DISTRIBUTION PROBABILISTIC LOAD FLOW SOLUTION CONSIDERING NETWORK RECONFIGURATION AND VOLTAGE CONTROL DEVICES

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Abstract – Electric power industry deregulation has forced utilities to perform studies to determine the changes that should be made for efficiency improvements, cost reductions, and power quality enhancements. At the distribution system level, there are a number of attributes can influence the system operation performance. To fully evaluate the distribution network operation performance, a distribution probabilistic load flow solution method based on Monte Carlo simulation is proposed in this paper. It is assumed that the uncertainties of daily time varying load, voltage control devices at the line segments, and feeder reconfigurations for service restorations and load balancing can be estimated or measured. The proposed method can be used to calculate distributions of the power flows at various sections of the feeder and voltage profiles at all nodes of the network for operation planning. This method allows probabilistic modeling of the distribution system operations and provides a base model for assessing the effects of distributed generation and voltage mitigation equipments on the operating performance of the distribution network. Flexibility of the proposed method is tested on a modified IEEE 13 node feeder test system.

Keywords – Distribution probabilistic load flow, Monte Carlo simulation, network reconfiguration, and voltage quality.

1 INTRODUCTION

Deregulation of the electric power industry has forced utilities to face new challenges. Many electric service companies are performing studies to determine the changes that should be made for efficiency improvements, cost reductions, and power quality enhancements. At the distribution system level, cost effective engineering design and system operations planning require detailed models of customer load characteristics, feeder load profiles, regulation controls settings, and service restoration strategy. Adding to the complexities of the problem are many different types of distributed generations installed in the distribution networks. To assess the operating performance of the distribution network for making the correct investment decisions, an effective engineering tool is essential for the utilities.

Distribution load flow widely used for operational type analysis and planning oriented analysis is one of the most important distribution system functions. It provides the analyst with the steady state of the system for a specified set of loads and network conditions. In the distribution system there are a number of attributes that can influence the system operations and planning. The load data, control functions such as voltage regulation via tap changing transformers or voltage regulators, reactive power compensation via switched capacitors, and network reconfiguration for service restoration and load balancing are uncertain parameters for the distribution system operations. From a system planning point of view, it has been shown worthwhile to approach the problem as a probabilistic one by using random variables. The probabilistic distribution load flow can take into account the uncertainty factors associated with the computation of distribution load flow and can provide the all probable values of the feeder voltages and the network flows with the probability.

Many probabilistic load flow (PLF) methods have been proposed to study load flow uncertainty problem. These methods emphasize the transmission system, but there are less literatures for distribution system [1,2]. In [1], a Monte Carlo simulation (MCS) based distribution PLF method is used to account for the load data and wind power uncertainties in the distribution load flow calculations. A radial distribution probabilistic load flow method is proposed in [2] to consider time varying load and wind generation variations and to assess the load flow solution uncertainty by using the convolution technique. In the great majority of distribution PLF methods, only the nodal data uncertainty is considered. As the distribution automation becomes wide spread, the uncertainties of the voltage and reactive power control device settings and network reconfiguration should be also taken into account in the system operation planning.

This paper proposes a probabilistic distribution load flow method based on Monte Carlo simulations to consider the distribution network operation uncertainties. It is assumed that the uncertainties of daily time varying load, voltage regulator settings, switched capacitor operation, and network reconfiguration can be estimated or measured. The proposed method can exactly model the stochastic behavior of the distribution system operations and the distributions of voltage profiles along the feeder and network flows on various sections on the network can be accurately estimated. The probabilistic modeling of the distribution system operations and simulation technique used are described in this paper. Simulation results of the application of the method to the modified IEEE 13 node feeder test system are presented.

2 PROBABILISTIC MODELING OF THE DISTRIBUTION SYSTEM OPERATIONS

2.1 Probabilistic Modeling of Time Varying Load

The distribution system involves different types of customer loads that vary with time due to the dynamic characteristics in power system. The average load usually are used to represent the load consumption condition. When modeling time varying load uncertainty in the distribution PLF calculation, a more detailed customer load model with a daily time varying load profile can be used to represent the stochastic behaviors of load variations. In the case the probability distributions of the load can be used to represent the type of load and the statistics such as mean and standard deviation are used to indicate the degree of the load variations in each time period.

2.2 Probabilistic Modeling of Switched Capacitor Operations

The switched capacitors strategically are installed at the substation or on the network to minimize power losses through the controls of network flows. The use of on/off switched capacitors provides reactive power compensations for considerable improvement in the voltage profile when the capacitors are controlled to respond to daily, weekly or seasonal changes in feeder loads. The operations of switched capacitors in the distribution network can be modeled with a discrete probability density function to represent the probabilistic operations of the reactive power compensation.

2.3 Modeling of Voltage Regulator Operations

In addition to switched capacitors, there are a number of voltage regulators that are installed on strategic points along the feeders for maintaining system voltage profile within a desired regulation and minimizing system losses through reactive power flow controls. The voltage regulators are the transformers equipped with taps on the windings to adjust either the voltage transformation or the reactive flow through the transformer. The tap position automatically changes to keep the voltage at the regulated node within a voltage range between the minimum and maximum voltage values. When the network conditions change, the voltages at all nodes change and are controlled by voltage relays with settings to respond to the changed network condition. In general they are controlled several times per day [3,4].

The tap position variations for regulating the voltage at the controlled bus are considered when voltage regulators are modeled in the distribution PLF. For this purpose, the automatic tap adjustments of the regulators can be used for modeling the voltage regulators in the probabilistic load flow calculations. Several approaches have been proposed for automatic tap adjustment in the load flow calculations [5-8]. They are mainly classified as two categories. One is that the tap position is modeled as a control variable [5,6]. In this method the tap position is changed to ensure whether the controlled voltage is within the specified range. If the tap position hits the tap limit, it becomes to be fixed and the variable is replaced by the controlled voltage. The main disadvantage of this method is that the Jacobian may be perturbed to lead to the iterative procedure to a solution quite different from the expected one when handling the tap limits [9]. The other method is that the tap position is used as the variable throughout the whole computation [7,8]. The value of the wanted tap position is calculated by using the sensitivity calculation when the controlled voltage is not within the permissible range. The controlled voltage then is corrected into the range by using the new tap position.

An efficient tap adjustment approach based on the sensitivity analysis [9] is used in this paper for modeling the operations of voltage regulators in the distribution PLF. In the method the controlled voltage is selected as the sensitivity function and the control variable is the corresponding tap position. When the controlled voltage is not within the predefined range due to the changes in network conditions, the voltage at the controlled bus is corrected through the sensitivity analysis.

2.4 Probabilistic Modeling of Network Reconfiguration

When modeling the probabilistic feeder reconfiguration operations, the changes of the network configurations due to service restoration and load balancing are considered [10,11]. The service restoration functions are implemented by the utilities to reduce the outage time and improve the system reliability. The network configuration changes when executing service restoration function, that is to isolate the faulted sections on the network by remotely controlling sectionalizing switches and perform service restoration through interfeeder tie switches if the fault is detected on the network. Another cause of the network reconfiguration is load balancing. The effective load transfer strategies can minimize system losses and enhance system reliability by balancing the feeders loading. The loads in the feeder with larger loading are transformed to other feeders through network reconfiguration. When the network configuration uncertainty is modeled in the distribution PLF, the configuration considered for service restoration and load balancing at each time period is associated with a probability to represent the probability of occurrence of the configuration. The sum of all configurations' probability at each time period is unity.

2.5 Monte Carlo Simulations for Computing Distribution Probabilistic Load Flow

The distribution PLF problem can be studied by using simulation methods, analytical methods, or a combination of both. The simplest evaluation of the PLF problem is through Monte Carlo simulations. The MCS method is a computer simulation technique for assessing the behavior of a statistic in random samples by the empirical process of actually drawing lots of random samples [12,13]. This method is highly suitable for analysis of the problem associated with more complex and extensive descriptions. The data involved are usually required to be assigned a probability distribution that characterizes the possible variation in the parameters. The random values from these distributions are selected and used to arrive at an estimate of the solution. The overall computational procedure of the proposed distribution PLF method based on Monte Carlo simulations for a whole 24 hour period is shown in Figure 1. In the computation all of the uncertainties described previously are included.

The number of the simulation trail is given and the probability of occurrence of each possible configuration considered at h hours for service restoration and load balancing is assigned. For the configuration i, the load data and switched capacitor data are randomly sampled according to the corresponding distributions of these parameters. The sampled data then are used in the distribution load flow calculations. The tap adjustments of the voltage regulator are performed if any of the controlled voltages is not within the desired limit. In case the controlled voltage is violated, then the wanted tap position is calculated by using the sensitivity analysis and the admittances are updated based on the new tap position value and the computation then returns to the load flow iteration. If all the regulated voltages are within the corresponding ranges, the computation procedure goes to next simulation trail. The above procedure for the configuration is repeated until the simulations reach to the number that is the product of the predefined simulation trails and configuration probability. When all of the configurations have been taken care of, the load flow result quantities for different configurations are evaluated. The distributions of the load flow solution at the time are obtained and the computation then goes to the next hour.

3 TEST RESULTS AND DISCUSSIONS

The flexibility of the proposed method is tested on a modified IEEE 13 node feeder test system [14]. Figure 2 shows the diagram of the tested distribution system. The system consists of four identical feeders that are connected by interfeeder tie switches. In each feeder, four sectionalizing switches, one voltage regulator, and one switched capacitor bank are considered. The optimal network reconfigurations of each feeder for service restoration and load balancing at different time periods can obtained through efficient optimization algorithms while satisfying overload and radial configuration constraints. The uncertainties considered for the feeders shown in Figure 2 are assumed to be identical. Tables 1 to 4 show the assumed uncertainties for the feeder 1 operations. In Table 1, load data are assumed to have a normal distribution with a constant standard deviation throughout the day equals 5% or a discrete distribution to present different types of loads. Figure 3 shows the assumed daily load pattern of the feeders. Using the data in Table 1 and Figure 3 as a basis, the mean load data and its standard deviation for all nodes in the feeder at different time periods are obtained and used in the analysis. The coefficient of variation (CV), defined as the standard deviation and mean ratio, is used to indicate the dispersion of the loads.

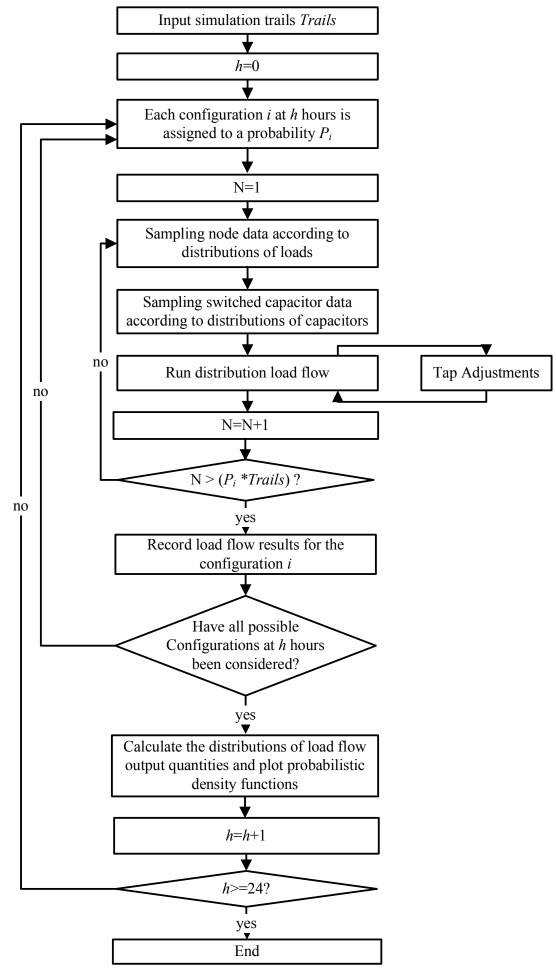


Figure 1: The computational procedure of the proposed method

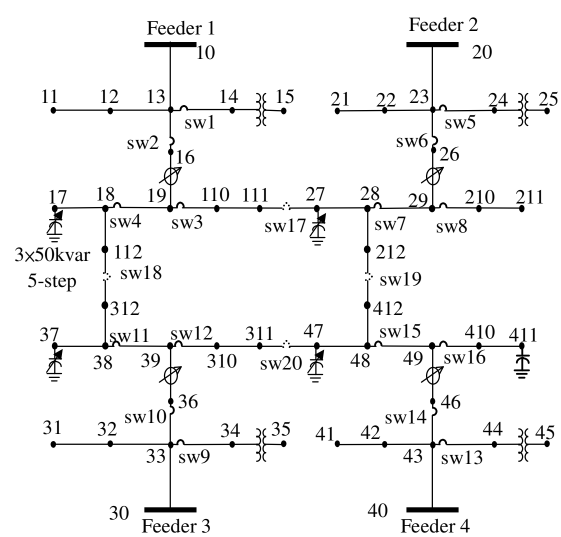


Figure 2: A modified IEEE 13 node feeder test system

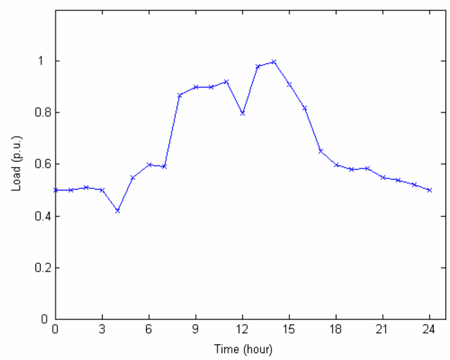


Figure 3: Daily time varying load pattern of the feeders

Table 1: Distributions of Peak Load Data

(a) Normal Distribution

Node No.	Mean and Standard Deviation of Load Data			
	Active Power		Reactive Power	
	μ(p.u.)	σ(p.u.)	μ(p.u.)	σ(p.u.)
11	0.767	0.038	0.440	0.022
12	0.567	0.028	0.417	0.021
13	0.667	0.033	0.387	0.019
14	0.567	0.028	0.417	0.021
15	1.333	0.067	0.967	0.048
16	2.810	0.141	1.540	0.077
18	0.427	0.021	0.287	0.014
19	3.850	0.193	2.200	0.110
110	0.567	0.028	0.503	0.025
112	0.427	0.021	0.287	0.014

(b) Discrete Distribution

Node No.	Active Power (p.u.)	Reactive Power (p.u.)	Probability
17	0.567	0.267	0.4
	0.667	0.314	0.2
	0.733	0.345	0.2
	0.800	0.376	0.1
	0.867	0.408	0.1
111	2.810	1.540	0.5
	3.000	1.644	0.3
	3.167	1.735	0.2

Table 2: Probabilistic Switched Capacitor Data

Switched Capacitor(p.u.)	Probability	Switching Time
0.3	0.1	9am
0.6	0.1	
0.9	0.1	
1.2	0.5	
1.5	0.2	
0.3	0.3	9pm
0.6	0.4	
0.9	0.1	
1.2	0.1	
1.5	0.1	

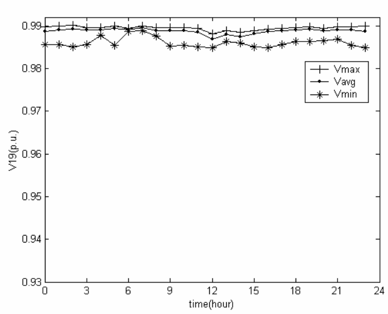
Table 3: Voltage Regulator and Transformer Data

From Node No.	14	16
To Node No.	15	19
Automatic Control	Fixed tap	Yes
Control Value	N/A	Voltage at node 19
Lower Limit (control Value)	N/A	0.985 p.u.
Upper Limit (control value)	N/A	0.99 p.u.
Lower Tap Limit	N/A	0.9
Upper Tap Limit	N/A	1.3

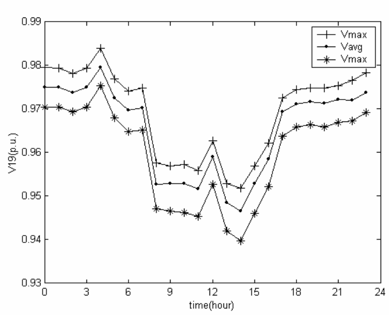
Table 4: Probabilistic Configuration Data

Operational Switches	None	(sw2,sw18) (sw3,sw17)	sw1	sw2, (sw3,sw17) (sw4,sw18)	sw4	sw3	(sw7,sw17)	(sw3,sw17)	(sw11,sw18)
Contingency (line segment on outage) or Load Balancing (operation time period)	N/A	Contingency (11-13,11-12, 12-13,13-16)	Contingency (13-14,14-15)	Contingency (16-19,18-19)	Contingency (17-18,18-112)	Contingency (19-110,110-111)	Load Balancing (11am-6pm)	Load Balancing (11am-6pm)	Load Balancing (8pm-5am)
Transferred Load (P(p.u.),Q(p.u.))	N/A	Feeder1→Feeder2 (3.5054, 1.6352) Feeder1→Feeder3 (8.1875, 0.532)	None	Feeder1→Feeder2 (3.5054, 1.6352) Feeder1→Feeder3 (1.5275, 0.345)	None	None	Feeder2 →Feeder1 (1.5275,0.345)	Feeder2 →Feeder1 (1.5275,0.345)	Feeder2 →Feeder1 (1.5275,0.345)
Configuration Probability — Time (hour)									
0	0.90	0.02	0.01	0.01	0.01	0.02	0.02	0.00	0.01
1	0.90	0.01	0.02	0.01	0.01	0.02	0.02	0.00	0.01
2	0.90	0.01	0.01	0.03	0.01	0.01	0.02	0.00	0.01
3	0.90	0.03	0.01	0.01	0.02	0.00	0.02	0.00	0.01
4	0.90	0.02	0.00	0.02	0.02	0.01	0.02	0.00	0.01
5	0.90	0.02	0.01	0.02	0.02	0.00	0.02	0.00	0.01
6	0.90	0.03	0.01	0.02	0.02	0.00	0.02	0.00	0.00
7	0.90	0.05	0.02	0.01	0.00	0.00	0.02	0.00	0.00
8	0.90	0.05	0.00	0.02	0.02	0.01	0.00	0.00	0.00
9	0.80	0.15	0.02	0.01	0.01	0.01	0.00	0.00	0.00
10	0.80	0.15	0.00	0.02	0.01	0.02	0.00	0.00	0.00
11	0.80	0.05	0.05	0.03	0.02	0.00	0.00	0.05	0.00
12	0.80	0.05	0.03	0.03	0.02	0.02	0.00	0.05	0.00
13	0.75	0.04	0.02	0.06	0.08	0.00	0.00	0.05	0.00
14	0.70	0.12	0.04	0.02	0.03	0.04	0.00	0.05	0.00
15	0.70	0.13	0.03	0.04	0.03	0.02	0.00	0.05	0.00
16	0.80	0.05	0.00	0.05	0.03	0.02	0.00	0.05	0.00
17	0.85	0.04	0.02	0.02	0.02	0.00	0.00	0.05	0.00
18	0.85	0.04	0.03	0.01	0.02	0.00	0.00	0.05	0.00
19	0.85	0.04	0.03	0.02	0.02	0.02	0.02	0.00	0.00
20	0.90	0.03	0.00	0.01	0.02	0.01	0.02	0.00	0.01
21	0.90	0.02	0.01	0.02	0.01	0.01	0.02	0.00	0.01
22	0.90	0.03	0.02	0.01	0.01	0.00	0.02	0.00	0.01
23	0.90	0.03	0.02	0.01	0.00	0.01	0.02	0.00	0.01

The probabilistic load flow solution of the feeder 1 is studied. The voltage regulator operation is first considered. Using the procedure shown in Figure 1, the distributions of the probabilistic load flow solution at different time periods are estimated by the proposed method. For each time period, 5,000 trails are used. Figures 4 and 5 show the effect of voltage regulation on the controlled voltage at node 19 for *CVs* of 5% and 20%, respectively. In the figures, the mean, the maximum and the minimum values obtained are shown for a whole 24 hour period. Figure 4(a) shows the probabilistic load flow result with the voltage regulators. In Figure 4(b) the test cases are the same as those used in Figure 4a, but considering that the voltage regulators are out of service. From Figure 4(b) it can be found that the voltage significantly varies with daily load changes. Comparing Figure 4(a) to Figure 4(b), it can be seen that when the voltage regulator is considered, the controlled voltage throughout the whole day is within the specified range (0.985 p.u. to 0.99 p.u) while the tap position is changed from 1.002 to 1.098. From the comparisons of the curves of Figures 4(a), 4(b), and 5, it can be seen that the voltage at the controlled node with voltage regulator does not significantly vary with load variations even though there is a larger uncertainty associated with the load change. The results have indicated that the proposed method gives a good modeling of voltage regulator operations and the distribution system with voltage regulators can have better voltage quality. For a better result, the voltage regulator operations should be considered in the distribution probabilistic load flow computation.



(a) with voltage regulator



(b) without voltage regulator

Figure 4: Statistic results of the voltage at node 19 under *CVs* of 5%

The voltage probability distributions of node 19 and node 15 at 2am and 2pm by using the proposed method are reported in Figures 6 and 7. As can be seen, the voltages at different nodes at different time periods can have different distributions. The shape may not be a Gaussian type. The standard deviations of the V_{19} at 2am and 2pm obtained are 0.000581 and 0.000632, respectively, and those for V_{15} are 0.000460 and 0.001300. As expected from the results that the installation of the voltage regulator can reduce the variations of the voltages at all nodes in the network. The results indicate that a probabilistic type of analysis can provide the increased amount of information obtained.

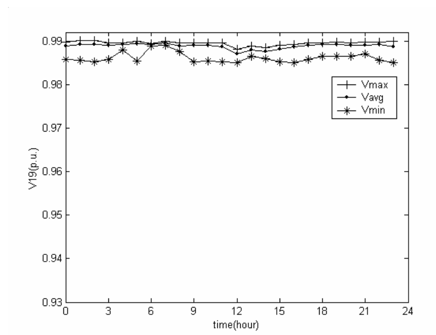
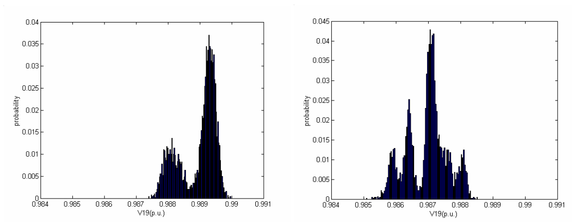
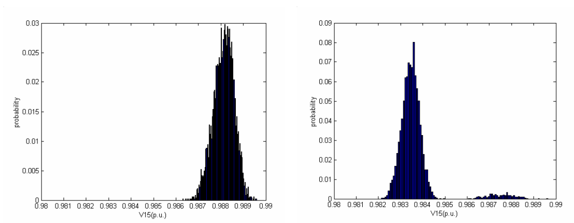


Figure 5: Statistic results of the voltage at node 19 under *CVs* of 20%



(a) 2am (b) 2pm

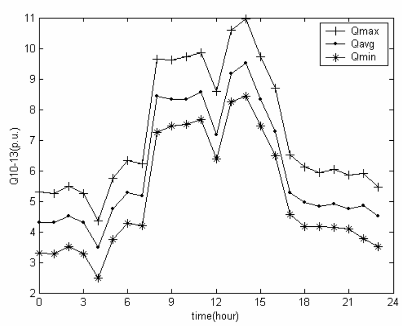
Figure 6: Distributions of the voltage at node 19 at different time periods



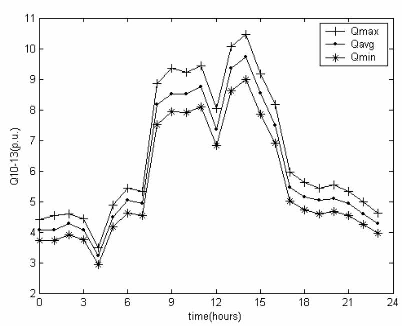
(a) 2am (b) 2pm

Figure 7: Distributions of the voltage at node 15 at different time periods

The effects of switched capacitor operations on the probabilistic load flow solution were tested and the results are reported in Figures 8(a) and 8(b). Figures 8(a) and 8(b) show the statistic results of the reactive power $Q_{10\text{-}13}$ supplied by the feeder 1 for one day period when considering the probabilistic switched capacitor data in Table 2 and a fixed compensation of 0.9 p.u., respectively. It can be seen from these figures that the standard deviation of $Q_{10\text{-}13}$ at 2pm for the probabilistic switched capacitor compensations is 0.5064 as compared to 0.2250 for the fixed compensation. Test results have shown that the variations of the reactive powers on the network are larger when the probabilistic switched capacitor compensation is modeled. This is also clear in Figures 9(a) and 9(b) which depict the probability distributions of the voltage at node 17 at 2pm with and without considering probabilistic switched capacitor operations, respectively. As can be seen from Figures 8, 9(a), and 9(b) that the probabilistic modeling of the switched capacitor operations has a larger variation in the voltages and distorts the probability distribution waveforms. For the unknown reactive compensation magnitudes, the valuable information can be obtained from these probability distributions.

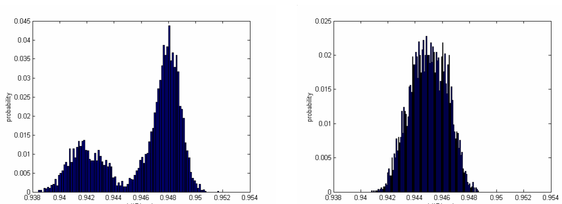


(a) with probabilistic compensations



(b) with a fixed compensation of 0.9 p.u.

Figure 8: Effects of switched capacitor operations on reactive power supplied by the feeder 1



(a) (b)

Figure 9: Distributions of the voltage at node 17 at 2pm (a) with probabilistic switched capacitor compensations (b) with a fixed switched capacitor compensation of 0.9 p.u.

The probabilistic load flow calculation considering network reconfiguration uncertainty was also performed. Using the probabilistic data in Tables 1, 2, and 3, the probabilistic load flow solution for the network reconfigurations considered in Table 4 are computed and test results are shown in Figures 10 to 13. Figure 10 shows the statistic results of the voltage at node 19 for one day period. As can be seen from Figure 10 that the minimum value of V_{19} equals zero. This is since a fault occurs on the line segment 16-19 or 18-19 and the node 19 is isolated due to the execution of the service restoration function. Figures 11(a) and 11(b) show the probability distributions of Figure 10 at 2am and 2pm, respectively. The mean and standard deviation of Figure 11(a) are 0.9575 and 0.1684 and they are 0.9673 and 0.1382 for Figure 11(b). Comparing Figures 10 and 11 to Figures 4(a) and 6, it can be found that the variation in the voltage distribution is much large and the distribution waveform is significantly distorted when network reconfiguration operations are considered. The influence of the network reconfiguration on the active power flow $P_{10\text{-}13}$ supplied by the feeder 1 is also clearly presented in Figure 12, where the probability distributions of $P_{10\text{-}13}$ at 2pm with and without considering network reconfiguration operations are shown in Figures 13(a) and 13(b), respectively. Comparing Figure 13(a) to Figure 13(b), it also can be found that the distortion of the probability density waveform due to network reconfiguration operations is clearly noted. The results have indicated that the network reconfiguration uncertainty significantly affects load flow solution distributions. The obtained information would provide a more informed observation of the distribution system operations to aid planning engineers in determining the correct system reinforcements and/or expansions.

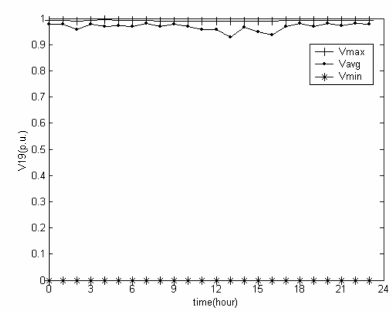
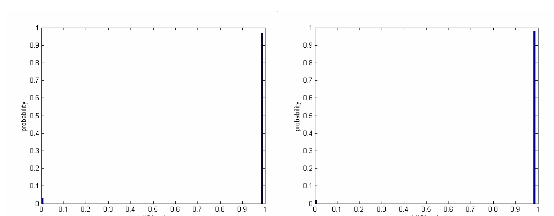


Figure 10: Statistic results of the voltage at node 19 when considering network reconfiguration operations



(a) 2am (b) 2pm

Figure 11: Distributions of the voltage at node 19 at different time periods when considering network reconfiguration operations

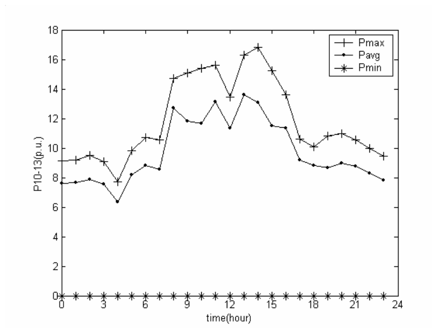
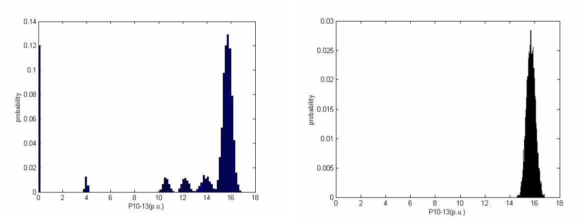


Figure 12: Statistic results of the active power supplied by the feeder 1 when considering network reconfiguration operations



(a) (b)

Figure 13: Distributions of P_{10-13} at 2pm (a) with considering network reconfiguration operations (b) without considering network reconfiguration operations

4 CONCLUSIONS

In the deregulated environment the utilities continuously assess the effects of operations strategies and system changes on their distribution network operation performance. This paper proposes a distribution probabilistic load flow method to take into account the operations of daily time varying load, voltage regulator, switched capacitor, and network reconfiguration in the load flow calculations. Based on the study results, it is shown that if the uncertainty of parameters considered in this paper can be estimated or measured, the proposed method can catch the stochastic behavior of the distribution system operations and provide true distributions of feeder voltage profiles and network flows. The system analyses models proposed in this paper can be used for modeling realistic distribution network operations and to build a base model for assessing impacts of distributed generators and voltage mitigation equipments on the performance of distribution system operations.

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BIOGRAPHY

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