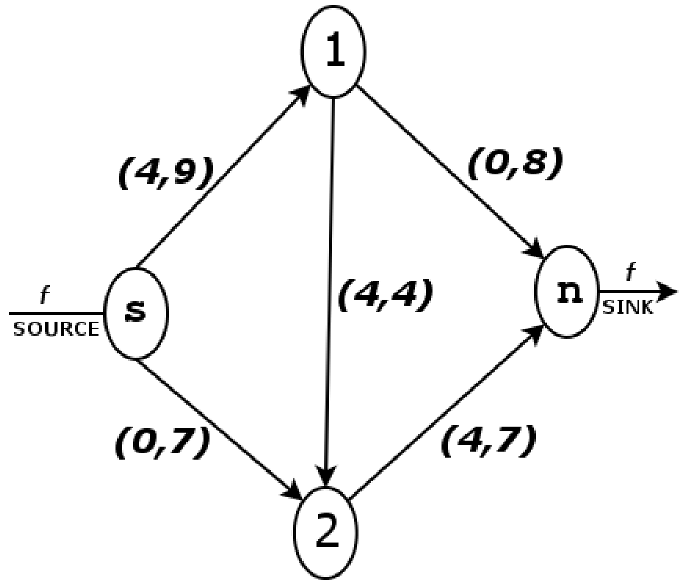


Fig. 6. Flow 4

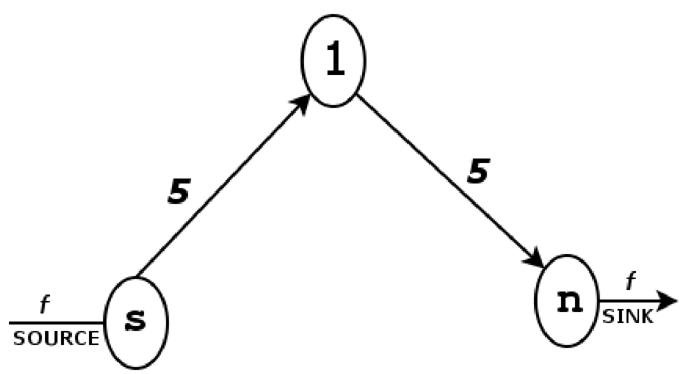


Fig. 7. Flow 5

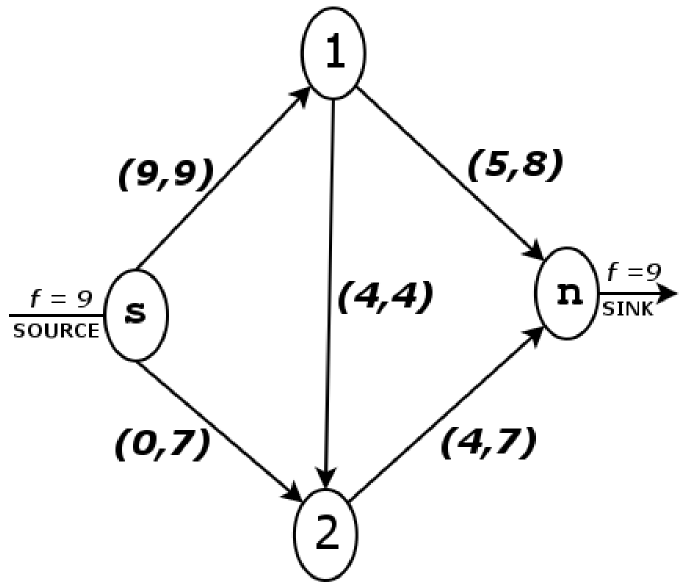


Fig. 8. Flow 6

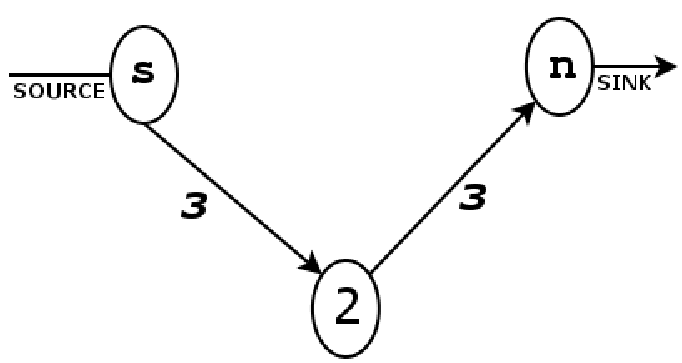


Fig. 9. Flow 7

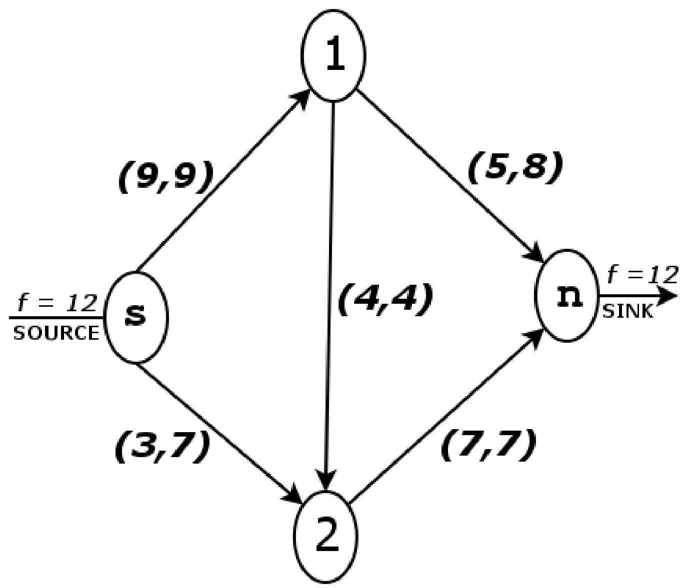


Fig. 10. Flow 8

Similarly, an augmentation path source-node 2-sink is traced with the unused capacity.Since, this path satisfies the minimum value criterion, some capacity still remains unused in the nework. Figure 9 and Figure 10 illustrate this case. The updated flow from source to sink in the network is 12. The capacity demand of the sink node is still greater than the flow supplied.

To maximize the flow going from the source to the sink node and to utilize the unused capacity an additional flow augmentation path must be found. This additional augmentation path can be found as shown in Figure 11. Here the assumption is made that a flow of 3 can be sent in the reverse direction for the arc going from node 1 to node 2. The flow appears to go in the opposite direction of the unidirectional arc, but equivalently it may be viewed as reducing the flow in this arc from 4 to 1 in the original orientation. Figure 12 gives the final flow network of magnitude 15. Hence, the bidirectional flow of the transmission arc results in a new value for the net flow of this arc. In a large power network, the number of possibilities of flow paths

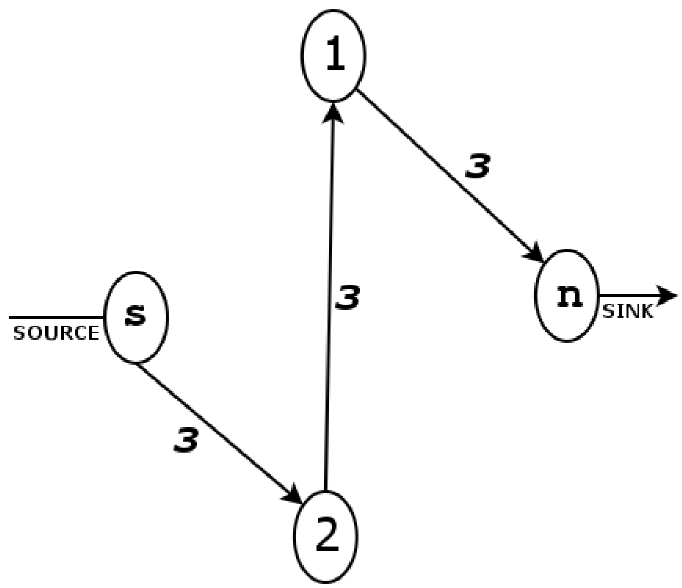


Fig. 11. Flow 9

increase substantially and the Ford-Fulkerson algorithm based on the Max flow-Min cut theorem ascertains that the maximum flow is ensured between the source and the sink nodes.

## C. Theory on the Ford-Fulkerson Algorithm

The Max-Flow Min-Cut theorem [13] states that for any network, the value of the maximum flow from source to sink is equal to the capacity of the minimum cut. The net flow in the network satisfies the three conditions viz.

1. Capacity constraint from any arc in the path

2. Flow conservation between nodes

3. Skew symmetry

The Max-Flow Min-Cut problem is computed using the Ford-Fulkerson Max Flow Labeling algorithm. To determine a feasible flow augmentation path from source

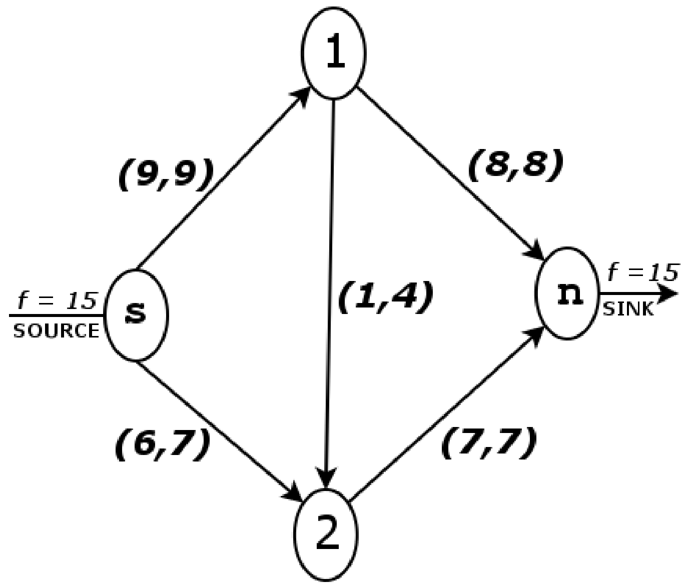


Fig. 12. Flow 10

node to the sink node a Labeling routine is used in the following manner

- Mark all nodes as unlabeled and unscanned.
- Label source node with value $-\infty$.
- While sink node not labeled, for any labeled and unscanned node $x$,
  - label each unlabeled successor node $y$ with excess capacity between $x$ and $y$.
  - label each unlabeled predecessor node $w$ with positive flow from $w$ to $x$.
  - Mark $x$ as scanned.
- If the sink is labeled, then an augmenting path has been found.
- If the sink is not labeled, then no augmenting paths exist.

This Labeling routine is used in the Ford-Fulkerson algorithm as shown is Figure 13 to compute the maximum flow in a network [13]. The algorithm initializes

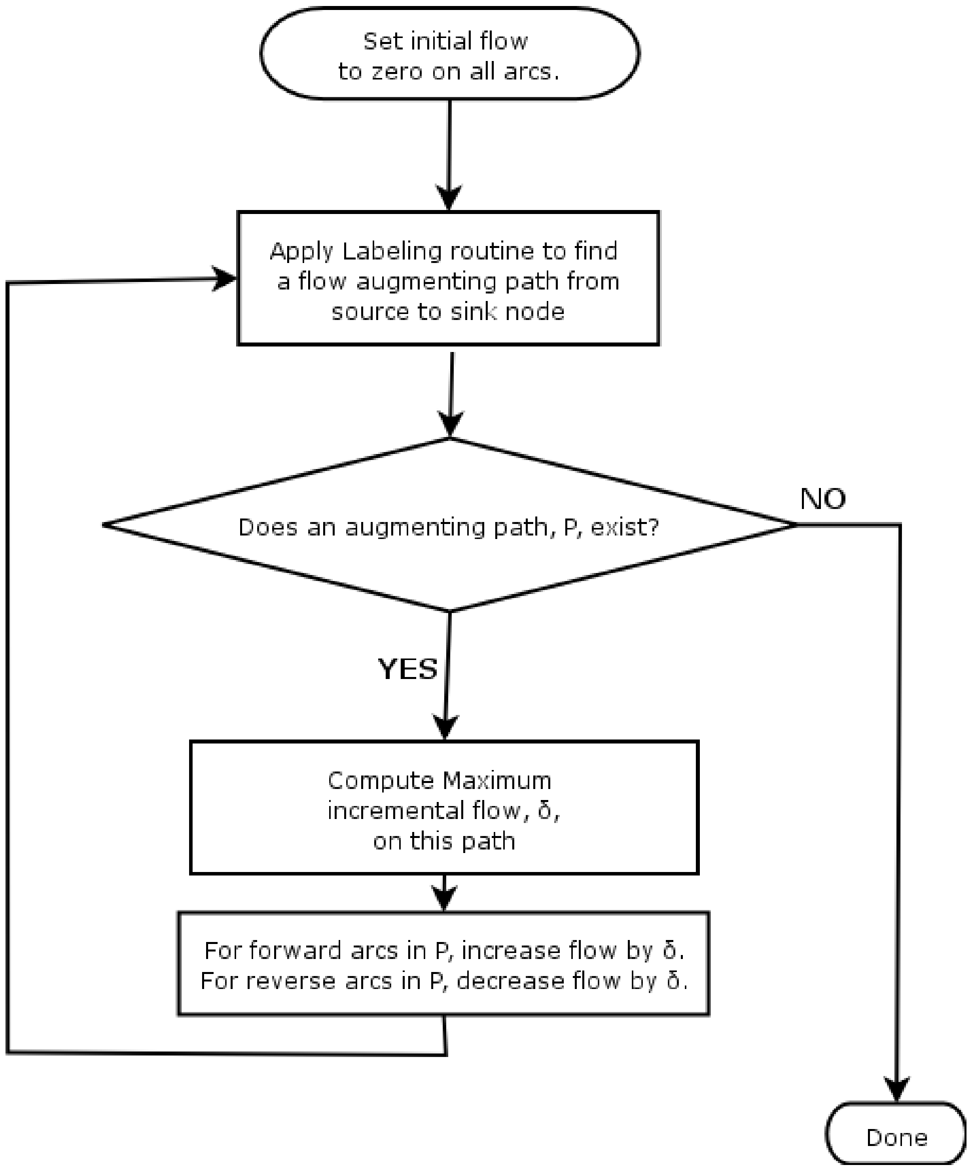


Fig. 13. Flow chart for the Ford-Fulkerson Algorithm

flow in all arcs in the network to zero and ascertains that capacity constraints and flow conservation at nodes are observed. If a flow augmenting path is found using the Labeling routine from the source to the sink node, the algorithm computes the maximum flow on that path. For arcs leaving the node or forward arcs, the flow is incremented by the maximum flow amount computed. For arcs entering the node or backward arcs, the flow is decremented by the the same computed amount. The Labeling routine is called to find another flow augmenting path and the entire process is repeated again. The algorithm terminates when all possible augmenting paths have been found.

## D. Implementation

A flexible and high-performance simulator was developed from scratch using C++. Some primary goals were to support features such as time-varying loads and multiple distributions for generator and line failure and repair rates. Additionally, given the computation-intensive nature of such simulations, fast simulation times were also desired.

### 1. Architecture

The simulator can be viewed as a harmonious collection of several independent modules. The Discrete Event module manages simulated time and keeps track of what events happen next. The Monte Carlo portion uses Monte Carlo techniques to simulate a stochastic model of the power system. In the stochastic model, each generator/line/load has two states: UP (functioning) and DOWN (failed). The Max-Flow module uses the augmentation algorithm to determine the amount of power flowing through every generator/line/load in the system. A fourth module is responsible for collecting system-level statistics. Lastly, the Visualization module creates a readable representation of the power system and collects statistics.

a. Discrete Event Simulator

The simulator uses a sequential simulation of the power system's stochastic model to collect a representative sampling of system states. To this end, it is necessary to manage and keep track of simulated time and events. However, the addition of time-varying loads and certain types of statistic-collection require artificial events to happen during the simulation. These events are artificial in the sense that they do not necessarily correspond to a physically-based action. Formally, the time model used in the simulator is a Discrete Event model, in which the simulation progresses as a sequence of instantaneous events.

In terms of the implementation, a priority queue is used to keep a list of events waiting to happen. The priority queue structure allows the next-event to be determined in $O(1)$ time. Associated with each event is the time of occurence (in hours), and a call-back method that will be executed upon occurence. Each object that schedules an event has its own call-back function to handle the event's occurence.

A subtle problem arose in the implementation of time-varying loads. Published data for time-varying loads assumes 52 weeks in a year. Unfortunately 365 is not a multiple of 7; some years actually contain a 53rd week. But a partial week would encumber time-varying load definitions and complicate other matters. This problem is avoided by assuming a year to contain 364 days. The inaccuracy of shorting the simulated year by a day appears to be very neglible compared to the typical uncertainty of the Monte Carlo simulation.

### b. Monte Carlo

For reasons previously mentioned, the handling of simulation time is kept separate from the Monte Carlo simulation of the power system. The components that are subject to failure and repair are generators and lines. Each generator and line is implemented as a object that interacts with the Discrete Event portion of the system. Each generator and transmission line (independently) schedules its own failure and repair events. This is sometimes referred to as an Agent-based approach. The failure distribution and repair distribution are specified (independently) for each component. Currently, fixed-interval (non-random), Exponential, and Log-Normal distributions are supported.

Each component (generator, line, load) maintains its own statistics. More specifically, each component monitors the durations in each of the UP and DOWN states, as well a count of the number of state changes. These two quantities permit availability and frequency of failure calculations to be computed.

### c. Max-Flow

A path-augmenting Max-Flow algorithm was implemented. It takes as inputs an adjacency matrix (representing the interconnection of components) and a list of maximum generation/transmission/demand capacity for each component. Constant and time-varying loads are supported and are evaluated at each time step. The Monte-Carlo state of the system determines which generators and lines are available for supplying power. Additionally, since Max-Flow algorithms generally have high computation-complexity, some novel techniques for accelerating the simulator are discussed later in the chapter.

A subtle detail arose in the implementation of the Max-Flow algorithm. Since the Max-Flow algorithm is inherently deterministic, for large classes of system states, result of the algorithm is the same for each class. For example, consider a system with two generators and two loads. Assume that each generator generates 1MW and each load demands 1MW. Since both loads are connected to both generators, a purely deterministic Max-Flow algorithm will cause only the second load to be unserved when either generator is down. The first load will always be served if either generator is up. Due to the symmetry of the system, one would generally expect both loads to have similar HLOLE/FLOL statistics. In reality, when there is insufficient generation to satistfy the load demand, rolling blackouts are typically used to evenly distribute the loss of load.

The order in which paths are discovered in augmenting-path Max-Flow algorithms is not easy to control. In this thesis, the problem of determinacy is solved by using a (pseudo) random number generator to randomize the element order of the adjacency matrix and capacity list provided to the MaxFlow algorithm. Randomizing the order of the elements has the effect of randomizing the order of augmenting paths discovered by the Max-Flow algorithm. This randomization gives symmetric results when such symmetry would be expected.

#### d. Collection of Statistics

A variety of statistics are collected for individual components as well to characterize system-wide behavior. Each generator and transmission line maintain durations of their respective Monte Carlo states as well as the number of state changes experienced since the beginning of the simulation. These are derived as follows:

$$E[YearlyDowntime] = \frac{Hours\ DOWN}{Number\ of\ years\ simulated} \tag{3.1}$$

$$E[Failure\ Frequency] = \frac{Num\ State\ Changes}{Number\ of\ years\ simulated} \tag{3.2}$$

Load elements collect the following:

$$E[HLOLE] = \frac{Hours\ UNSERVED}{Number\ of\ years\ simulated} \tag{3.3}$$

$$E[FLOL] = \frac{Num\ SERVED->UNSERVED State\ Changes}{Number\ of\ years\ simulated} \tag{3.4}$$

$$E[EUE] = \sum_{all\ events} (UNSERVED\ duration) * (Demand - Supply) \tag{3.5}$$

Note that in the case of time-varying loads, the load statistics are updated upon every change of any time-varying load. For all loads, system-level statistics are collected. At a particular time instance, the system is defined to be UNSERVED if at least one load is in an UNSERVED state. System-level HLOLE, FLOL, and EUE statistics are maintained. Also a statistic for convergence is maintained. At each simulated year, the coefficient of variation of the system-wide HLOLE is sampled and a running mean and standard deviation are updated:

$$COV = \frac{StdDev\,(HLOLE_{each\ year})}{Mean\,(HLOLE_{each\ year})} \tag{3.6}$$

e. Visualization

For visualizing simulation results, a popular open-source package named GraphViz is used to graphically display the power system being simulated and each component's associated statistics. Such a display permits easy visualization of the power system and allows quick verification of results. Secondly, a textual representation of the collected statistics is output as a Comma Separated File, which is readable by many popular programs such as Microsoft Excel.

## 2. Simulation Procedure

The following steps are carried out at every simulated instant:

1. Run Max-Flow.
2. Update per-load statistics with flows computed from Max-Flow.
3. Update system-level statistics.
4. If all Generators and lines are UP and all loads SERVED:
   (a) Advance simulation time to next event
   (b) Execute next event

   Else at least one component is DOWN / UNSERVED

   (a) Advance simulation time to next load-change

The simulation is run as long at least one of the following are true:

1. Coefficient of Variation for System HLOLE $<$ a theshold
2. Number of simulated time steps $<$ a threshold

When time-varying loads are present, the COV of the system HLOLE does not strictly decrease over simulated time. It is observed that near the beginning of the simulation, the COV varies wildly and even steadily increases. Thus, the second termination condition is intended to allow the simulation to progress far enough until the COV becomes strictly decreasing.

## 3. Performance Enhancements

### a. Early Prototype

An early prototype of the simulator was developed in Matlab. Matlab was initially chosen for its ease of use and for rapid prototyping. However, Monte-Carlo simulations for Markov Chains are highly control-intensive. Being an interpreted language, Matlab exhibited poor performance. A speedup of approximately 1000x was noticed by rewriting the simulator in C++.

### b. Time-Varying Loads

The inclusion of time-varying loads posed a significant problem. Implementing a Next-Event Monte Carlo simulation with time-varying loads poses additional performance challenges. This thesis proposes that such simulations can be efficiently executed by only simulating time-varying loads when some component in the system is either DOWN or UNSERVED. The implicit assumption is that when all generators and transmission lines are UP, and all time-varying loads at their maximum, all loads will be served. Under this assumption, the simulation can proceed in a Next Event manner until some component goes down. After such a transition, the system is simulated in a Sequential method until all components are back up. When compared to the purely sequential Monte Carlo technique, the proposed method results in a simulation speedup of approximately $\frac{HOURS\ PER\ YEAR}{SysHLOLE}$. For example, if the system HLOLE is 500 hours per year, then this technique has a speedup of approximately 17. This technique provides the greatest simulation speedup when used on highly reliable power systems.

### c. Max-Flow Cache/Precomputation

The Max-Flow algorithms generally have high computational complexity, and finding implementations for such is still an open problem. For the simulator described in this thesis, code profiling is performed using the *oprofiled* daemon. Measurements indicate that over most of the execution time is spent performing Max-Flow. Since the power system simulated has only a finite number of generators, lines, and loads, theoretically it would be possible to enumerate all possible generator and line states, and run Max-Flow on each one to determine which loads would be satisfied (assuming no varying loads). However, for a system with a total of $N$ generators and lines, there are $2^N$ possible states. Clearly, even for small systems ($< 100$ *elements*), it is intractable to enumerate all such states. However, since component failures are generally assumed to be independent, basic probability dictates that with extremely high probability, at most only a very small number of components may be simultaneously failed at any time.

Thus, this thesis proposes that high-performance relability simulations should use a caching strategy. Such a strategy tries to avoid running the Max-Flow algorithm multiple times on equivalent system states. If it is desired that all states in which $K$ or fewer failed elements are to be cached, then the number of states to cache is significantly less than $2^N$. Although more accurate simulations could involve a large number of time-varying loads, it is often the case that all such loads vary at the same points in time (seasonally, etc). Thus for caching strategies, the number of classes of time-varying loads is of primary concern rather than the total number of instances of time-varying loads. It should also be noted that the enumeration and caching of the limited set of systems states described can be performed off-line and in a parallel manner (e.g. distributed over a cluster of workstations).

# CHAPTER IV

# SYSTEM MODEL

## A. Component Model

For the reliability analysis of the power network, the components of the network are modeled on the failure and repair characteristics. All the components, generation supply and distribution lines, are represented by two-state Markov models of full capacity or zero capacity. Figure 14 shows a 2-state Markov model with failure and repair transition rates. The transition rate between the up state and down state is given by failure rate, $\lambda$. The repair rate, $\mu$, gives the transition rate from the down state to up state. Reliability assessment can be done by analytical methods or simulation techniques.

## B. Small System Illustration

The reliability indices, HLOLE and FLOL for a small power network is evaluated using:

1. Method 1 uses an analytical approach using state enumeration/Markov Models

2. Method 2 uses the developed simulation methodology


Fig. 14. 2-State Markov Model

Table I. Load Model

| Hour | Load (MW) |
|---|---|
| 1-4 | 49 |
| 4-8 | 101 |
| 8-12 | 151 |
| 12-16 | 101 |
| 16-24 | 49 |

The distribution system comprises of four generators. Each generator either has full capacity of 50 MW or 0 MW when failed. The failure rate, $\lambda$, for each generation is 0.1/day and the mean repair time is 24 hours.The daily load cycle is given by Table I.

### 1. Analytical Approach

The analytical approach uses state enumeration/Markov modeling to evaluate the system reliability indices of HLOLE and FLOL. The initial generation system model is expressed as a 15-state Markov model. The combined capacity of all four generators in operation is 200 MW and represents the all UP state. Outage of any one of the four generators results in total capacity of 150 MW, which are represented by 4 equivalent states. The failure rate is the transistion rate from all units UP to three units UP and one unit DOWN. Similarly, two generators in outage results in total system capacity of 100 MW represented by six equivalent states and so forth. Finally, all four generators in outage results in system capacity of 0 MW representing the all DOWN state.

Figure 15 shows the 15-state Markov model and the transition between the difer-

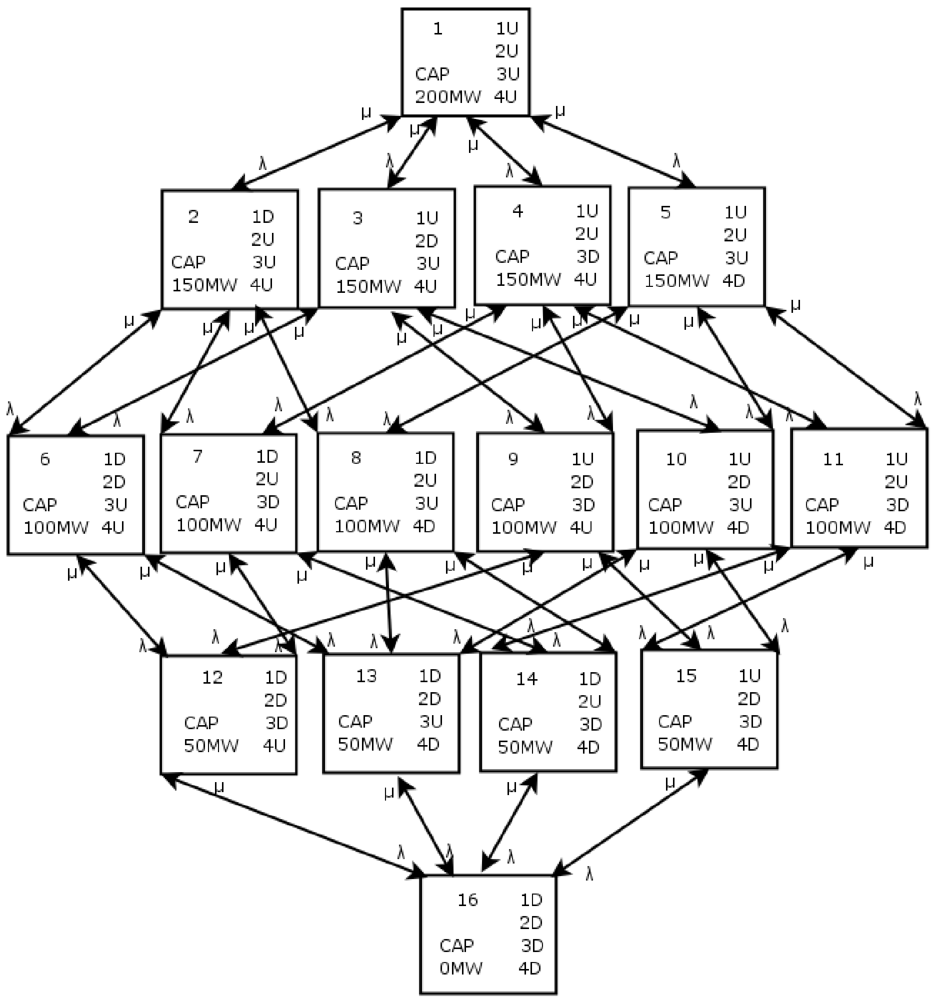


Fig. 15. 15-State Markov Model

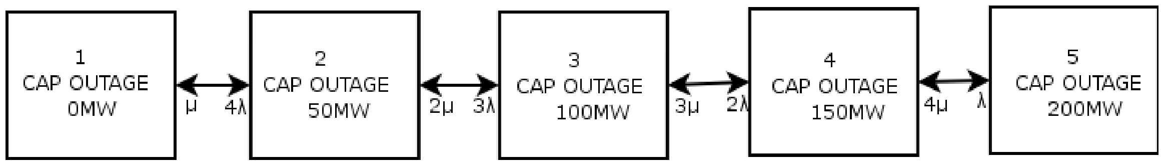


Fig. 16. 5-State Updated Model

ent capacity states. The probabilities of a generator to be up or down is given by:

$$P_{UP} = \frac{\mu}{\lambda + \mu} \tag{4.1}$$

$$P_{DN} = \frac{\lambda}{\lambda + \mu} \tag{4.2}$$

$$\tag{4.3}$$

Hence, the exact probabilities of each capacity level in terms of capacity outages are given by:

$$p_1 = p(CapOut = 0) = \frac{\mu^4}{(\lambda + \mu)^4} \tag{4.4}$$

$$p_2 = p(CapOut = 50) = \frac{4\mu^3\lambda}{(\lambda + \mu)^4} \tag{4.5}$$

$$p_3 = p(CapOut = 100) = \frac{6\mu^2\lambda^2}{(\lambda + \mu)^4} \tag{4.6}$$

$$p_4 = p(CapOut = 150) = \frac{4\mu\lambda^3}{(\lambda + \mu)^4} \tag{4.7}$$

$$p_5 = p(CapOut = 200) = \frac{\lambda^4}{(\lambda + \mu)^4} \tag{4.8}$$

Combining the equivalent states of each capacity level, the number of states are reduced from 15 to 5. The transition rates between the states are updated accordingly. Figure 16 gives the reduced model with updated transition rates between each capacity level. The cumulative probabilities for each state is given by:

$$
\begin{aligned}
P_5 &= P(CapOut >= 200) = p_5 = \frac{\lambda^4}{(\lambda+\mu)^4} && (4.9)\\
P_4 &= P(CapOut >= 150) = P_5 + p_4 = \frac{\lambda^4 + 4\mu\lambda^3}{(\lambda+\mu)^4} && (4.10)\\
P_3 &= P(CapOut >= 100) = P_4 + p_3 = \frac{\lambda^4 + 4\mu\lambda^3 + 6\mu^2\lambda^2}{(\lambda+\mu)^4} && (4.11)\\
P_2 &= P(CapOut >= 50) = P_3 + p_2 = \frac{\lambda^4 + 4\mu\lambda^3 + 6\mu^2\lambda^2 + 4\mu^3\lambda}{(\lambda+\mu)^4} && (4.12)\\
P_1 &= P(CapOut >= 0) = P_2 + p_1 = \frac{(\lambda^4+\mu)^4}{(\lambda+\mu)^4} = 1 && (4.13)
\end{aligned}
$$

Computation of Cumulative Frequencies:

$$
\begin{aligned}
F_1 &= p(CapOut >= 0) = 0 && (4.14)\\
F_2 &= p(CapOut >= 50) = p_2\mu = \frac{4\mu^4\lambda}{(\lambda+\mu)^4} && (4.15)\\
F_3 &= p(CapOut >= 100) = p_3(2\mu) = \frac{12\mu^3\lambda^2}{(\lambda+\mu)^4} && (4.16)\\
F_4 &= p(CapOut >= 150) = p_4(3\mu) = \frac{12\mu^2\lambda^3}{(\lambda+\mu)^4} && (4.17)\\
F_5 &= p(CapOut >= 200) = p_5(4\mu) = \frac{4\mu\lambda^4}{(\lambda+\mu)^4} && (4.18)
\end{aligned}
$$

Based on the hourly load data, a load cycle from 0 MW to 151 MW can be developed with discrete load level steps of 50 MW. For the discrete load levels, $L_k$:

$$
P(L_k) = \frac{Number\ of\ Hours\ where\ Load\ Capacity >= L_k}{Total\ Hours\ in\ the\ Interval} \quad (4.19)
$$

$$
F(L_k) = \frac{No.\ of\ transitions\ from\ Load < L_k\ to\ Load >= L_k}{Total\ Hours\ in\ the\ Interval} \quad (4.20)
$$

where $P(L_k)$ and $F(L_k)$ are the probability and frequency of load greater than or equal to $L_k$ MW. Tables II and III give the probabilities and frequencies of the capacity states generated from the generation system model and the load model.

Table II. Generation System Model Indices

| $C_k$ : Outage Level | $P_k$ : Prob.of Outage >= $C_k$ | $F_k$ : Freq of Outage >= $C_k$ |
|---|---|---|
| $C_1$ =0MW | $P_1$ =1 | $F_1 = 0$ |
| $C_2$ =50MW | $P_2$ =0.317 | $F_2 = 0.0114$/hr |
| $C_3$ =100MW | $P_3$ =0.044 | $F_3 = 0.0034$/hr |
| $C_4$ =150MW | $P_4$ =0.003 | $F_4 = 0.0003$/hr |
| $C_5$ =200MW | $P_5$ =0.00007 | $F_5 = 0.0000114$/hr |

Table III. Load Model Indices

| $L_k$ : Load Level | $P_k$ : Prob.of Load >= $L_k$ | $F_k$ : Freq of Transition from < $L_k$ to >= $L_k$ |
|---|---|---|
| $L_1$ =0MW | $P_1$ =1 | $F_1 = 0$ |
| $L_2$ =50MW | $P_2$ =0.5 | $F_2 = 0.04167$/hr |
| $L_3$ =100MW | $P_3$ =0.5 | $F_3 = 0.04167$/hr |
| $L_4$ =150MW | $P_4$ =0.167 | $F_4 = 0.04167$/hr |

Table IV. Margin Availability between Load Demand and Generation Capacity Levels

| State | Cap In Levels | Load Level of 150MW | Load Level of 100MW | Load Level of 50MW | Load Level of 0MW |
|---|---|---|---|---|---|
| 1 | 200MW | 50 | 100 | 150 | 200 |
| 2 | 150MW | 0 | 50 | 100 | 150 |
| 3 | 100MW | -50 | 0 | 50 | 100 |
| 4 | 50MW | -100 | -50 | 0 | 50 |
| 5 | 0MW | -150 | -100 | -50 | 0 |

Using the theory of Generation Reserve Model [12], the load demand and generation capacities can be combined to evaluate the margin between capacity generated versus load demand. A zero margin represents the state where load demand is exactly satisfied by generation. Above this margin load demand is satisfied and there is surplus generation, while below this margin loss of load occurs. The reliability indices HLOLE and FLOL can be computed using this technique. Table IV gives all possible margins for each state between capacity available and load demand.

Using the values from Table IV the probability and frequency of zero margin can be evaluated. HLOLE index is obtained from the product of this probability and number of hours in a year. The frequency of zero margin transition occurs from generation capacity changes as well as changes in the load cycle. FLOL is the sum of these two frequencies. System HLOLE is computed to be 591.23 hrs/yr. System FLOL value is 0.01625/hr.

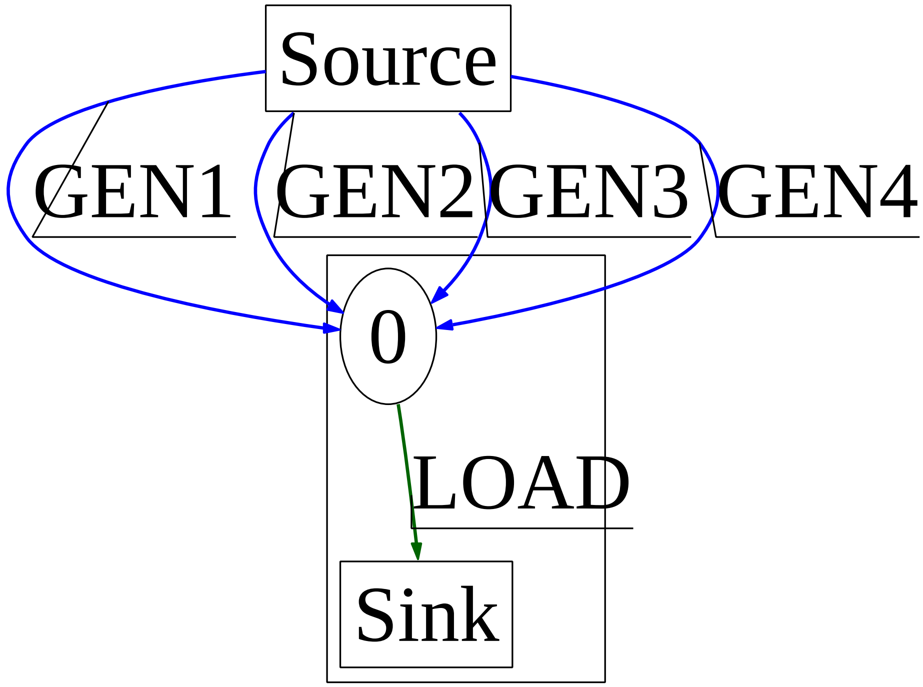


Fig. 17. Small System Graph Simulation

2. Developed Simulation Methodology

The reliability indices of the same network are computed and validated using the Monte Carlo-Max Flow based methodology developed in this thesis. The failure and repair history of the generators is created using using random variables with exponential distribution. Figure 17 shows the graphical view of the network flow for this system.

Based on convergence criterion of COV of 2.5 for the system HLOLE, the reliability indices are computed to be

1. System HLOLE of 591.14 hrs/yr

2. System FLOL of 142.25/yr or 0.01624/hr

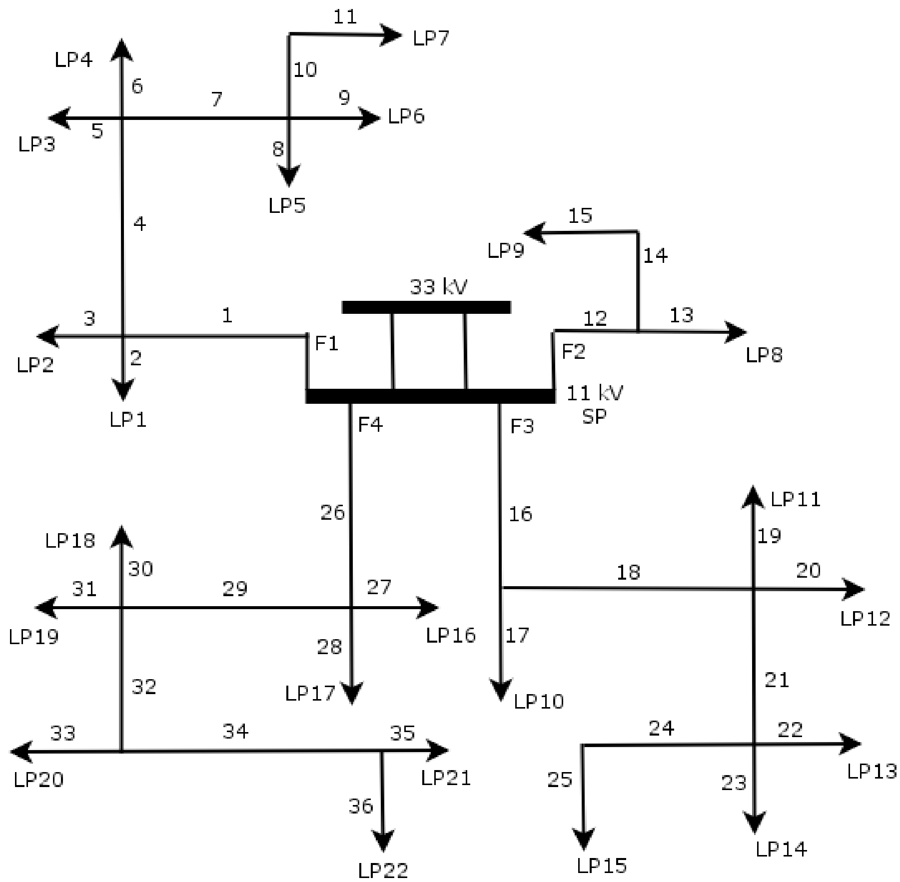


Fig. 18. Distribution System for RBTS BUS 2

## C. Distribution System Data

Two types of networks used for the case studies are shown in Figure 18 and 19. These are distribution systems connected to bus 2 and bus 4 of the RBTS [14] modified for DG analysis. Transformers and breakers are not included in the analysis. Both networks are configured to have two main supply points, each of capacity equal to half of the total energy supplied to the network.

For the analysis, different capacity levels for the supply points are considered. In addition, DG is included at various points in the networks. The network points with

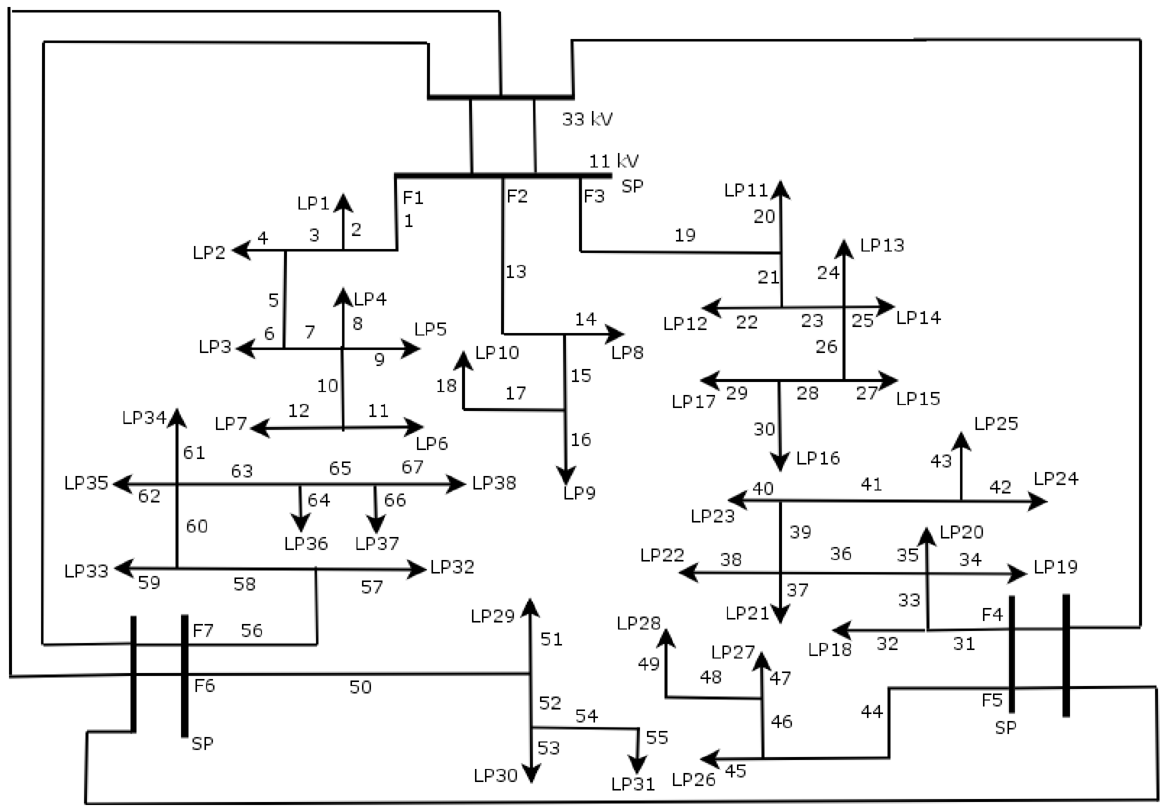


Fig. 19. Distribution System for RBTS BUS 4

loads having the highest indices for HLOLE and EUE are chosen for DG placment. Some of these cases will be analysed in the next chapter. The load points with lower reliability indices usually occur in the end of the feeders, farthest from the supply points.

## 1. Distributions for Component Models

For both the networks, the supply point failure rates and mean repair times are 4.42 failures/year and 20 hours respectively. Distribution line failure rates and mean repair times are 0.44 failures/year and 10 hours respectively. DG is modeled in the same manner as the main supply with the same failure rates and repair times.

The mean Time-To-Failure (TTF) for the generation and lines are assumed to have exponential distribution. The mean Time-To-Repair (TTR) for the generation and lines are assumed to have log-normal distribution. The relation between the transition times and transition rates is given by

$$\lambda = \frac{1}{TTF} \tag{4.21}$$

$$\mu = \frac{1}{TTR} \tag{4.22}$$

Exponential distributions have cumulative distribution functions of the form:

$$P(X <= x) = F_x(x) = 1 - e^{-\rho x}; \tag{4.23}$$

with mean $\frac{1}{\rho}$.

For simulation using Monte Carlo methods, it is useful to generate random numbers from an exponential distribution. For example, it is a standard practice to model a component's TTF using an exponential distribution, especially when rate of failure is assumed to be relatively constant (no aging). Generally, most software languages provide a floating-point random number generator that is uniform on $[0, 1)$. For a random number $z$ taken from a uniform distribution on $[0, 1)$, a realization of an exponentially distributed random variable $X$ with parameter $\rho$ can be obtained by :

$$x = -\frac{\ln(z)}{\rho} \tag{4.24}$$

Similarly, it is a commonly believed that a log-normal distribution is a good representation of repair time. Log-normal distributions with parameters $(M, S)$ are defined by:

$$P(X = x) = \frac{1}{S\sqrt{2\pi}x} e^{-\frac{(\ln(x)-M)^2}{2S^2}} \tag{4.25}$$

$$\begin{aligned} mean &= e^{M+\frac{S^2}{2}} && (4.26) \\ variance &= e^{S^2+2M}\left(e^{S^2}-1\right) && (4.27) \end{aligned}$$

A variety of techniques exist [15] for computing realizations of a normal distribution using a uniform random number generator. Furthermore, a realization, $x$, of a log-normal distribution with parameters $(M, S)$ can be obtained from a realization, $z$, of a standard normal distribution by computing:

$$x = e^{M+Sz} \tag{4.28}$$

## 2. Load Models

The different load categories and classifications are obtained from the RBTS network data [14]. Bus 2 has four types of customers viz. residential, small user, government/institution and commercial. Bus 4 has three types of customers viz. residential, small user and commercial. All the load points of the two networks are classified as one of these customer types. The total peak load for Bus 2 is 20 MW, while the total peak for Bus 4 is 40 MW.

For the load modeling, hourly time-varying characteristics is incorporated. The weekly loads for 52 weeks are expressed as percentages of the annual peak load for the different customer types mentioned above. Figure 20 gives the load cycle for all the weeks in a year. An electric utility data [16] is used for the percent weekly, daily and hourly values.

Figure 21 gives the daily loads for seven days as percentages of the weekly peak. Finally, the hourly load data as percentages of the daily peak as weekday or weekend for summer, winter and spring/fall weeks as shown in Figures 22, 24 and 23 respectively.

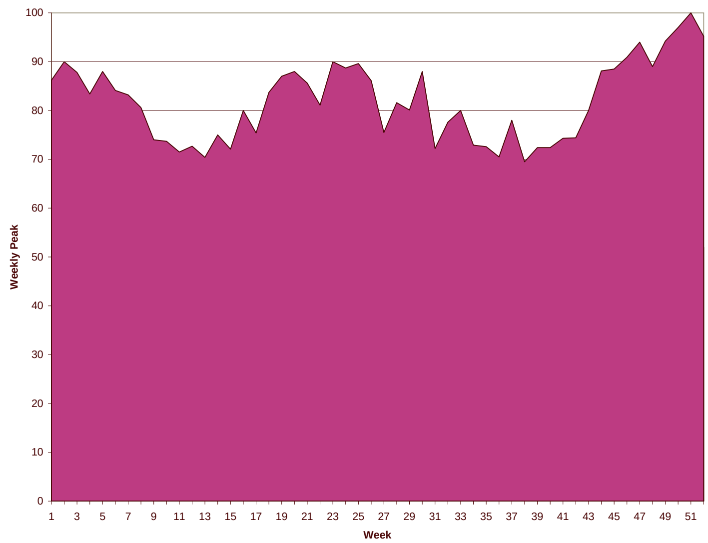


Fig. 20. Weekly Load as Percent of Annual Peak

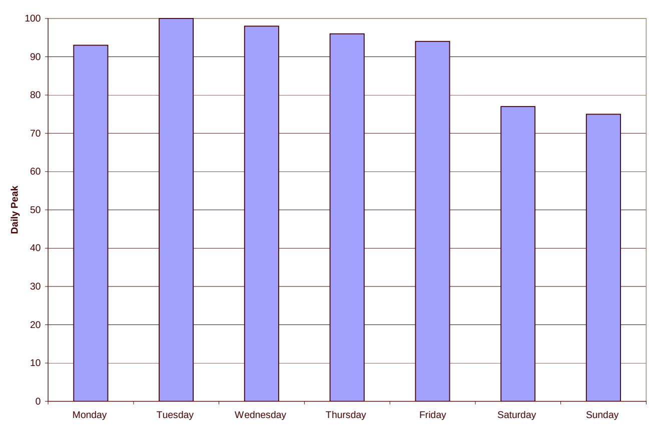


Fig. 21. Daily Load as Percent of Weekly Peak

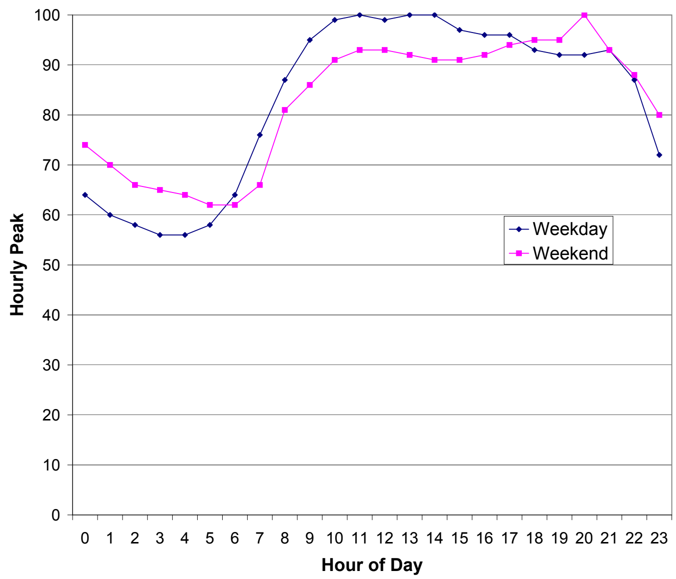


Fig. 22. Hourly Load as Percent of Daily Peak in Summer Weeks

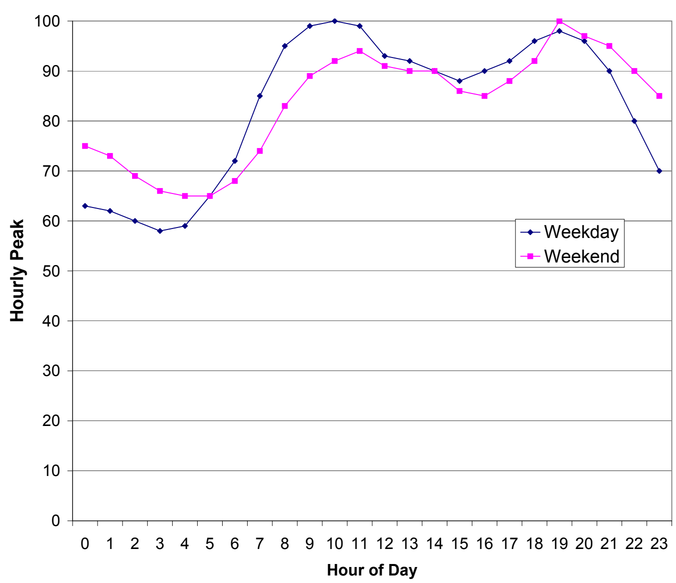


Fig. 23. Hourly Load as Percent of Daily Peak in Spring/Fall Weeks

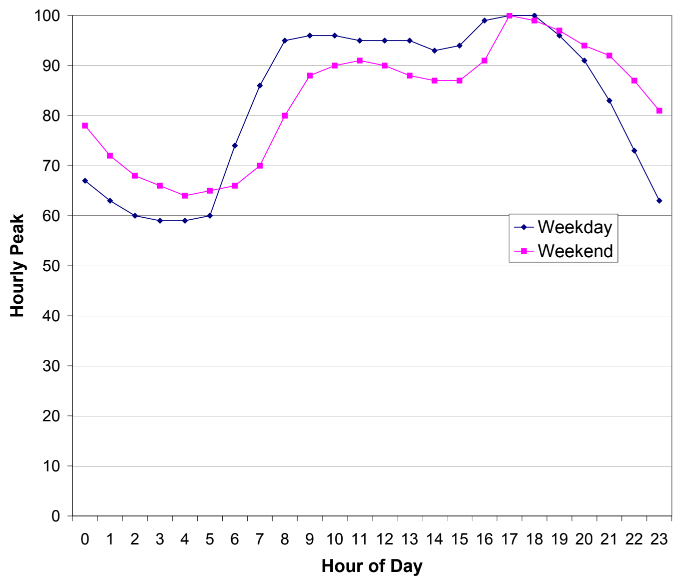


Fig. 24. Hourly Load as Percent of Daily Peak in Winter Weeks

# CHAPTER V

# CASE STUDIES

A wide range of scenarios are simulated and studied to assess the reliability of the modified distribution networks of the RBTS Bus 2 and Bus 4 described in the previous chapter. Using the Monte Carlo-Max Flow methodology, distributions for component models and time varying load characteristics described in the earlier chapters, the networks are simulated and various reliability indices are evaluated.

## A. BUS 2 Reliability Results

The first study considers the Bus 2 network. This network has 4 feeders, 36 distribution lines and 22 load points. A statistic for convergence, COV, described in chapter III is maintained. At each simulated year, the coefficient of variation of the system-wide HLOLE is sampled and a running mean and standard deviation are updated. The system level statistics for all the cases are recorded when the sampled HLOLE reaches a COV of 2.5. However, in order to compare the individual load point indices, convergence of system HLOLE doesn't necessarily imply convergence of load point statistics. This is due to the fact that the system converges faster than the individual load points. Hence, a convergence criterion based on the load point EUE index is used for collecting load statistics and for comparing the specific load status. A COV of 2.5 gives a 95 percent confidence margin for the obtained statistics.

The graphical illustration for all these cases represent the actual distribution network links with added nodes to show the interconnections between distribution lines, supply points and loads. Lines in blue indexed G01 etc represent generation supply arcs, lines in brown indexed T01, T02 etc represent distribution arcs and green lines represent load points indexed as L01, L02 etc. DG arcs are also represented by blue line but with index DG01, DG02 etc. To run the Max-Flow module all generation arcs including DG arcs are connected to the source node and all load arcs terminate into the sink node. The nodes into which DG arcs terminate represent the actual placement location for the DG.

### 1. Supply Capacity of 20 MW

In this case, the total supply capacity is assumed to be 20 MW, which is exactly equal to the maximum peak load. Two generators with identical failure and repair characteristics, each of capacity 10 MW, are used to represent the supply points to the distribution network. Loss of load may occur from either generation or line outage. For this particular case, outage of any one of the generators reduces the system supply to 10 MW or half the peak load demand. Hence, loss of load occurs frequently since there is no redundancy in the total generation supply.

The graphical flow overview for the simulated network for the base case is shown in Figure 25. The reliability indices are divided into two categories; system level indices and individual load point indices. The system EUE index is the sum of all the individual load point EUE indices. However, the system HLOLE is not the sum of the load point HLOLE. Any instance of loss of load in the network counts as one instance of system loss of load irrespective of the number of load points unsupplied. Hence, one load point unsupplied or multiple load points unsupplied at the same instance of time are equivalent where system HLOLE is concerned.

The load point indices, HLOLE and EUE are the worst at the end of feeder locations since these loads are supplied from the longest chains of distribution lines, the failure rates of which add up. A good choice for DG placement should improve the load point reliability of such loads. In the next case, 1 DG is added as standby supply at node 9 of the Bus 2 network and simulated as shown in Figure 26. This

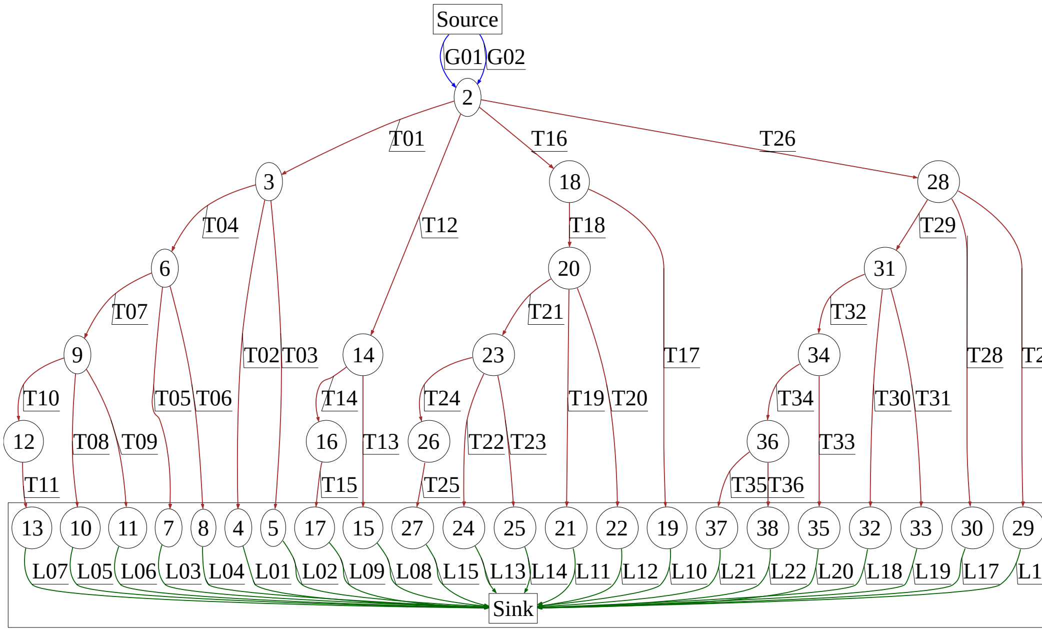


Fig. 25. Bus 2 Network with Supply of 20 MW

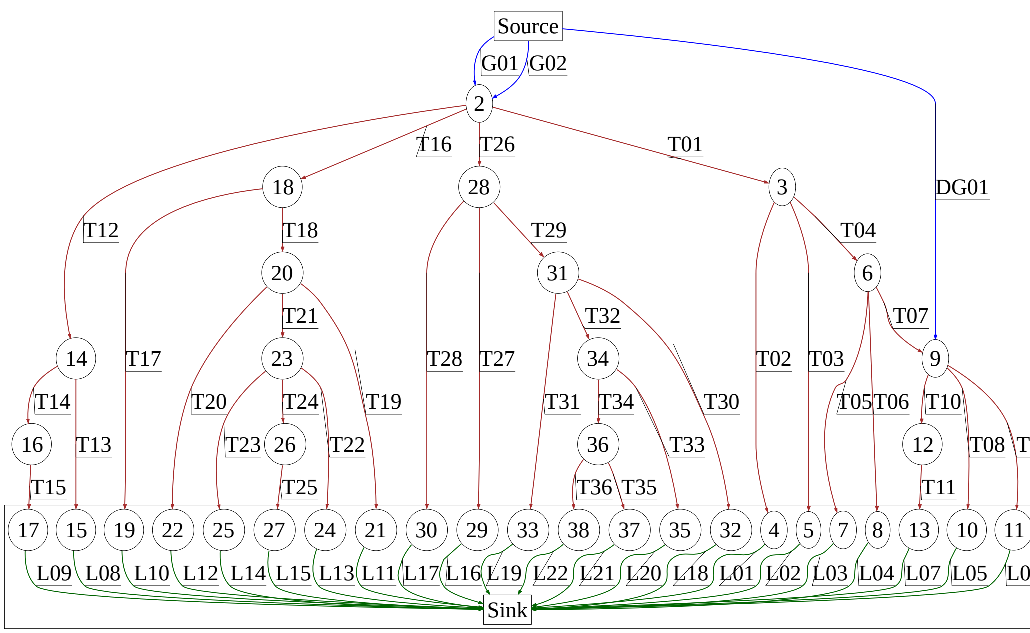


Fig. 26. Bus 2 Network with Supply of 20 MW and 1 DG

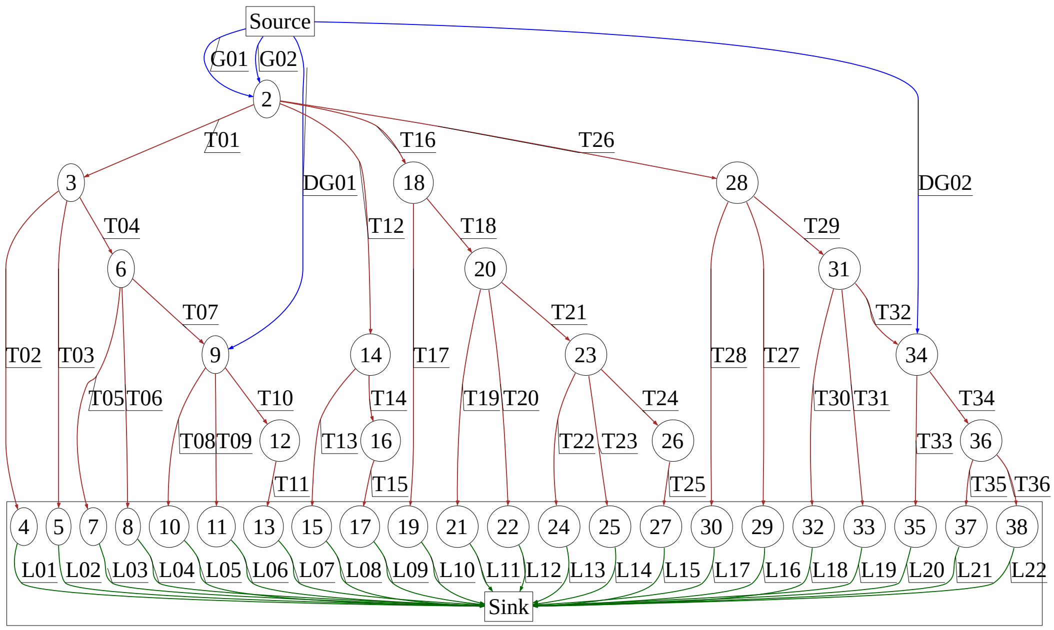


Fig. 27. Bus 2 Network with Supply of 20 MW and 2 DG

Table V. Comparison of System Level Indices for Bus 2 Supply of 20 MW

| Reliability Index | No DG | 1 DG | 2 DG |
|---|---|---|---|
| EUE | 966.47 | 661.29 | 352.10 |
| HLOLE | 408.31 | 380.85 | 299.76 |
| FLOL | 31.1 | 31.1 | 28.2 |

node is located near the end of Feeder 1 and supplies load points 5, 6 and 7 in the event of system generation outage or failure of lines upstream that would feed these loads. In the base case, these loads have significantly higher HLOLE and EUE. The DG capacity is 3 MW which is slighly higher than the sum of demands of the three load points. In addition to improving the individual indices for load points directly fed by the DG, the system level statistics show significant improvement. The next case studies the same network with 2 DG connected at nodes 9 and 34 respectively as shown in Figure 27. The DG at node 34 offers standby support to load points 20, 21 and 22. Table V gives the system level EUE, HLOLE and FLOL indices for Bus 2 network at generation of 20 MW. The base case is compared with the cases where 1 and 2 DG are added. The EUE index shows the most significant improvement and is the best index of assessment. Figure 28 compares the load point EUE for all 22 loads in the network for the three cases.At some load points where the EUE index is very low to begin with,addition of DG doesn't cause much difference. The load points directly benefitting from DG show significant drop in EUE. In the event of any system generation outage, the available generation can be assigned to the loads where DG is not connected, thereby improving the reliability of loads that originally experienced high loss.

### 2. Supply Capacity of 30 MW

In power networks, it is common practice to have some margin between the supply and maximum load demand. Hence, in the cases considered in this section, the total supply capacity is assumed to be 30 MW. Each of the two equivalent generators now supply 5 MW more than the previous case. It is probable that in the event of loss of any one generation, the load demand may still be met by the standing generation of 15 MW as long as the minimum load demand in its time varying cycle is not above 15

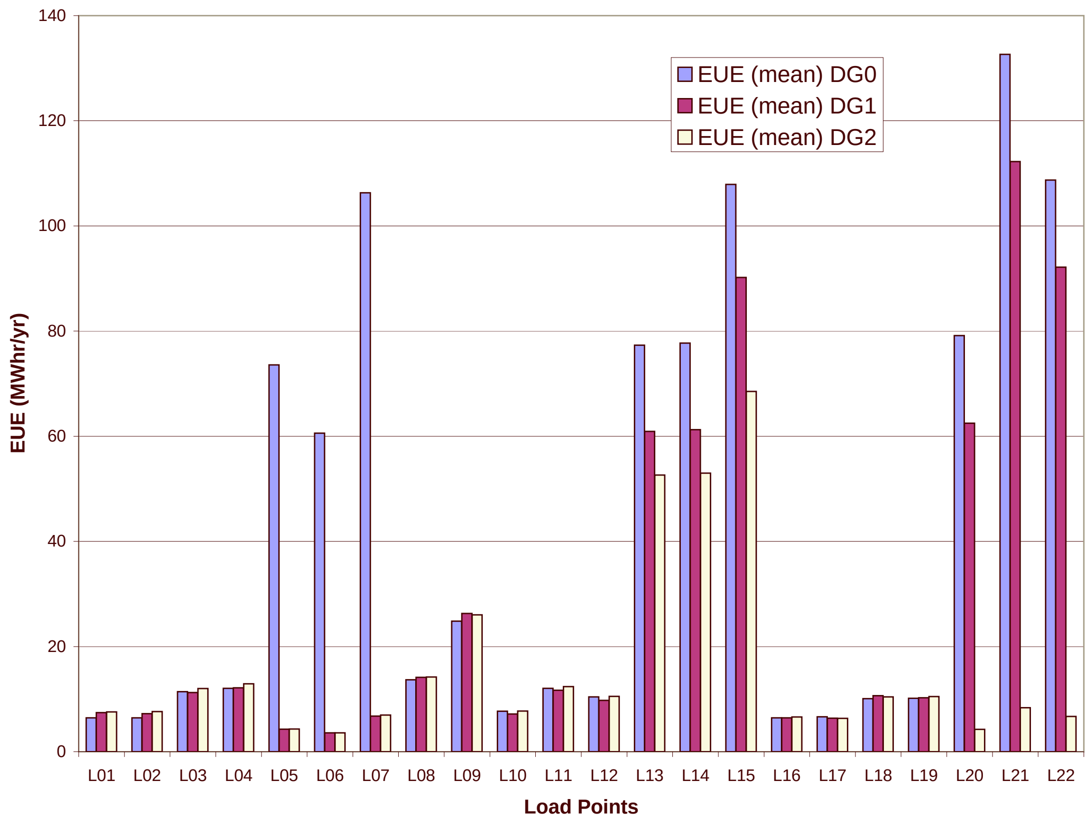


Fig. 28. Load Point EUE Indices for Bus 2 Supply of 20 MW

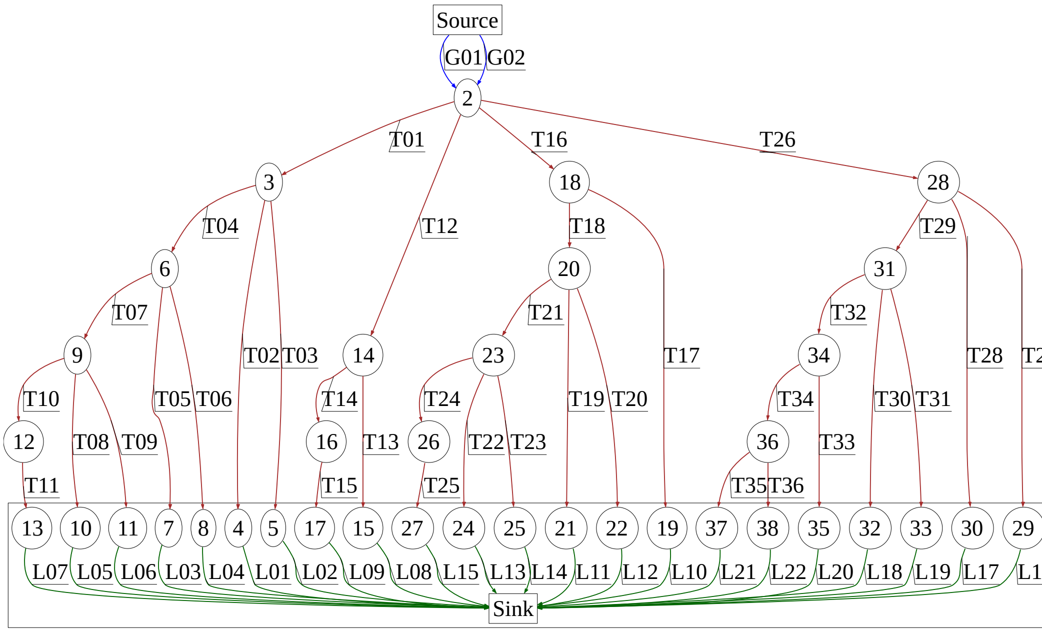


Fig. 29. Bus 2 Network with Supply of 30 MW

MW. Also, with the surplus generation, the line failure rates have greater influence on the loss of load and unserved energy indices. This is not true in the previous section when the supply, when fully available, exactly satisfied the demand and the generation failure rate being significantly greater than line failure rate, dictated the status of the load.

Figures 29, 30, 31 show the graphical overview of the distribution network at supply capacity of 30 MW for the base case, for 1 DG added at node 9 and for 2 DG added node 9 and 34 of the network respectively. For the three cases, Table VI compares the EUE, HLOLE and FLOL indices. Firstly, it is observed that for the base case, EUE index is about a third of the previous base case due to surplus supply. The HLOLE and FLOL indices are reduced as well. However, the addition of DG result in comparable reductions in system EUE and HLOLE indices.

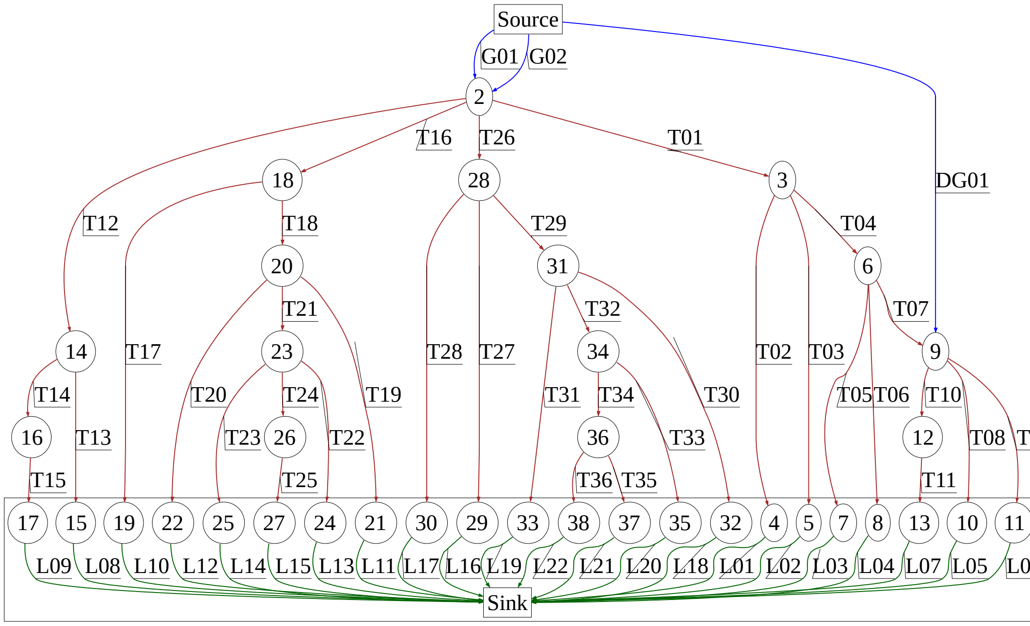


Fig. 30. Bus 2 Network with Supply of 30 MW and 1 DG

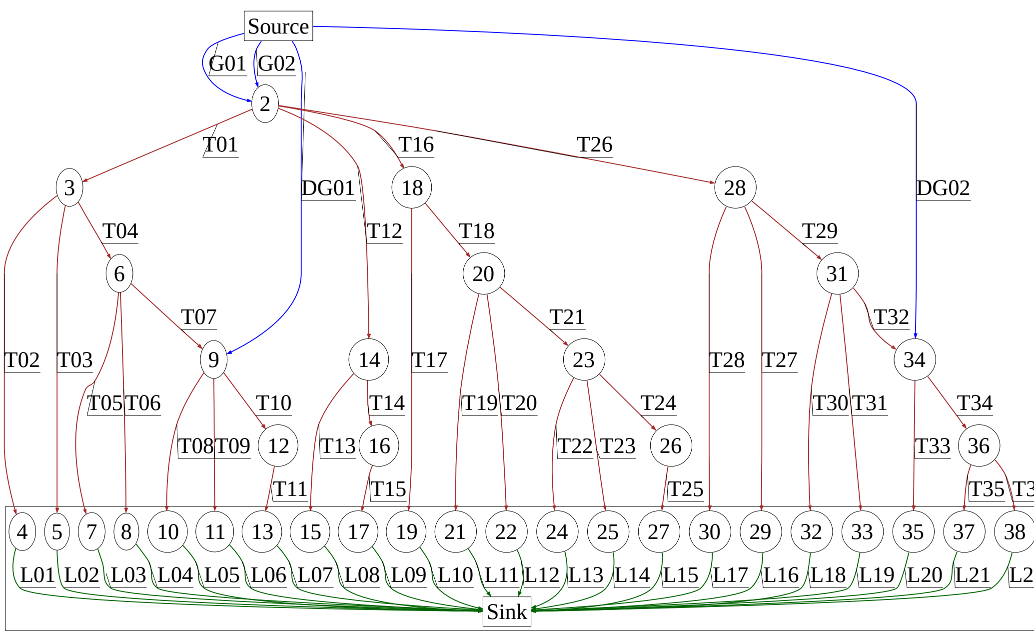


Fig. 31. Bus 2 Network with Supply of 30 MW and 2 DG

Table VI. Comparison of System Level Indices for Bus 2 Supply of 30 MW

| Reliability Index | No DG | 1 DG | 2 DG |
|---|---|---|---|
| EUE | 316.98 | 245.21 | 205.69 |
| HLOLE | 261.78 | 214.85 | 198.44 |
| FLOL | 23.7 | 17.6 | 14.8 |

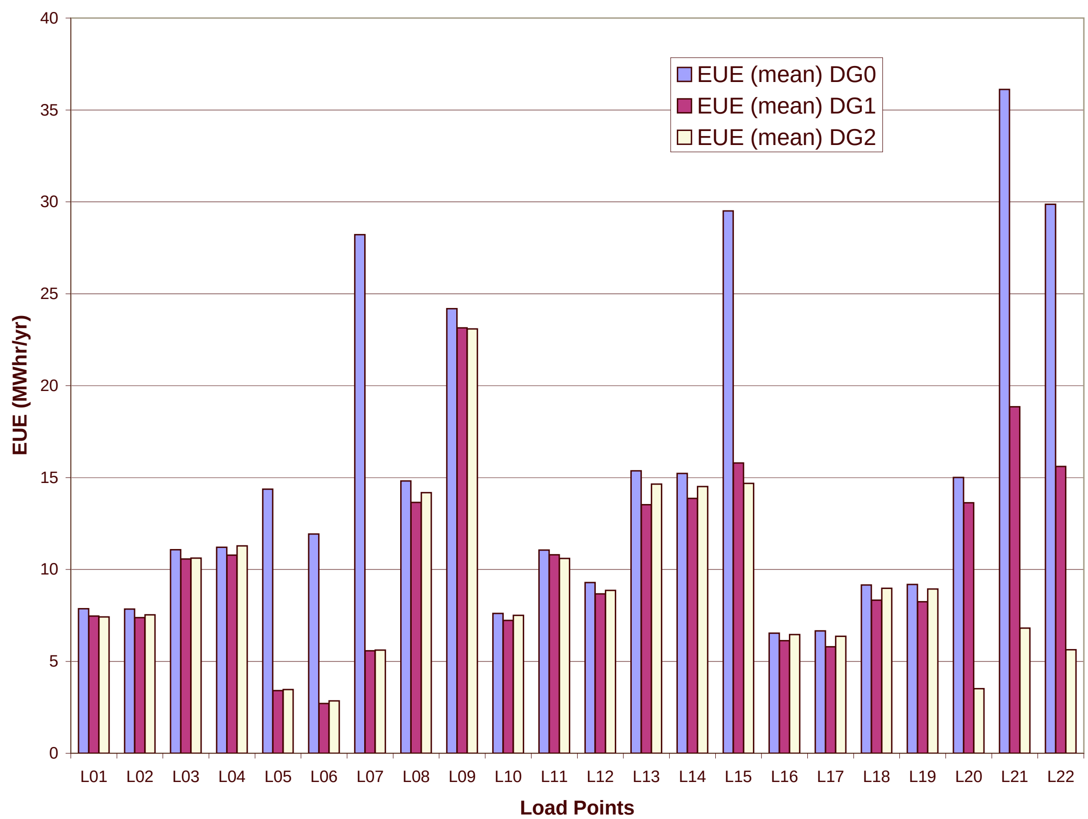


Fig. 32. Load Point EUE Indices for Bus 2 Supply 30 MW

The differences in the load point EUE for the three cases is recorded in Figure 32. The load point EUE values are significantly lower than those in the previous section. Loads directly served by the DG, in the event of supply outage, show similar improvements from the base case as seen in the previous section. However, for all other loads that experienced the most outage, addition of DG does not produce much difference. This is again due to the fact that generation outage is a less influencing factor than line outage when there is surplus generation. Hence, for loads that are not directly fed from DG, loss of load is caused more often by line outage than generation outage and the reliability indices stand unaffected.

### 3. Supply Capacity of 40 MW

The final case for the Bus 2 distribution network considers supply of 40 MW. The two equivalent generators each supplying 20 MW are individually capable of handling the maximum load demand of the entire network. Hence, loss of one generator will never result in loss of load in the network even if the load demand at that instance is the maximum in the cycle. Loss of load can only occur in the event that both generators are in outage or any distribution line is failed.

Figures 33, 34, 35 illustrate the simulated network state with Supply of 40 MW in the base case and with 1 and 2 DG added to it. Table VII gives the comparison of the reliability indices for the three cases. The significant difference from the previous cases is seen in the system indices. Although, the addition of DG causes some lowering in these indices, the improvement is significantly less than that in the previous sections. Comparison of individual load point EUE values given in Figure 36 shows DG to still have positive effect on the load points directly supplied from it. However, for all other cases, the individual load point indices have no correlation with the presence of the DG since the capacity of DG is negligible compared to the high surplus of the Supply.

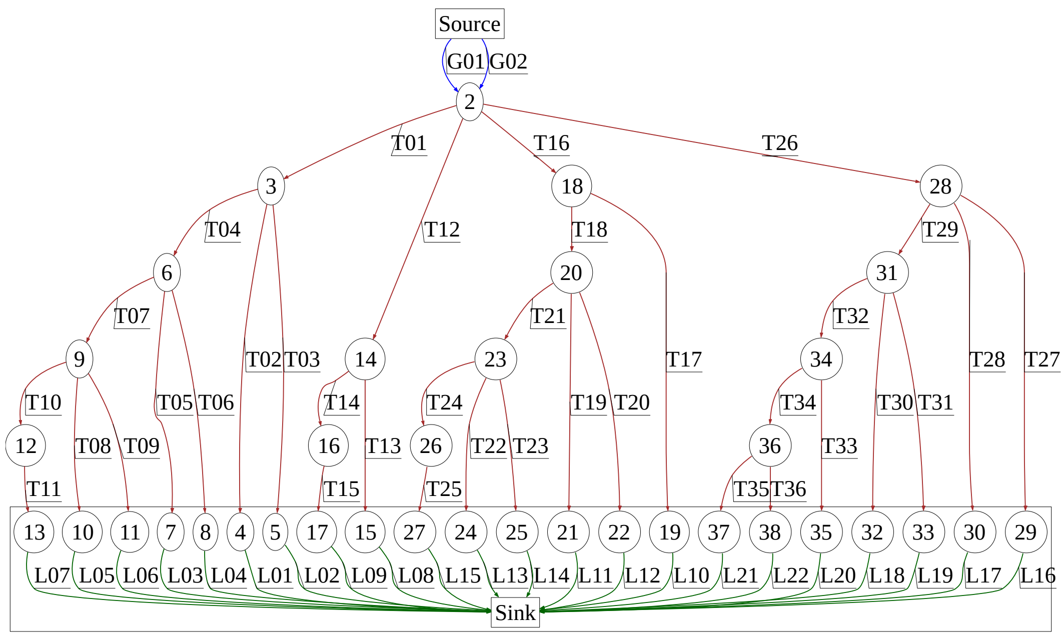


Fig. 33. Bus 2 Network with Supply of 40 MW

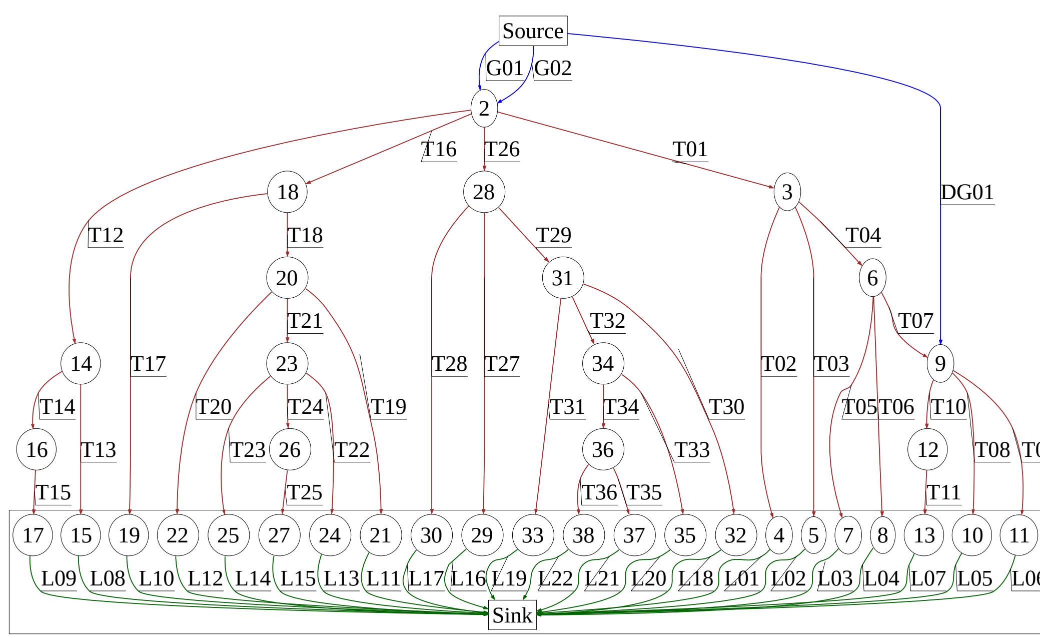


Fig. 34. Bus 2 Network with Supply of 40 MW and 1 DG

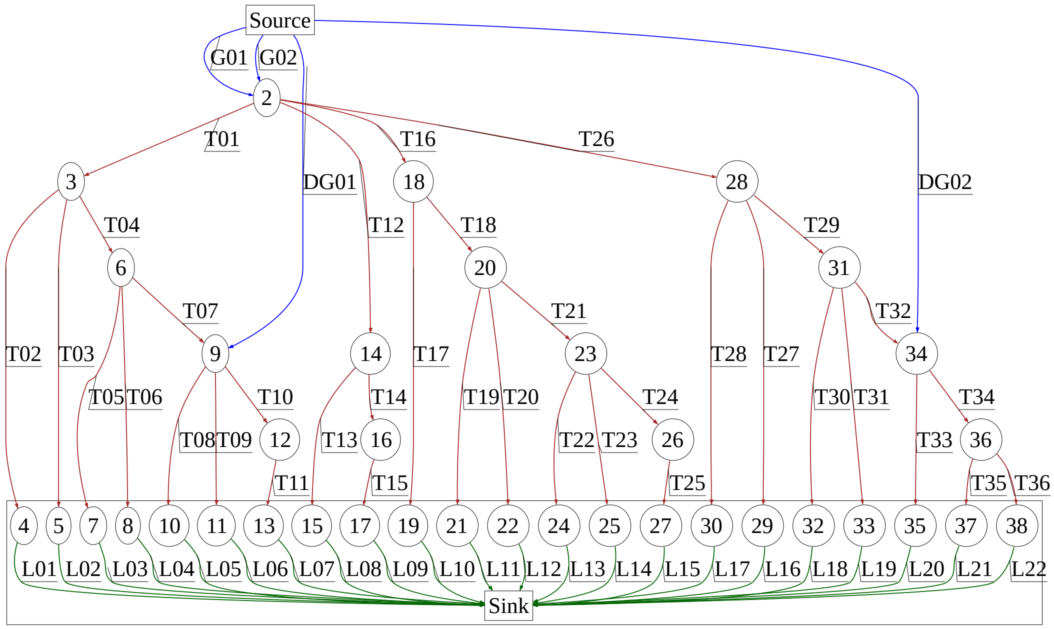


Fig. 35. Bus 2 Network with Supply of 40 MW and 2 DG

Also, the failure rate of the DG is now greater than the rate of overlapping failure of the two system generators. Hence, in such a case, other that small improvement to directly connected load points, addition of DG has no positive effect to the distribution network.

Table VII. Comparison of System Level Indices for Bus 2 Supply of 40 MW

| Reliability Index | No DG | 1 DG | 2 DG |
|---|---|---|---|
| EUE | 267.89 | 250.06 | 197.88 |
| HLOLE | 213.73 | 207.26 | 197.21 |
| FLOL | 15.7 | 15.3 | 14.5 |

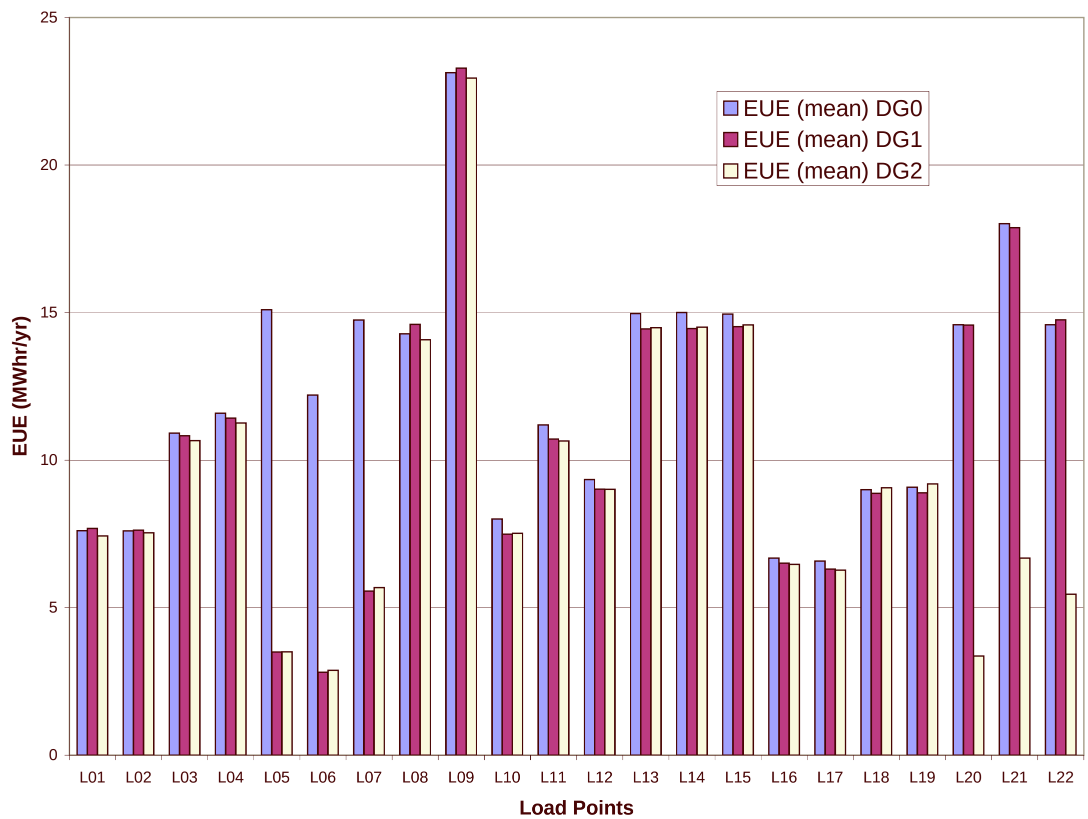


Fig. 36. Load Point EUE Indices for Bus 2 Supply 40 MW

## B. BUS 4 Reliability Results

The distribution system of the RBTS Bus 4 is also evaluated by the developed methodology. Some modifications are made to the network as described in the previous chapter. Different capacity levels for supply are considered in a similar fashion to the Bus 2 network. Bus 4 is a larger network than Bus 2 with 7 feeders, 67 distribution lines and 38 loads. For more details of the networks please refer to the previous chapter.

### 1. Supply Capacity of 40 MW

The maximum system load demand for this network is 40 MW. The first study assumes the supply capacity to be exactly equal to this maximum demand. The system supply is represented by two generators each of capacity half of the total supply. Hence, loss of load occurs when any one of the generators or lines are failed. The generator failure rate assumed to be ten times the line failure rate has the greatest influence on the status of load satisfaction. Figure 37 gives the graphical overview of the simulated network.

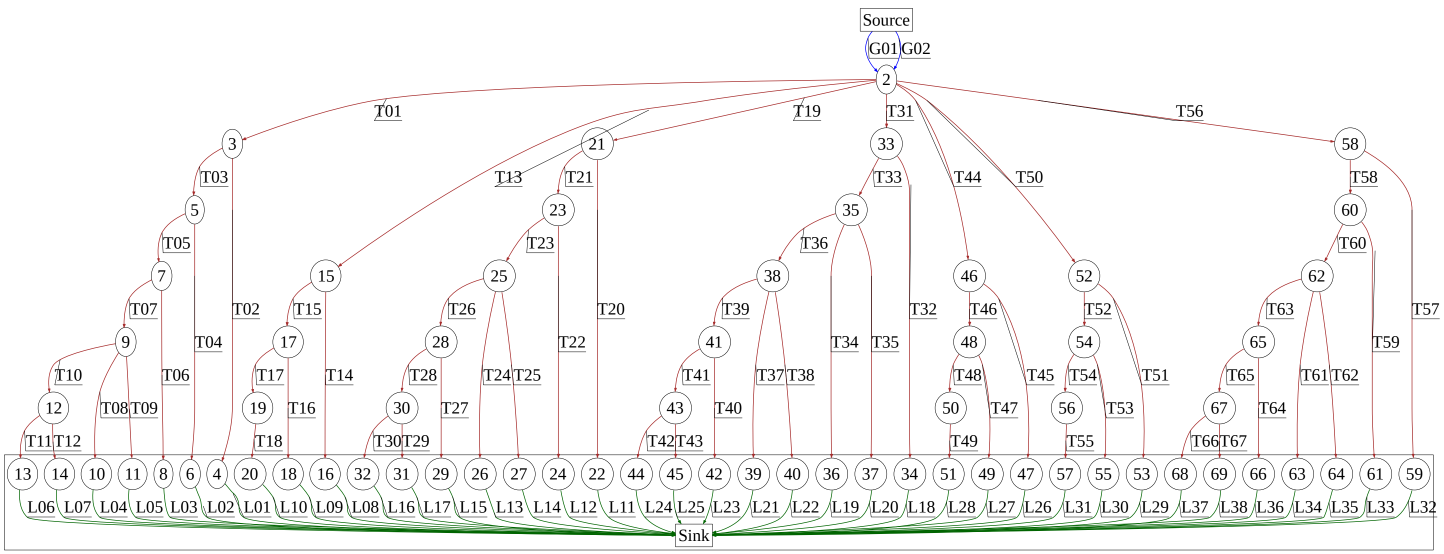


Fig. 37. Bus 4 Network with Supply of 40 MW

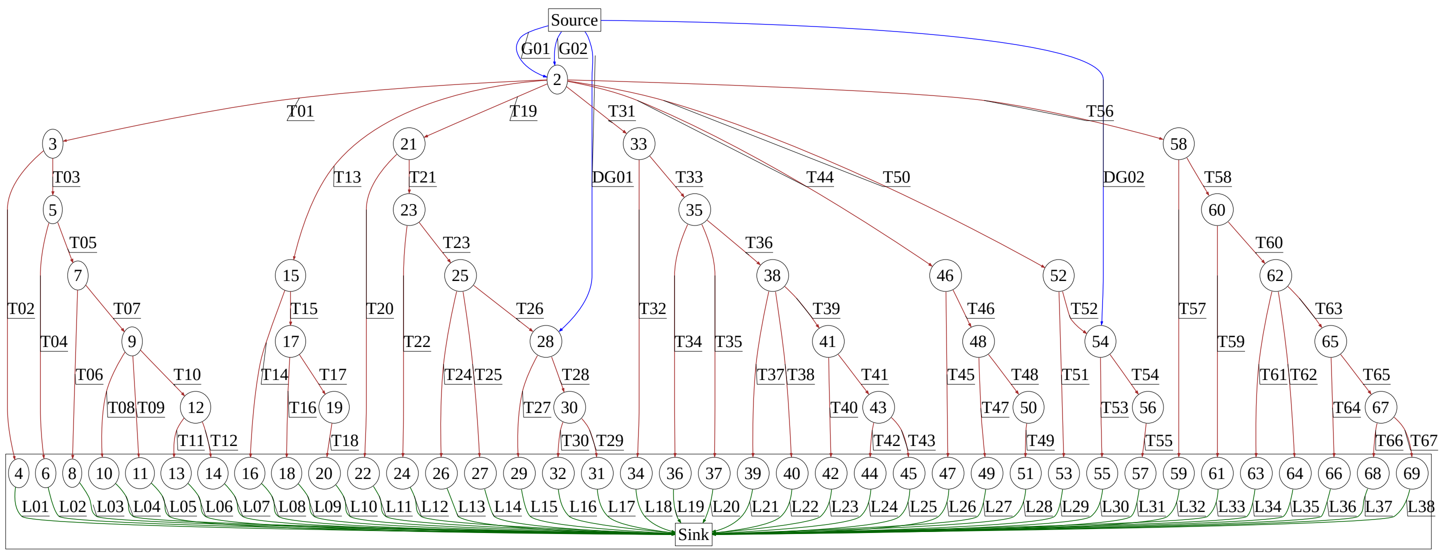


Fig. 38. Bus 4 Network with Supply of 40 MW and 2 DG

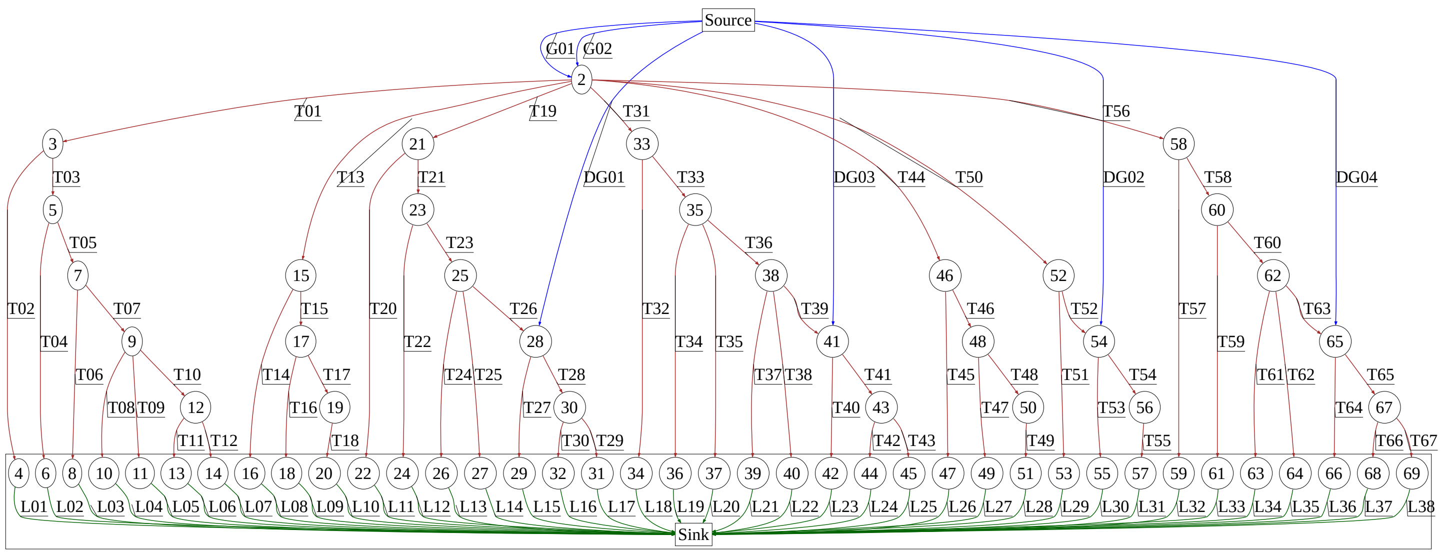


Fig. 39. Bus 4 Network with Supply of 40 MW and 4 DG

Table VIII. Comparison of System Level Indices for Bus 4 Supply of 40 MW

| Reliability Index | No DG | 2 DG | 4 DG |
|---|---|---|---|
| EUE | 2107.32 | 1197.13 | 682.15 |
| HLOLE | 598.04 | 519.95 | 461.56 |
| FLOL | 43.8 | 41.69 | 39.2 |

The load points at the end of the feeders that have the most number of distribution arcs show the highest indices for EUE and HLOLE. Hence, DG operating in standby mode is added to the network to assess the system reliability. First case considers addition of 2 DG at nodes 28 and 54. These nodes connect the load points farthest from the supply. In addition, node 54 is connected to loads that have the highest individual peak load of the entire network. Hence, these load points experience much higher loss of load than others. Installed DG at node 28 will offer standby support to loads 15, 16 and 17 and DG at node 54 supplies to loads 30 and 31. The capacity of the DG at node 28 is 2.5 MW and the capacity of the DG at node 54 is 4.1 MW. These values are the sum of the peak demand of the supplied load points. Figure 38 shows the flow network of the Bus 4 distribution network with 2 DG.

Since the network is large, there are several load points which experience substantially high outage indices. Hence, the final case considers addition of 4 DG to the network. As in the previous case, there are 2 DG each at node 28 and 54 as well as a DG at nodes 41 and 65 of capacity 2.5 MW. Node 41 connects to load points 23, 24 and 25 and node 65 connects to load points 36, 37 and 38 as shown in Figure 39. Comparison of system reliability indices in Table VIII show marked improvement when 2 and 4 DG are added. In this case, where outage of any one of the system generators result in loss of load, the load point EUE significantly improve on addition

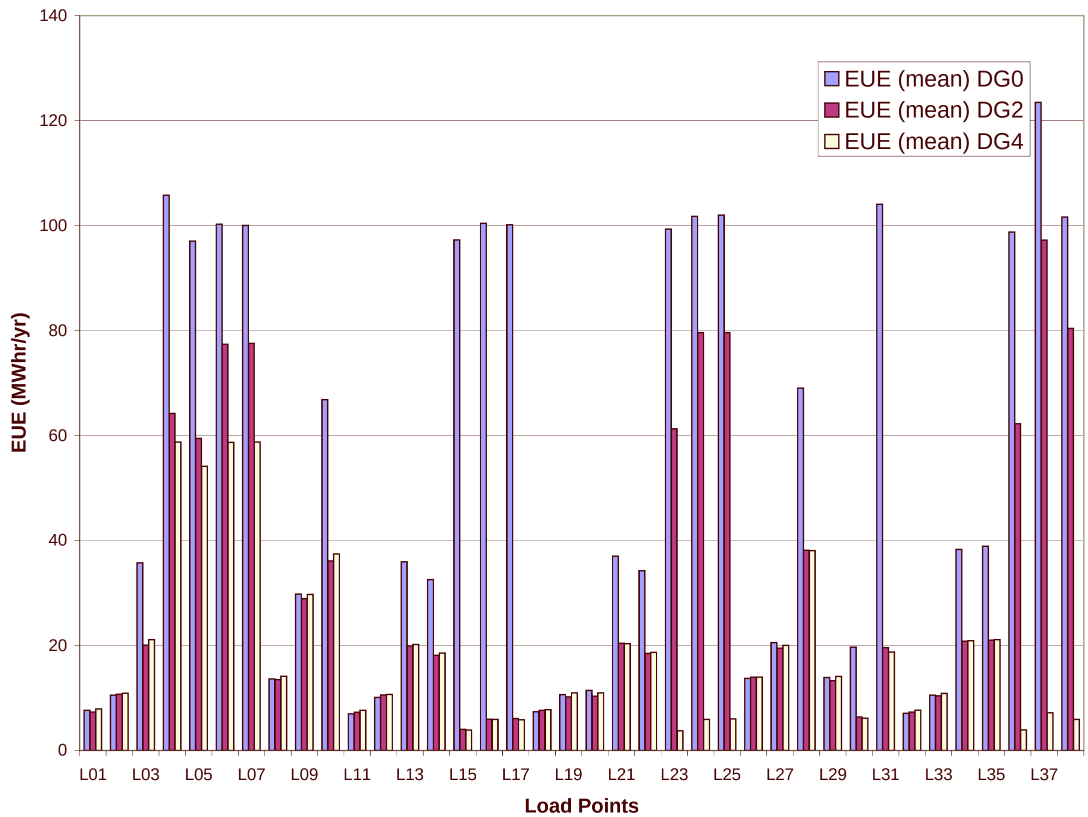


Fig. 40. Load Point EUE Indices for Bus 4 Supply 40 MW

of DG. All load points, whether they are supplied by the DG or not show significantly reduced EUE in Figure 40. This again is attributed to the fact that limited available generation is fed to loads not connected to DG which is a lesser number than the number of loads to be supplied during partial generation outage and no DG. Hence, reliability of all load points are improved with addition of DG when the supply outage is the main factor for loss of load.

### 2. Supply Capacity of 60 MW

The next case considers the Bus 4 network with an increased supply capacity of 60 MW. The two generators now supply 30 MW each. If the minimum point in the system load cycle is less than 30 MW, then outage of any one of the generators does not result in loss of load.

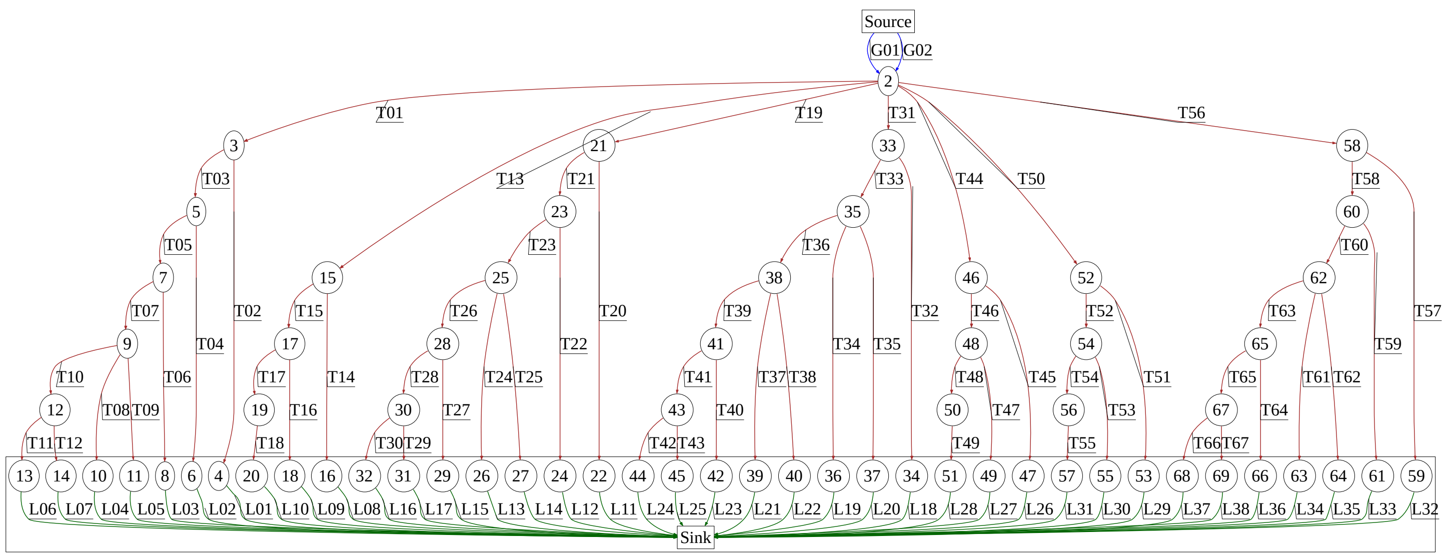


Fig. 41. Bus 4 Network with Supply of 60 MW

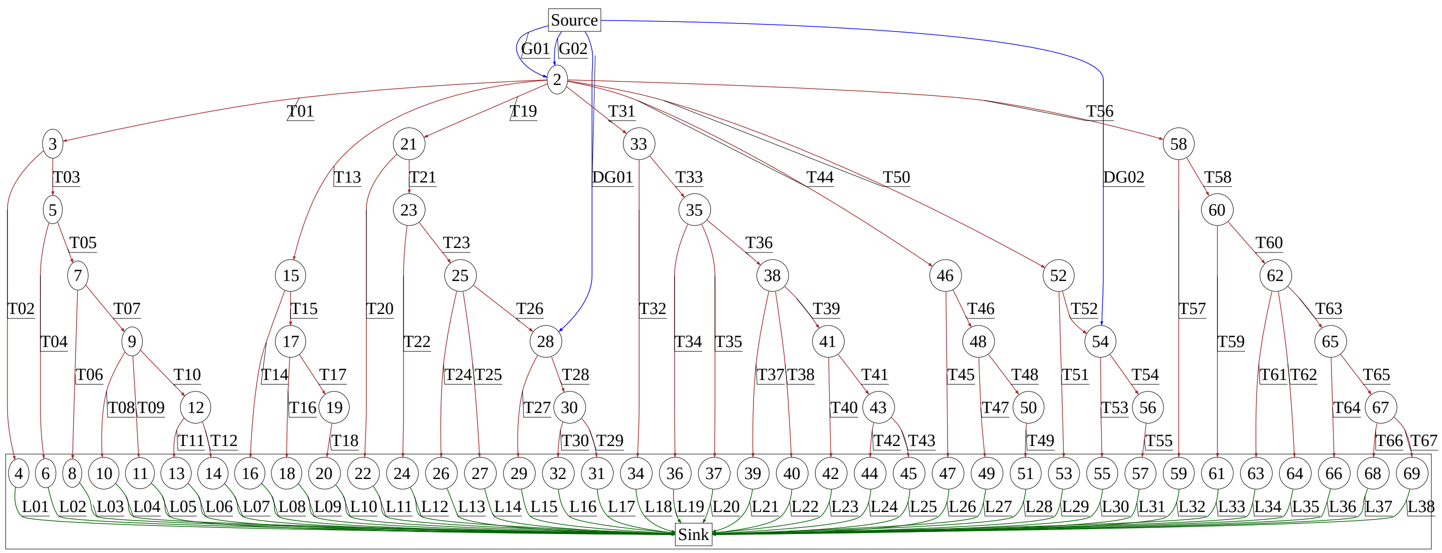


Fig. 42. Bus 4 Network with Supply of 60 MW and 2 DG

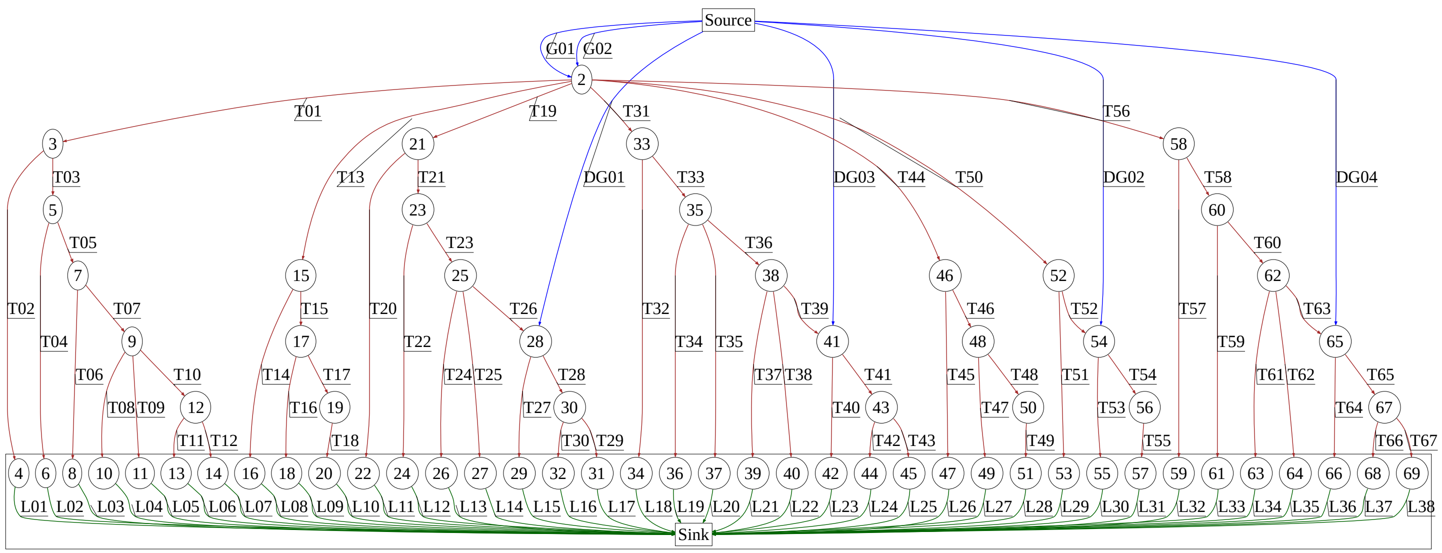


Fig. 43. Bus 4 Network with Supply of 60 MW and 4 DG

Table IX. Comparison of System Level Indices for Bus 4 Supply of 60 MW

| Reliability Index | No DG | 2 DG | 4 DG |
|---|---|---|---|
| EUE | 700.64 | 587.81 | 453.17 |
| HLOLE | 431.99 | 392.79 | 362.15 |
| FLOL | 35.5 | 29.5 | 27.5 |

Figures 41, 42, 43 show the graphical flow networks for the base case, 2 DG added and 4 DG added to the network at the same nodes as the previous cases. Table IX compares the reliability indices for no DG, 2 DG and 4 DG in the Bus 4 distribution network. As observed in the Bus 2 cases, the EUE index shows significant reduction from the lower generation case. The addition of DG improves the indices in the same manner as in the case of Supply of 40 MW. For the load point reliability indices, the loads directly supplied from the DG show improvement in unserved energy. This is demonstrated in Figure 44.

### 3. Supply Capacity of 80 MW

Finally, the last case for the Bus 4 network considers the capacity of supply to be double the maximum system load. Irrespective of the magnitude of load, any one of the two generators is capable of supplying the entire system load. Loss of load due to generation occurs only when both system generators are in outage in the same time.

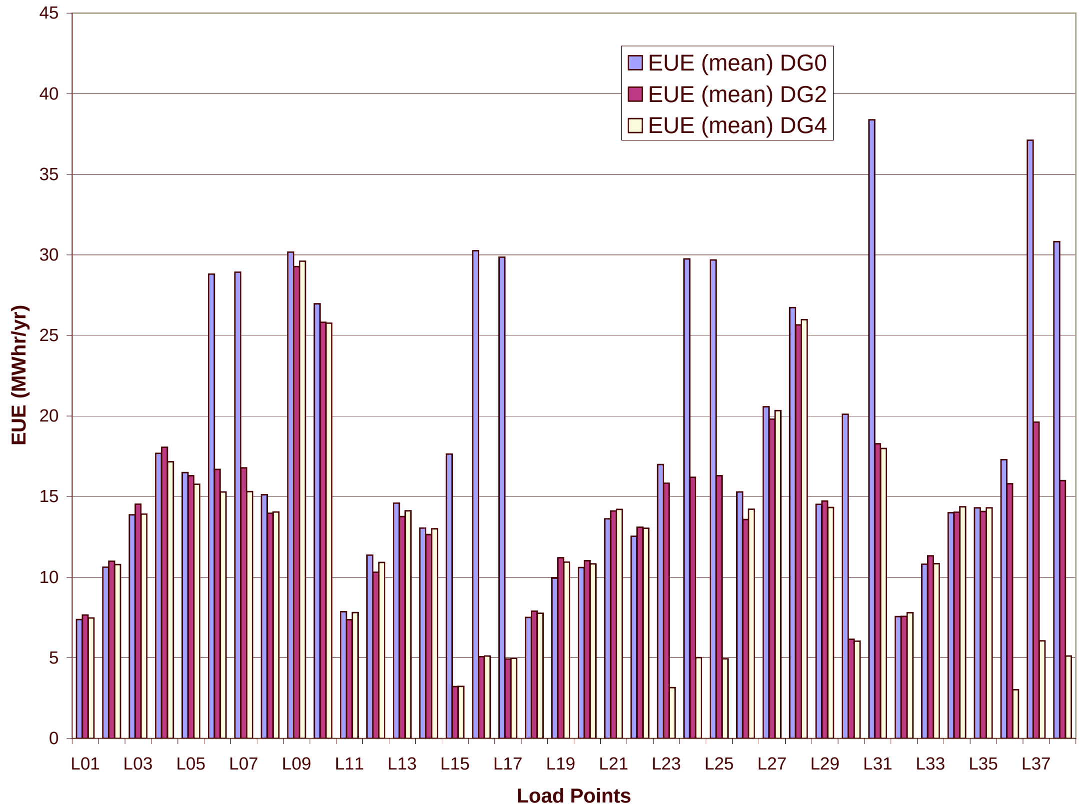


Fig. 44. Load Point EUE Indices for Bus 4 Supply 60 MW

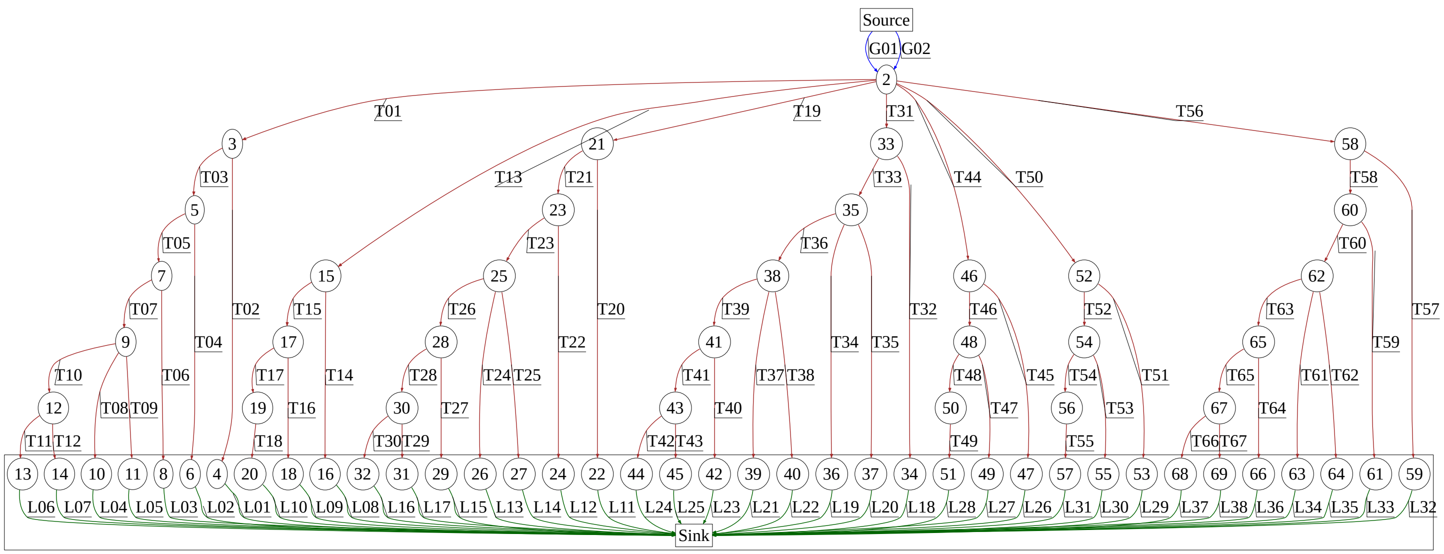


Fig. 45. Bus 4 Network with Supply of 80 MW

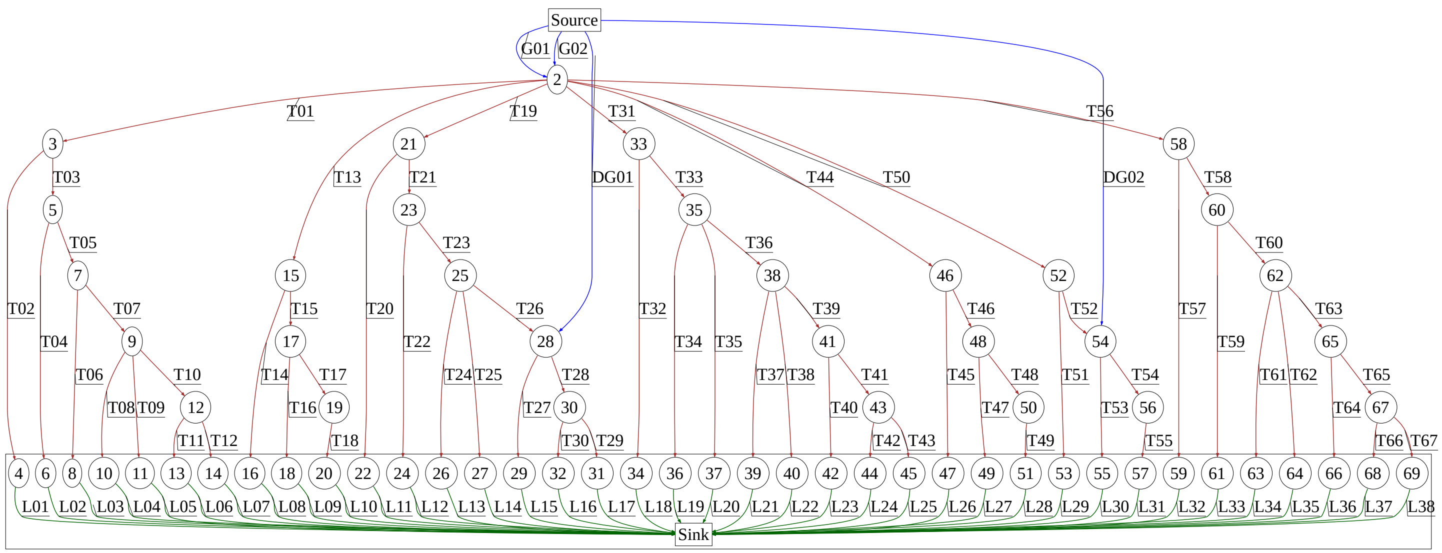


Fig. 46. Bus 4 Network with Supply of 80 MW and 2 DG

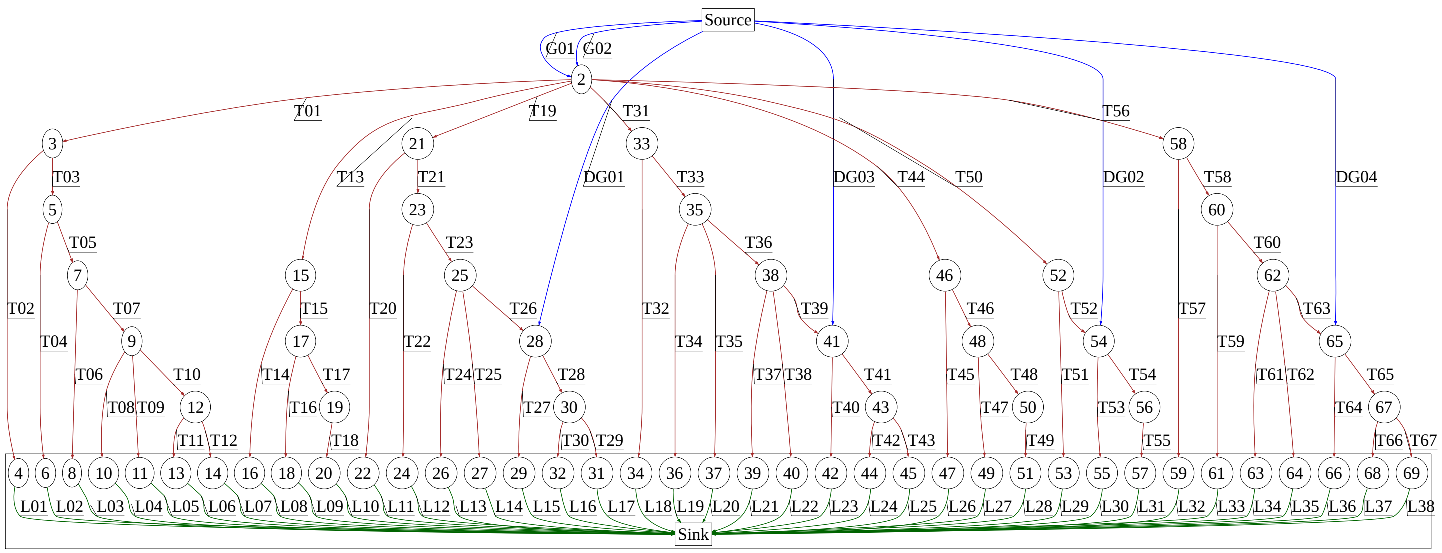


Fig. 47. Bus 4 Network with Supply of 80 MW and 4 DG

Table X. Comparison of System Level Indices for Bus 4 Supply of 80 MW

| Reliability Index | No DG | 2 DG | 4 DG |
|---|---|---|---|
| EUE | 562.22 | 555.38 | 478.33 |
| HLOLE | 383.04 | 373.53 | 371.58 |
| FLOL | 28.3 | 27.7 | 27.4 |

Figures 45, 46, 47 show the graphical flow networks for the base case, 2 DG added and 4 DG added to the network. Comparison of the system reliability indices in Table X show relatively low improvement on the already reduced indices by adding DG to the network. This is also demonstrated in the trend of the load point EUE for the three cases in Figure 48. Since there already exists a large redundancy in the supply capacity as opposed to the load demand, the combined input of the DG is negligible to impact the load indices with the exception of loads directly fed by DG when both system generators or upstream line fail.

In conclusion, analysis of the two different distribution networks validates general reliability assessments for load points and overall system. EUE is shown to be the most sensitive index of reliablity and the relative influence of DG in a network is seen be closely related to the capacity redundancy of the supply. Loads connected to DG always demonstrate improved reliability, however the improvement of other load point reliability indices depend on whether the generation outage or line outage is the principle contributor for loss of load.

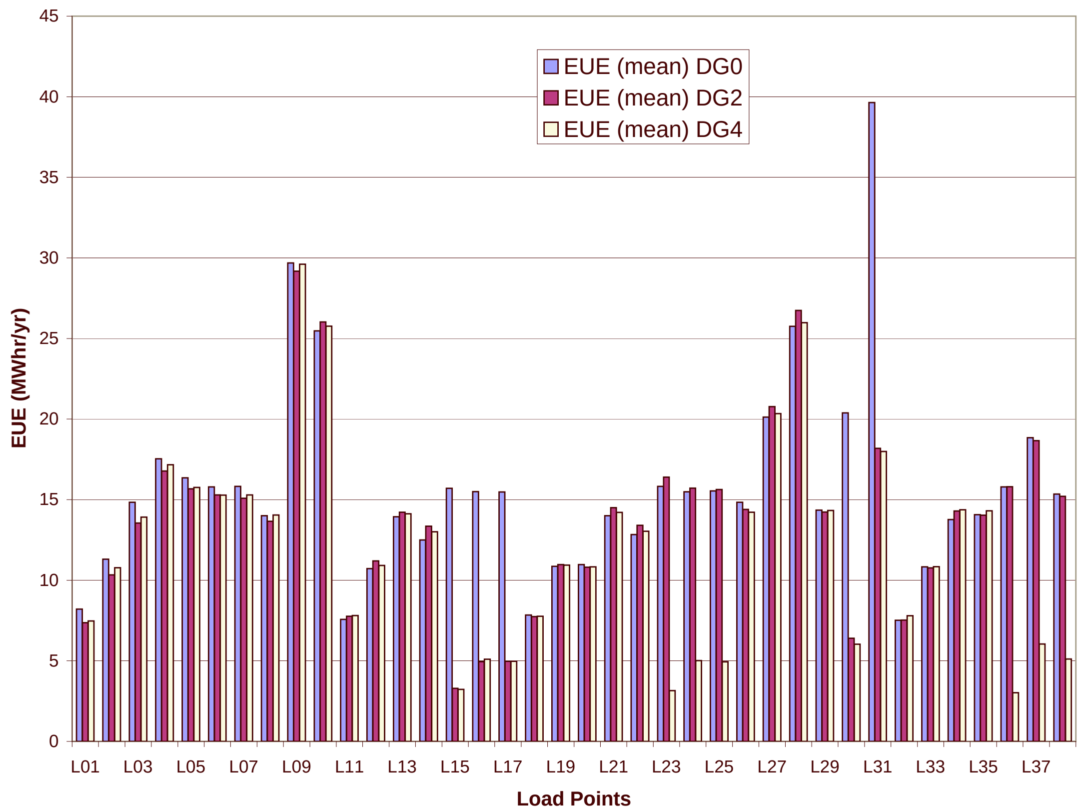


Fig. 48. Load Point EUE Indices for Bus 4 Supply 80 MW

# CHAPTER VI

## CONCLUSIONS

This research has presented a new methodology that can simulate the operation of a distribution network with Distributed Generation and evaluate the status of load demand and system reliability in such a network. The methodology combines a sequential Montel Carlo simulation of the system's stochastic model states with a path augmenting Max flow algorithm to determine the status of load demand in the system and to generate reliability statistics at the system and load point levels.

A flexible and efficient simulator has been developed in C++ to implement this methodology. Various additional features such as multiple distributions for the supply and distribution line outage and repair rates and time-varying load characteristics have been incorporated. Further, techniques to enhance the performance of this computation-intensive simulation have also been discussed.

Cases of different supply level distribution networks with variable number of DG have been studied to analyze the reliability impact of DG to the network at system level and at specific load points. The reliability assessment is based on computation of indices such as HLOLE, FLOL and EUE.

Based on the results, EUE is observed to be the most responsive index of reliablity for this application. Also, the relative impact of DG in a network is seen be related to the capacity redundancy of the supply in the network. Loads connected to DG always demonstrate improved reliability. Elsewhere in the network DG enhanced reliability to a lesser degree by reducing the feeder loadings. However, the improvement of these load point reliability indices depends on whether the generation outage or line outage is the principle contributor for loss of load. Further research on this aspect can be done to device a new index of reliability for a distribution network with DG.

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# APPENDIX A

# SIMULATION RESULTS FOR SYSTEM COMPONENTS

Bus 2 and Bus 4 supply points, distributed generators and distribution lines statistics for hours of outage and frequency of outages per year are recorded in the following tables.

Table XI. Bus 2 Results, Supply Capacity 20 MW

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 142.831 | 4.32176 | 140.577 | 4.25853 | 143.694 | 4.34766 |
| Gen02 | 141.273 | 4.35417 | 140.23 | 4.27118 | 142.772 | 4.34984 |
| Dist. Gen. | | | | | | |
| DG01 | | | 143.504 | 4.32783 | 142.149 | 4.34553 |
| DG02 | | | | | 143.529 | 4.35315 |
| Dist. Line | | | | | | |
| T01 | 5.64622 | 0.427662 | 5.84779 | 0.431793 | 5.84138 | 0.434028 |
| T02 | 5.52842 | 0.415509 | 6.28272 | 0.455996 | 5.89657 | 0.440817 |
| T03 | 5.41182 | 0.429977 | 5.99952 | 0.438944 | 5.79242 | 0.43208 |
| T04 | 6.06655 | 0.453704 | 5.90102 | 0.431793 | 5.78878 | 0.43267 |
| T05 | 6.22208 | 0.446759 | 5.44187 | 0.405391 | 5.84014 | 0.440876 |
| T06 | 5.75727 | 0.463542 | 6.13695 | 0.459846 | 5.92464 | 0.440581 |
| T07 | 5.62716 | 0.431134 | 5.81346 | 0.438944 | 5.80918 | 0.435327 |
| T08 | 5.87695 | 0.425347 | 5.80888 | 0.441694 | 5.89336 | 0.442057 |
| T09 | 6.35251 | 0.471065 | 6.21774 | 0.446095 | 5.86634 | 0.437452 |
| T10 | 5.75981 | 0.433449 | 5.8365 | 0.431243 | 5.95444 | 0.439577 |
| T11 | 5.84482 | 0.444444 | 5.82418 | 0.438394 | 6.00725 | 0.443237 |
| T12 | 5.93914 | 0.442708 | 5.86899 | 0.437844 | 6.00687 | 0.44306 |
| T13 | 5.69898 | 0.434028 | 5.79553 | 0.438394 | 5.97067 | 0.445304 |
| T14 | 5.65394 | 0.41088 | 5.91221 | 0.438944 | 5.82343 | 0.436389 |
| T15 | 5.65363 | 0.425926 | 5.83855 | 0.438394 | 5.95219 | 0.439932 |
| T16 | 5.98595 | 0.446759 | 5.32424 | 0.40374 | 5.92013 | 0.437983 |
| T17 | 5.89051 | 0.45081 | 5.94215 | 0.432343 | 6.03849 | 0.441407 |
| T18 | 6.16268 | 0.458333 | 5.77837 | 0.451595 | 5.84279 | 0.437393 |
| T19 | 5.63417 | 0.424769 | 6.09569 | 0.447745 | 5.82365 | 0.434087 |
| T20 | 5.93751 | 0.458333 | 5.62589 | 0.421342 | 5.88499 | 0.441998 |
| T21 | 5.15016 | 0.417245 | 5.93055 | 0.443344 | 5.81944 | 0.440463 |
| T22 | 6.10678 | 0.446759 | 6.23082 | 0.455446 | 5.77149 | 0.433497 |
| T23 | 5.77498 | 0.443866 | 6.20241 | 0.461496 | 5.93374 | 0.446189 |
| T24 | 5.71124 | 0.428241 | 5.64892 | 0.431793 | 6.02515 | 0.442706 |

Table XI. Continued,

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T25 | 5.69488 | 0.431713 | 6.05522 | 0.444444 | 5.80621 | 0.432965 |
| T26 | 5.7431 | 0.457176 | 6.47383 | 0.471397 | 5.91103 | 0.442352 |
| T27 | 5.95066 | 0.431713 | 5.6883 | 0.414191 | 5.99636 | 0.447606 |
| T28 | 6.45391 | 0.477431 | 6.10702 | 0.474147 | 6.03266 | 0.442824 |
| T29 | 5.73156 | 0.421296 | 5.548 | 0.435094 | 5.76124 | 0.432788 |
| T30 | 5.71305 | 0.422454 | 6.36895 | 0.467547 | 5.80314 | 0.433024 |
| T31 | 5.76961 | 0.444444 | 6.31652 | 0.461496 | 5.97348 | 0.439459 |
| T32 | 6.10301 | 0.435764 | 5.69988 | 0.430143 | 5.8941 | 0.437747 |
| T33 | 5.33186 | 0.430556 | 5.88814 | 0.443344 | 5.81443 | 0.445658 |
| T34 | 6.2025 | 0.454282 | 5.5843 | 0.418592 | 5.71465 | 0.43574 |
| T35 | 5.72624 | 0.429398 | 5.58567 | 0.421342 | 5.9791 | 0.44737 |
| T36 | 5.77389 | 0.44213 | 6.23289 | 0.447195 | 5.77756 | 0.437511 |

Table XII. Bus 2 Results, Supply Capacity 30 MW

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 142.234 | 4.33808 | 140.513 | 4.26254 | 142.262 | 4.34687 |
| Gen02 | 143.631 | 4.3668 | 141.293 | 4.34808 | 142.699 | 4.33577 |
| Dist. Gen. | | | | | | |
| DG01 | | | 144.043 | 4.3648 | 142.952 | 4.34849 |
| DG02 | | | | | 143.182 | 4.36279 |
| Dist. Line | | | | | | |
| T01 | 5.9346 | 0.431931 | 5.89321 | 0.444936 | 5.92637 | 0.4401 |
| T02 | 5.81049 | 0.440751 | 6.05986 | 0.432153 | 5.80447 | 0.433858 |
| T03 | 5.89685 | 0.433967 | 6.12495 | 0.451819 | 5.82655 | 0.432756 |
| T04 | 5.79761 | 0.431479 | 5.94235 | 0.450836 | 5.87749 | 0.43711 |
| T05 | 6.06785 | 0.429218 | 5.93101 | 0.44297 | 5.87496 | 0.440519 |
| T06 | 5.75032 | 0.437585 | 5.69869 | 0.433628 | 5.93766 | 0.439575 |
| T07 | 5.63446 | 0.433514 | 5.34216 | 0.415438 | 5.85271 | 0.43551 |
| T08 | 5.78554 | 0.43962 | 5.98321 | 0.469027 | 5.84921 | 0.441621 |
| T09 | 5.80745 | 0.425373 | 5.66301 | 0.428712 | 5.90949 | 0.44503 |
| T10 | 6.00624 | 0.458616 | 5.67038 | 0.43412 | 5.82838 | 0.440047 |
| T11 | 5.94019 | 0.438716 | 5.81777 | 0.446411 | 5.97249 | 0.445686 |
| T12 | 5.92545 | 0.443012 | 5.84736 | 0.443461 | 5.98195 | 0.445292 |
| T13 | 5.67009 | 0.436906 | 5.82916 | 0.437561 | 5.8579 | 0.439864 |
| T14 | 5.75521 | 0.431253 | 5.5769 | 0.426745 | 5.87852 | 0.442355 |
| T15 | 6.28806 | 0.450249 | 5.91303 | 0.443953 | 5.79486 | 0.437687 |
| T16 | 5.81199 | 0.42967 | 6.18226 | 0.468043 | 5.79826 | 0.438159 |
| T17 | 5.97124 | 0.445726 | 6.24612 | 0.447886 | 5.965 | 0.443745 |
| T18 | 6.10627 | 0.449344 | 5.58971 | 0.419371 | 5.93956 | 0.440362 |
| T19 | 5.78199 | 0.430122 | 6.62796 | 0.47591 | 5.87654 | 0.441254 |
| T20 | 6.11956 | 0.448213 | 5.62953 | 0.418387 | 5.78853 | 0.438159 |
| T21 | 6.01367 | 0.445726 | 5.56844 | 0.436087 | 5.98901 | 0.444479 |
| T22 | 5.71555 | 0.438263 | 5.60376 | 0.444936 | 5.91335 | 0.438683 |

Table XII. Continued,

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T23 | 5.44083 | 0.414971 | 5.81523 | 0.421337 | 5.88225 | 0.439339 |
| T24 | 5.57424 | 0.430122 | 6.17413 | 0.448378 | 5.92279 | 0.439339 |
| T25 | 5.89728 | 0.433288 | 5.92238 | 0.430187 | 5.96167 | 0.443011 |
| T26 | 6.15258 | 0.446857 | 5.5345 | 0.441986 | 5.89027 | 0.441411 |
| T27 | 5.62774 | 0.424242 | 5.77992 | 0.453786 | 5.83036 | 0.435877 |
| T28 | 6.13388 | 0.444369 | 5.78381 | 0.445428 | 6.04722 | 0.445528 |
| T29 | 5.91926 | 0.436228 | 5.69167 | 0.426254 | 5.9397 | 0.442775 |
| T30 | 5.66611 | 0.424921 | 5.88687 | 0.443461 | 5.90164 | 0.436612 |
| T31 | 5.92165 | 0.442108 | 6.0426 | 0.452802 | 5.87521 | 0.435248 |
| T32 | 6.03543 | 0.443012 | 5.77263 | 0.441003 | 5.90556 | 0.439392 |
| T33 | 5.78459 | 0.431253 | 6.00651 | 0.448869 | 5.87371 | 0.440598 |
| T34 | 5.43847 | 0.425147 | 6.02188 | 0.460669 | 5.93542 | 0.440572 |
| T35 | 5.96896 | 0.446178 | 5.80696 | 0.436087 | 5.89656 | 0.438474 |
| T36 | 5.88605 | 0.444595 | 5.68454 | 0.43707 | 5.88205 | 0.441568 |

Table XIII. Bus 2 Results, Supply Capacity 40 MW

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 144.091 | 4.35487 | 143.271 | 4.34543 | 143.291 | 4.35334 |
| Gen02 | 143.381 | 4.31971 | 140.962 | 4.32468 | 144.374 | 4.35888 |
| Dist. Gen. | | | | | | |
| DG01 | | | 143.38 | 4.35754 | 143.329 | 4.35731 |
| DG02 | | | | | 144.054 | 4.34663 |
| Dist. Line | | | | | | |
| T01 | 5.96223 | 0.444841 | 6.01834 | 0.44087 | 5.81169 | 0.435122 |
| T02 | 5.66736 | 0.414852 | 5.9299 | 0.441952 | 5.95422 | 0.44354 |
| T03 | 5.76157 | 0.441806 | 6.03966 | 0.444018 | 5.97008 | 0.443197 |
| T04 | 6.02922 | 0.438058 | 5.93781 | 0.436147 | 6.05358 | 0.445456 |
| T05 | 6.0101 | 0.44377 | 5.95698 | 0.439394 | 6.11448 | 0.443129 |
| T06 | 6.19175 | 0.456087 | 6.04364 | 0.44205 | 5.89669 | 0.445456 |
| T07 | 5.66618 | 0.429489 | 6.04911 | 0.446379 | 5.69828 | 0.426362 |
| T08 | 6.22277 | 0.435023 | 5.83156 | 0.436049 | 5.93104 | 0.447098 |
| T09 | 5.8782 | 0.435559 | 5.8089 | 0.44451 | 5.93468 | 0.441966 |
| T10 | 5.96518 | 0.437701 | 5.78523 | 0.431326 | 5.97478 | 0.442034 |
| T11 | 5.78276 | 0.439843 | 5.9507 | 0.442247 | 6.05213 | 0.447783 |
| T12 | 5.85038 | 0.439129 | 6.14397 | 0.447757 | 5.79973 | 0.435327 |
| T13 | 5.68366 | 0.420743 | 6.04485 | 0.448249 | 5.98756 | 0.444635 |
| T14 | 6.03001 | 0.44734 | 5.839 | 0.425325 | 5.96255 | 0.444361 |
| T15 | 5.71399 | 0.437701 | 6.04295 | 0.450807 | 5.80485 | 0.428757 |
| T16 | 6.13696 | 0.451981 | 5.88198 | 0.438902 | 5.87222 | 0.437449 |
| T17 | 6.23997 | 0.457872 | 6.05055 | 0.44087 | 5.75802 | 0.427252 |
| T18 | 6.08826 | 0.441271 | 6.05178 | 0.444805 | 5.86195 | 0.441623 |
| T19 | 5.76604 | 0.439307 | 5.74417 | 0.439 | 5.92258 | 0.442581 |
| T20 | 5.80997 | 0.442164 | 5.86476 | 0.438312 | 5.93312 | 0.440665 |

Table XIII. Continued,

| | No DG case | | 1 DG case | | 2 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T21 | 5.79643 | 0.427883 | 5.79879 | 0.433884 | 5.89923 | 0.433616 |
| T22 | 5.58705 | 0.422885 | 5.79911 | 0.440181 | 5.79097 | 0.431974 |
| T23 | 5.89481 | 0.438593 | 5.84152 | 0.429752 | 5.83164 | 0.43916 |
| T24 | 6.2607 | 0.456444 | 5.91502 | 0.443625 | 5.92622 | 0.438612 |
| T25 | 5.4202 | 0.409854 | 5.69472 | 0.430933 | 5.83451 | 0.437312 |
| T26 | 5.91184 | 0.438593 | 5.78067 | 0.436738 | 5.94252 | 0.437654 |
| T27 | 5.92727 | 0.44502 | 5.98096 | 0.442444 | 5.86917 | 0.433753 |
| T28 | 5.9885 | 0.443949 | 5.8976 | 0.441067 | 5.71799 | 0.430879 |
| T29 | 5.61106 | 0.422885 | 5.8968 | 0.439984 | 5.81848 | 0.437517 |
| T30 | 5.90418 | 0.438772 | 5.72882 | 0.428473 | 5.97305 | 0.442239 |
| T31 | 5.90417 | 0.440021 | 5.80417 | 0.433786 | 6.08942 | 0.444224 |
| T32 | 6.00513 | 0.446983 | 5.83994 | 0.436639 | 5.82759 | 0.440528 |
| T33 | 6.10686 | 0.447697 | 5.98765 | 0.442444 | 5.79732 | 0.437654 |
| T34 | 5.85249 | 0.434488 | 5.89192 | 0.441854 | 5.7533 | 0.430194 |
| T35 | 6.17286 | 0.451803 | 5.97309 | 0.436147 | 5.70888 | 0.4317 |
| T36 | 5.65374 | 0.432167 | 6.00589 | 0.448052 | 5.93587 | 0.437106 |

Table XIV. Bus 4 Results, Supply Capacity 40 MW

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 141.955 | 4.35224 | 141.943 | 4.34157 | 141.021 | 4.32607 |
| Gen02 | 142.046 | 4.337 | 141.786 | 4.28111 | 141.995 | 4.33663 |
| Dist. Gen. | | | | | | |
| DG01 | | | 141.942 | 4.3045 | 143.592 | 4.34636 |
| DG02 | | | 141.78 | 4.2842 | 143.122 | 4.36466 |
| DG03 | | | | | 142.403 | 4.32546 |
| DG04 | | | | | 145.188 | 4.3771 |
| Dist. Line | | | | | | |
| T01 | 5.73605 | 0.446232 | 6.21043 | 0.45278 | 6.02228 | 0.44172 |
| T02 | 6.19287 | 0.436071 | 5.81188 | 0.434687 | 5.9791 | 0.443532 |
| T03 | 5.96006 | 0.469941 | 6.19642 | 0.456311 | 5.84882 | 0.439063 |
| T04 | 5.75515 | 0.404742 | 6.00846 | 0.457635 | 5.90953 | 0.436647 |
| T05 | 5.41351 | 0.413209 | 5.29743 | 0.407326 | 6.04959 | 0.438821 |
| T06 | 5.78814 | 0.432684 | 5.86856 | 0.451015 | 5.95052 | 0.44178 |
| T07 | 5.60437 | 0.42337 | 5.99226 | 0.447926 | 5.90026 | 0.438519 |
| T08 | 6.38562 | 0.458933 | 5.67608 | 0.421889 | 5.75577 | 0.435137 |
| T09 | 5.91009 | 0.444539 | 5.73488 | 0.426302 | 5.924 | 0.441176 |
| T10 | 5.65028 | 0.429297 | 6.02283 | 0.458959 | 5.74488 | 0.43091 |
| T11 | 6.22672 | 0.434378 | 5.94309 | 0.443071 | 5.89572 | 0.43864 |
| T12 | 5.8171 | 0.430991 | 6.19005 | 0.451015 | 5.76366 | 0.427588 |
| T13 | 5.88752 | 0.441998 | 5.90528 | 0.440424 | 5.95526 | 0.436707 |
| T14 | 6.1098 | 0.448772 | 5.91785 | 0.444395 | 6.08214 | 0.451443 |
| T15 | 6.09081 | 0.458933 | 5.86907 | 0.454104 | 5.9418 | 0.436949 |
| T16 | 6.21093 | 0.449619 | 5.70682 | 0.424095 | 5.82522 | 0.439727 |

Table XIV. Continued,

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T17 | 5.76587 | 0.419983 | 5.94675 | 0.447485 | 6.03471 | 0.438882 |
| T18 | 5.87011 | 0.430144 | 5.61672 | 0.412621 | 5.91604 | 0.440331 |
| T19 | 6.03447 | 0.456393 | 5.98762 | 0.445278 | 5.89735 | 0.442988 |
| T20 | 5.45262 | 0.411516 | 5.48308 | 0.417917 | 5.96355 | 0.445706 |
| T21 | 5.07221 | 0.403048 | 6.03999 | 0.432039 | 5.79514 | 0.439606 |
| T22 | 6.16999 | 0.434378 | 5.75262 | 0.438658 | 5.87891 | 0.435258 |
| T23 | 5.45261 | 0.402202 | 5.75298 | 0.426743 | 5.90262 | 0.442384 |
| T24 | 6.96306 | 0.510584 | 5.97025 | 0.436011 | 5.94768 | 0.437432 |
| T25 | 5.64509 | 0.408975 | 5.73986 | 0.420124 | 5.94188 | 0.439365 |
| T26 | 5.08489 | 0.431837 | 5.85659 | 0.450132 | 5.85974 | 0.435983 |
| T27 | 5.91012 | 0.430991 | 5.98081 | 0.435128 | 5.95759 | 0.446552 |
| T28 | 6.52423 | 0.477561 | 6.11908 | 0.456311 | 5.86737 | 0.437311 |
| T29 | 5.97415 | 0.430991 | 5.67857 | 0.424095 | 5.88604 | 0.442022 |
| T30 | 6.14216 | 0.456393 | 5.94152 | 0.455428 | 5.99122 | 0.448363 |
| T31 | 5.78127 | 0.42337 | 5.86522 | 0.449691 | 5.79821 | 0.43399 |
| T32 | 6.06418 | 0.413209 | 6.34037 | 0.466902 | 6.10201 | 0.44637 |
| T33 | 6.74946 | 0.513971 | 5.33348 | 0.415711 | 5.90566 | 0.437915 |
| T34 | 5.53142 | 0.436071 | 5.59639 | 0.439982 | 5.97297 | 0.434412 |
| T35 | 6.01274 | 0.433531 | 5.78084 | 0.426302 | 6.02225 | 0.451141 |
| T36 | 5.94963 | 0.427604 | 5.95909 | 0.441748 | 5.97014 | 0.442082 |
| T37 | 6.02317 | 0.453006 | 5.96467 | 0.432921 | 6.0262 | 0.440935 |
| T38 | 5.87982 | 0.444539 | 5.60874 | 0.436011 | 5.88174 | 0.439787 |
| T39 | 6.00985 | 0.45724 | 5.8476 | 0.434245 | 5.9409 | 0.444438 |
| T40 | 6.28423 | 0.491109 | 5.72841 | 0.448367 | 5.91674 | 0.443049 |
| T41 | 5.50345 | 0.406435 | 6.09941 | 0.441748 | 5.99463 | 0.447216 |
| T42 | 5.31453 | 0.421677 | 6.16117 | 0.454545 | 5.85481 | 0.44015 |
| T43 | 5.61031 | 0.419983 | 6.36759 | 0.440865 | 5.82657 | 0.437613 |
| T44 | 6.00851 | 0.426757 | 6.18422 | 0.44925 | 5.82805 | 0.442988 |
| T45 | 5.96286 | 0.421677 | 5.75262 | 0.443513 | 5.87413 | 0.439244 |
| T46 | 5.90949 | 0.441152 | 5.58987 | 0.440424 | 5.88861 | 0.440633 |
| T47 | 6.27705 | 0.461473 | 5.35831 | 0.415711 | 5.96092 | 0.440633 |
| T48 | 6.0737 | 0.436918 | 5.47898 | 0.429832 | 5.90553 | 0.438942 |
| T49 | 5.64659 | 0.445385 | 6.41142 | 0.458959 | 6.01942 | 0.443894 |
| T50 | 6.11002 | 0.414903 | 5.75045 | 0.432039 | 5.87257 | 0.440271 |
| T51 | 5.79908 | 0.427604 | 5.55343 | 0.425419 | 5.89543 | 0.437553 |
| T52 | 5.7688 | 0.445385 | 6.39163 | 0.464254 | 5.75922 | 0.432903 |
| T53 | 6.1642 | 0.439458 | 6.16518 | 0.46293 | 5.83338 | 0.437372 |
| T54 | 6.08636 | 0.46232 | 6.2479 | 0.446161 | 5.84261 | 0.439123 |
| T55 | 6.09777 | 0.454699 | 5.93988 | 0.440865 | 5.73624 | 0.434956 |
| T56 | 5.87573 | 0.46232 | 5.85157 | 0.436893 | 6.02617 | 0.449813 |
| T57 | 5.5578 | 0.431837 | 5.94798 | 0.457193 | 5.92326 | 0.441056 |
| T58 | 5.55565 | 0.429297 | 5.80648 | 0.437776 | 5.89997 | 0.440391 |
| T59 | 6.0437 | 0.444539 | 5.43966 | 0.416593 | 5.80529 | 0.440331 |
| T60 | 5.91937 | 0.450466 | 5.82547 | 0.448808 | 5.97134 | 0.442445 |
| T61 | 5.84297 | 0.440305 | 6.0045 | 0.44263 | 5.78916 | 0.437674 |
| T62 | 6.00664 | 0.441152 | 5.83972 | 0.435569 | 5.97601 | 0.44172 |
| T63 | 5.19058 | 0.421677 | 6.15729 | 0.447926 | 5.88135 | 0.438157 |

Table XIV. Continued,

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T64 | 6.09854 | 0.453006 | 6.11257 | 0.442189 | 5.889 | 0.440693 |
| T65 | 6.09027 | 0.448772 | 5.79099 | 0.436893 | 5.82303 | 0.439667 |
| T66 | 6.30137 | 0.451312 | 5.82625 | 0.451015 | 5.95414 | 0.440391 |
| T67 | 6.72513 | 0.478408 | 5.70472 | 0.427626 | 5.95961 | 0.442203 |

Table XV. Bus 4 Results, Supply Capacity 60 MW

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 141.64 | 4.33247 | 139.323 | 4.30598 | 144.037 | 4.34445 |
| Gen02 | 143.486 | 4.4038 | 144.424 | 4.39265 | 142.827 | 4.31609 |
| Dist. Gen. | | | | | | |
| DG01 | | | 140.44 | 4.33935 | 141.919 | 4.33513 |
| DG02 | | | 144.226 | 4.37461 | 142.026 | 4.33771 |
| DG03 | | | | | 143.362 | 4.33592 |
| DG04 | | | | | 142.375 | 4.32772 |
| Dist. Line | | | | | | |
| T01 | 6.11361 | 0.440986 | 5.90176 | 0.451207 | 5.76868 | 0.436532 |
| T02 | 5.53498 | 0.418936 | 5.75394 | 0.435887 | 5.86369 | 0.43916 |
| T03 | 5.6786 | 0.415478 | 5.83349 | 0.434837 | 5.89887 | 0.442068 |
| T04 | 5.85753 | 0.428448 | 5.87369 | 0.433368 | 6.0015 | 0.44159 |
| T05 | 5.94586 | 0.434068 | 6.33131 | 0.452466 | 5.87605 | 0.438563 |
| T06 | 5.71101 | 0.426719 | 6.07772 | 0.449318 | 5.94814 | 0.443223 |
| T07 | 5.64172 | 0.446174 | 5.78554 | 0.447429 | 5.87838 | 0.437448 |
| T08 | 5.48788 | 0.427583 | 6.26089 | 0.451417 | 5.82073 | 0.438961 |
| T09 | 5.91127 | 0.440986 | 5.58303 | 0.425184 | 5.80558 | 0.434859 |
| T10 | 5.94361 | 0.440121 | 6.13658 | 0.451626 | 5.79252 | 0.433983 |
| T11 | 6.36434 | 0.457847 | 5.94044 | 0.443022 | 5.95484 | 0.445653 |
| T12 | 6.27975 | 0.451794 | 5.77892 | 0.429801 | 5.80363 | 0.437089 |
| T13 | 6.21356 | 0.442283 | 5.87247 | 0.424764 | 5.79466 | 0.42518 |
| T14 | 6.18483 | 0.453524 | 5.68727 | 0.423085 | 5.91495 | 0.442028 |
| T15 | 5.64244 | 0.437095 | 5.91601 | 0.438405 | 5.80104 | 0.436492 |
| T16 | 5.46291 | 0.408993 | 5.58565 | 0.418468 | 5.99324 | 0.440674 |
| T17 | 5.76849 | 0.442283 | 5.79619 | 0.44575 | 5.90443 | 0.441789 |
| T18 | 6.28004 | 0.46217 | 5.91134 | 0.445331 | 5.89518 | 0.440754 |
| T19 | 6.13155 | 0.453091 | 5.5468 | 0.43064 | 5.95275 | 0.444776 |
| T20 | 5.69195 | 0.433636 | 5.83732 | 0.426023 | 5.91037 | 0.441749 |
| T21 | 6.10799 | 0.446174 | 5.90402 | 0.433368 | 5.87668 | 0.437846 |
| T22 | 5.59872 | 0.434933 | 5.6852 | 0.425393 | 5.99194 | 0.447684 |
| T23 | 5.4556 | 0.42326 | 5.9392 | 0.435257 | 5.79412 | 0.438842 |
| T24 | 5.89863 | 0.438392 | 5.90306 | 0.447219 | 5.92908 | 0.4439 |
| T25 | 5.79824 | 0.42888 | 5.87914 | 0.434837 | 5.8978 | 0.43928 |
| T26 | 6.12464 | 0.447903 | 5.92135 | 0.442183 | 5.85557 | 0.438005 |
| T27 | 6.19345 | 0.458712 | 5.96534 | 0.436726 | 5.95441 | 0.441471 |
| T28 | 6.01633 | 0.438392 | 5.68537 | 0.428751 | 5.87045 | 0.438005 |

Table XV. Continued,

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T29 | 5.59209 | 0.438392 | 6.18101 | 0.445121 | 5.82366 | 0.435297 |
| T30 | 5.92261 | 0.444012 | 5.97115 | 0.437356 | 5.98127 | 0.441948 |
| T31 | 5.45864 | 0.419369 | 6.16774 | 0.453305 | 6.05146 | 0.444418 |
| T32 | 6.04702 | 0.433204 | 5.76686 | 0.428332 | 5.89468 | 0.43916 |
| T33 | 6.00294 | 0.449633 | 5.6658 | 0.437775 | 5.85552 | 0.436054 |
| T34 | 5.39617 | 0.411587 | 5.79574 | 0.432949 | 5.88026 | 0.437766 |
| T35 | 5.98353 | 0.43623 | 5.86074 | 0.440084 | 5.86245 | 0.439519 |
| T36 | 5.77713 | 0.432339 | 5.58445 | 0.424764 | 5.90114 | 0.440634 |
| T37 | 5.93992 | 0.451362 | 5.98168 | 0.443022 | 5.92687 | 0.440674 |
| T38 | 5.64401 | 0.440121 | 5.9683 | 0.440923 | 5.90176 | 0.438921 |
| T39 | 5.6303 | 0.425854 | 6.36481 | 0.46149 | 6.06373 | 0.4439 |
| T40 | 5.95946 | 0.456118 | 5.78048 | 0.435677 | 5.87734 | 0.438204 |
| T41 | 6.22227 | 0.453956 | 6.1236 | 0.456453 | 6.028 | 0.441072 |
| T42 | 6.18081 | 0.466494 | 5.91712 | 0.435257 | 5.87106 | 0.435576 |
| T43 | 5.8685 | 0.439256 | 6.03231 | 0.452046 | 5.77706 | 0.436213 |
| T44 | 5.81793 | 0.43061 | 5.78758 | 0.434627 | 5.92694 | 0.442068 |
| T45 | 6.25007 | 0.448335 | 5.80836 | 0.427072 | 5.79302 | 0.432788 |
| T46 | 5.69281 | 0.429745 | 6.00217 | 0.44659 | 5.82649 | 0.434978 |
| T47 | 5.91013 | 0.437095 | 6.02849 | 0.443022 | 5.87331 | 0.441032 |
| T48 | 6.12461 | 0.472114 | 6.05252 | 0.444701 | 5.91861 | 0.442267 |
| T49 | 5.97787 | 0.445309 | 5.81937 | 0.435257 | 5.85968 | 0.43462 |
| T50 | 5.91356 | 0.436662 | 6.04152 | 0.443232 | 5.88712 | 0.439559 |
| T51 | 6.17058 | 0.474276 | 6.114 | 0.44596 | 6.04984 | 0.444537 |
| T52 | 5.79656 | 0.436662 | 5.74364 | 0.43106 | 5.80002 | 0.434899 |
| T53 | 5.75246 | 0.451794 | 5.83408 | 0.436726 | 5.88948 | 0.439559 |
| T54 | 5.91074 | 0.440121 | 5.68677 | 0.432529 | 5.91125 | 0.441271 |
| T55 | 5.48351 | 0.427151 | 6.05504 | 0.442602 | 5.98656 | 0.442108 |
| T56 | 5.76676 | 0.430177 | 5.99713 | 0.432949 | 5.8268 | 0.432628 |
| T57 | 5.89034 | 0.428448 | 5.65615 | 0.425813 | 5.96987 | 0.447485 |
| T58 | 6.22576 | 0.449633 | 6.15628 | 0.447849 | 5.99217 | 0.441032 |
| T59 | 5.95766 | 0.437959 | 6.15796 | 0.449948 | 5.77413 | 0.430995 |
| T60 | 6.08769 | 0.453091 | 5.70371 | 0.423924 | 6.04184 | 0.44398 |
| T61 | 5.79432 | 0.429745 | 5.96755 | 0.447219 | 6.01727 | 0.447803 |
| T62 | 5.85594 | 0.446606 | 6.0252 | 0.444911 | 5.89916 | 0.444498 |
| T63 | 6.00853 | 0.437095 | 6.06537 | 0.444071 | 5.88077 | 0.443064 |
| T64 | 5.75056 | 0.430177 | 6.02022 | 0.447219 | 5.91425 | 0.434261 |
| T65 | 5.92338 | 0.442715 | 5.98669 | 0.442183 | 6.00393 | 0.440793 |
| T66 | 6.17624 | 0.459144 | 6.10481 | 0.440294 | 5.85281 | 0.436571 |
| T67 | 5.89444 | 0.448335 | 5.51995 | 0.434418 | 5.95836 | 0.4439 |

Table XVI. Bus 4 Results, Supply Capacity 80 MW

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Supply Points | | | | | | |
| Gen01 | 141.861 | 4.30746 | 145.096 | 4.35246 | 143.237 | 4.3253 |

Table XVI. Continued,

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| Gen02 | 140.321 | 4.33987 | 141.766 | 4.33164 | 142.208 | 4.30513 |
| Dist. Gen. | | | | | | |
| DG01 | | | 142.076 | 4.3517 | 142.379 | 4.34501 |
| DG02 | | | 140.689 | 4.3352 | 141.268 | 4.32236 |
| DG03 | | | | | 143.874 | 4.33833 |
| DG04 | | | | | 142.046 | 4.3155 |
| Dist. Line | | | | | | |
| T01 | 6.32301 | 0.456919 | 5.55002 | 0.429914 | 5.69845 | 0.430951 |
| T02 | 5.89406 | 0.440198 | 5.79668 | 0.445912 | 5.8159 | 0.438444 |
| T03 | 6.05167 | 0.449241 | 5.76164 | 0.418994 | 5.86909 | 0.443112 |
| T04 | 5.82269 | 0.432861 | 6.02059 | 0.434992 | 6.01403 | 0.441153 |
| T05 | 6.16612 | 0.455895 | 6.01454 | 0.44261 | 5.88887 | 0.437522 |
| T06 | 5.93109 | 0.442587 | 5.90239 | 0.432199 | 5.97608 | 0.445591 |
| T07 | 5.71715 | 0.42689 | 5.80573 | 0.44642 | 5.93615 | 0.440692 |
| T08 | 5.84241 | 0.438833 | 5.78486 | 0.444134 | 5.84343 | 0.437349 |
| T09 | 5.83292 | 0.430302 | 6.22725 | 0.442357 | 5.77849 | 0.436369 |
| T10 | 5.98005 | 0.437639 | 5.69404 | 0.430422 | 5.76045 | 0.432046 |
| T11 | 6.02109 | 0.442416 | 5.9907 | 0.447943 | 5.962 | 0.443285 |
| T12 | 5.94344 | 0.43798 | 5.89236 | 0.448451 | 5.85097 | 0.440173 |
| T13 | 5.77631 | 0.42706 | 5.71196 | 0.435246 | 5.85638 | 0.425418 |
| T14 | 5.94854 | 0.439004 | 5.78541 | 0.440325 | 5.91216 | 0.440115 |
| T15 | 5.7595 | 0.439686 | 5.94304 | 0.441595 | 5.74561 | 0.436081 |
| T16 | 5.88457 | 0.437297 | 6.01299 | 0.449467 | 5.99717 | 0.439712 |
| T17 | 6.04043 | 0.445146 | 6.0711 | 0.440833 | 5.85894 | 0.438156 |
| T18 | 5.83634 | 0.442587 | 5.99602 | 0.438547 | 5.93082 | 0.442248 |
| T19 | 5.90347 | 0.44071 | 5.94936 | 0.447943 | 5.91836 | 0.444265 |
| T20 | 5.85056 | 0.445316 | 5.9697 | 0.450482 | 5.96237 | 0.44611 |
| T21 | 5.66924 | 0.429961 | 6.41006 | 0.460386 | 5.91106 | 0.437003 |
| T22 | 5.92113 | 0.438492 | 5.97444 | 0.45099 | 5.91798 | 0.44317 |
| T23 | 5.69535 | 0.433032 | 6.03705 | 0.44261 | 5.87041 | 0.442133 |
| T24 | 6.16602 | 0.448388 | 5.79986 | 0.424581 | 5.93236 | 0.443112 |
| T25 | 5.92263 | 0.436786 | 5.98648 | 0.437786 | 5.85863 | 0.44 |
| T26 | 6.02116 | 0.441904 | 5.72324 | 0.438801 | 5.82966 | 0.435043 |
| T27 | 5.70969 | 0.434397 | 6.07893 | 0.445404 | 5.9622 | 0.444438 |
| T28 | 5.88553 | 0.452312 | 5.99753 | 0.441849 | 5.93372 | 0.442478 |
| T29 | 6.05146 | 0.436615 | 5.9333 | 0.450229 | 5.76164 | 0.434006 |
| T30 | 5.84966 | 0.437639 | 5.73107 | 0.432199 | 5.98033 | 0.440749 |
| T31 | 5.96481 | 0.452312 | 6.13315 | 0.437786 | 6.15386 | 0.452219 |
| T32 | 5.98419 | 0.445658 | 5.72717 | 0.432453 | 5.85216 | 0.437522 |
| T33 | 5.86469 | 0.446511 | 5.88692 | 0.430675 | 5.77722 | 0.43245 |
| T34 | 5.84797 | 0.444122 | 5.77402 | 0.435754 | 5.89411 | 0.441556 |
| T35 | 5.90198 | 0.435421 | 5.5481 | 0.42839 | 5.844 | 0.440403 |
| T36 | 5.8799 | 0.431838 | 6.14769 | 0.458862 | 5.92672 | 0.442824 |
| T37 | 6.16414 | 0.439515 | 5.74601 | 0.442864 | 5.93712 | 0.443573 |
| T38 | 5.85075 | 0.432179 | 5.96781 | 0.439817 | 5.96113 | 0.442248 |
| T39 | 6.07771 | 0.437127 | 6.18897 | 0.439309 | 6.13808 | 0.446225 |
| T40 | 5.974 | 0.434738 | 5.87023 | 0.445658 | 5.82839 | 0.436023 |

Table XVI. Continued,

| | No DG case | | 2 DG case | | 4 DG case | |
|---|---|---|---|---|---|---|
| | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr | Hrs/yr | Freq/yr |
| T41 | 6.18626 | 0.450435 | 6.00337 | 0.44388 | 6.00688 | 0.440749 |
| T42 | 5.76893 | 0.431326 | 6.11351 | 0.444896 | 5.84848 | 0.431297 |
| T43 | 5.96547 | 0.443781 | 5.47215 | 0.41417 | 5.71354 | 0.433487 |
| T44 | 5.84222 | 0.427913 | 5.93155 | 0.435754 | 5.9101 | 0.438732 |
| T45 | 6.07279 | 0.446511 | 5.96723 | 0.446166 | 5.82862 | 0.431816 |
| T46 | 5.92289 | 0.440198 | 6.14632 | 0.456577 | 5.85717 | 0.435908 |
| T47 | 5.8943 | 0.441904 | 5.77784 | 0.444896 | 6.00002 | 0.447839 |
| T48 | 5.8729 | 0.439857 | 5.8309 | 0.433215 | 5.89798 | 0.441614 |
| T49 | 5.90265 | 0.444975 | 6.07836 | 0.449213 | 5.85789 | 0.433948 |
| T50 | 5.87597 | 0.439345 | 5.8952 | 0.441341 | 5.80089 | 0.436715 |
| T51 | 6.07121 | 0.448217 | 5.90164 | 0.438294 | 6.07931 | 0.446859 |
| T52 | 5.97103 | 0.443098 | 5.86879 | 0.433469 | 5.83689 | 0.440403 |
| T53 | 5.9614 | 0.441051 | 5.98258 | 0.457339 | 5.84967 | 0.437637 |
| T54 | 5.83148 | 0.436274 | 5.91081 | 0.433469 | 5.86508 | 0.442594 |
| T55 | 6.09859 | 0.444805 | 5.54399 | 0.421026 | 5.93197 | 0.440519 |
| T56 | 5.72239 | 0.426037 | 5.7475 | 0.430929 | 5.85806 | 0.433718 |
| T57 | 5.94268 | 0.439174 | 5.6389 | 0.431437 | 6.02678 | 0.449741 |
| T58 | 5.8044 | 0.439174 | 5.94631 | 0.436516 | 6.03264 | 0.442363 |
| T59 | 5.78209 | 0.430302 | 5.6802 | 0.424835 | 5.77628 | 0.433256 |
| T60 | 5.62128 | 0.434056 | 5.73844 | 0.423311 | 5.96332 | 0.442594 |
| T61 | 5.83751 | 0.445487 | 6.0811 | 0.46064 | 6.03712 | 0.445476 |
| T62 | 5.94809 | 0.43815 | 5.74313 | 0.432199 | 5.92006 | 0.445418 |
| T63 | 5.88519 | 0.445146 | 5.73455 | 0.425851 | 5.87543 | 0.44438 |
| T64 | 5.63889 | 0.426719 | 5.81028 | 0.439817 | 5.88152 | 0.4317 |
| T65 | 5.8574 | 0.441392 | 6.16729 | 0.441087 | 5.97325 | 0.441383 |
| T66 | 6.28016 | 0.442245 | 5.73443 | 0.4355 | 5.76789 | 0.432968 |
| T67 | 5.62176 | 0.42962 | 5.62749 | 0.432453 | 6.04895 | 0.448184 |

# VITA

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