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Support of distribution system using distributed wind and PV systems

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Abstract

The application of renewable distributed generation (DG) could be considered as an alternative approach for distribution system expansion planning not only to reduce power loss and carbon emission, but also to improve system voltage profile. This paper investigates technical aspects relatedto voltage support and loss reduction in distribution systems with distributed wind and solar generation. The probabilistic wind, solar, and load models have been developed in order to address uncertain nature of wind speed, solar radiation, and load demand. Investigations have been carried out using Monte Carlo based probabilistic load flow analysis to estimate the probability distributions of system state variables such as lowes nodal voltage and overall real power loss. The proposed approach is tested on a remote 11kV radial distribution feeder derived from an Integral Energy Electricity Network in NewSouth Wales, Australia.

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Support of Distribution System using Distributed Wind and PV Systems

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***Abstract*—The application of renewable distributed generation (DG) could be considered as an alternative approach for distribution system expansion planning not only to reduce power loss and carbon emission, but also to improve system voltage profile. This paper investigates technical aspects related to voltage support and loss reduction in distribution systems with distributed wind and solar generation. The probabilistic wind, solar, and load models have been developed in order to address uncertain nature of wind speed, solar radiation, and load demand. Investigations have been carried out using Monte Carlo based probabilistic load flow analysis to estimate the probability distributions of system state variables such as lowest nodal voltage and overall real power loss. The proposed approach is tested on a remote 11kV radial distribution feeder derived from an Integral Energy Electricity Network in New South Wales, Australia.**

I. Introduction

Renewable distributed generation (DG) units, such as Photovoltaic (PV) systems and wind turbine generators (WTG), have been playing an important role in recent years due to their positive impact on distribution system in terms of economical operation, energy savings, reliability improvement, and environmental benefits. However, the renewable resources are inherently intermittent and uncertainty of power availability is one of the biggest challenges associated with their integration. Therefore, it is important that the renewable DG units should be applied in a proper manner by addressing the uncertainties related to it.

To address the impact of renewable energy uncertainties on system states, many mathematical models for uncertainty analysis have been proposed in the literature. Two wind speed models based on Markov modelling technique have been proposed in [1]. An auto-regressive (AR) model has been proposed in [2] to simulate the wind speed. A time series wind speed model, named auto-correlation and moving average (ARMA) model, based on long-term measured data for different locations has been proposed in [3]. For solar radiation modelling, a Markov transition-matrix approach operating on atmospheric transmittance has been proposed in [4] to describe the statistical features of solar radiation. In [5], the simulated solar radiation has been generated based on beta distribution and the performance of the utility-interactive PV systems have been assessed. The mathematical models developed in [6] and [7] can successfully generate the hourly clearness index to model the hourly cloudy weather conditions by using monthly average clearness index as the only input. For load demand modelling, fuzzy load models [8] and probabilistic load models [9] are often used to simulate the load demand uncertainties.

In order to assess system performance with uncertain input variables, the probabilistic load flow could be a useful approach [9]. In comparison with the deterministic load flow wherein, specific values of power generations and load demands are used as inputs to obtain a crisp solution, the probabilistic load flow requires probabilistic inputs with probability distribution function (PDF) to obtain the probability distributions of system states. More system information can be obtained by using probabilistic load flow analysis, which allows planners to closely investigate the overall performance of the system. The probabilistic load flow analysis can be implemented either by using analytical approaches or numerical approaches. Although the use of the analytical approaches (such as combined Cumulants and Gram-Charlier expansion method [10], point estimation method [11]) can obtain approximate solutions with less computational burden, the assumptions made in these analytical approaches may limit the flexibility of using various probabilistic models. Alternatively, the Monte Carlo simulation [12], as one of the numerical approaches, would be more flexible to incorporate different probabilistic models and network configurations.

In this paper, a probabilistic approach for evaluating the system performance with the integration of renewable DG units is proposed. The probabilistic wind, solar and load demand models have been introduced in Section II. The proposed Monte Carlo approach for performing probabilistic load flow analysis is described in Section III. Section IV reports the realistic historical measured data and presents the simulation results for a remote 11kV radial distribution feeder derived from NSW, Australia.

II. Probabilistic Models

In order to accurately evaluate the probability distributions of system states with uncertain load demand and intermittent renewable power generation, the probabilistic models for wind, solar generation, and load demand need to be developed based on the long-term historical measured data. However, the detailed measured data may not always be available at some specific sites and the collection of measured data may need a long time with concerted effort. In such cases, it is more practical to use the probabilistic models based on the limited available measured data. This paper focuses on probabilistic load flow analysis using probabilistic system input variables (such as loading conditions and the power generated by wind and solar systems).

A. Probabilistic Load Demand

The statistical mean and standard variance of the load demand for a distribution system could be obtained in a stipulated time frame by using the historical measured data. The probability distribution of load demand statistically follows the normal distribution [9]. Therefore, the system load demand $S_{(i,t)}$ at node i in time frame t can be obtained by using the inverse normal distribution function [12] given as:

$$L_{(i,t)} = \exp(L_{\mu(i,t)}U_{(i,t)} + \frac{(L_{\sigma(i,t)}U_{(i,t)})^2}{2}) \quad (1)$$

$$S_{(i,t)} = S_{base(i)}L_{(i,t)} \quad (2)$$

where $L_{(i,t)}$ is the stochastic loading level, $L_{\mu(i,t)}$ and $L_{\sigma(i,t)}$ are the statistical mean and standard variance of loading level at node i in time frame t respectively, $U_{(i,t)}$ is a uniform distributed random number, and $S_{base(i)}$ is the base case load demand which could be derived from the average loading of a distribution feeder.

It should be noted that the detailed loading information for each node may not be available for some distribution utilities. However, the overall loading level of a distribution feeder can be measured at the substation and the load types can be identified in advance. In this paper, it is assumed that the same types of loads vary with the same trend. Consequently, the probability distribution of loading level will be identical for the same type of loads.

B. Probabilistic Wind Power Generation

In this paper, the Weibull probability distribution is used to simulate long-term wind speed characteristics. The simulated wind speed can be generated by using the inverse Weibull distribution function [13] given as:

$$v(t) = c(-\ln U(t))^{\frac{1}{k}} \quad (3)$$

where $v(t)$ is the simulated wind speed, k is the shape parameter, c is the scale parameter, and $U(t)$ is a uniform distributed random number.

With acceptable approximation, the shape parameter k and the scale parameter c can be obtained by using the statistical mean v_μ and variance v_σ of wind speed [13]:

$$k = (\frac{v_\sigma}{v_\mu})^{-1.086} \quad (4)$$

$$c = \frac{v_\mu}{\Gamma(1+\frac{1}{k})} \quad (5)$$

where $\Gamma(\cdot)$ is the Gamma function [12].

Since the simulated wind speed has been generated by using (3), the active power generated by WTG can be evaluated based on the simulated wind speed $v(t)$, the cut-in wind speed v_{ci}, the cut-out wind speed v_{co}, the rated wind speed v_r, and the rated power P_r of the WTG. The active power $P_{out}(t)$ generated by a WTG in a specified time frame t could be obtained using [14]:

$$P_{out}(t) = \begin{cases} 0 & 0 \le v(t) < v_{ci} \\ (A + Bv(t) + Cv^2(t)) \times P_r & v_{ci} \le v(t) < v_r \\ Pr & v_r \le v(t) < v_{co} \\ 0 & v_{co} \le v(t) \end{cases} \quad (6)$$

where constants A, B, C can be expressed as:

$$A = \frac{v_{ci}}{(v_{ci}-v_r)^2}(v_{ci}+v_r-4v_r(\frac{v_{ci}+v_r}{2v_r})^3) \quad (7)$$

$$B = \frac{v_{ci}+v_r}{(v_{ci}-v_r)^2}(4(\frac{v_{ci}+v_r}{2v_r})^3 - \frac{3v_{ci}-v_r}{v_{ci}+v_r}) \quad (8)$$

$$C = \frac{1}{(v_{ci}-v_r)^2}(2-4(\frac{v_{ci}+v_r}{2v_r})^3) \quad (9)$$

C. Probabilistic Solar Power Generation

In this paper, the solar power generated by the PV array is evaluated based on the intensity of the solar radiation. The hourly solar radiation incident on the PV array H_t^{pv} could be obtained using the hourly extra-terrestrial radiation data H_t^{ex} and the hourly simulated clearness index k_t:

$$H_t^{pv} = k_t H_t^{ex} \quad (10)$$

The extra-terrestrial radiation is the solar radiation on the atmosphere of the earth, which can be accurately calculated based on the earth's orbit and the location of the site. It has been indicated in [15] that the uncertainty of solar radiation on the ground is due to the stochastic cloudy weather condition rather than the extra-terrestrial radiation. The laws for calculating the extra-terrestrial radiation are not described in this paper due to the space constraint. Since the uncertain amount of solar radiation incident on the PV array is mainly affected by the cloudy weather condition. The clearness index can be used to simulate the stochastic nature of cloudy weather condition. In this paper, the hourly stochastic clearness index is obtained by using Graham's algorithm [6], [7]. The advantage of using this algorithm is that it can use monthly average clearness index as the only input for generating reasonable synthetic solar radiation data and it is applicable globally. The overall procedure of generating hourly solar radiation data is shown in Fig. 1. Once the hourly clearness index is known, the power generated by PV array P_t^{pv} could be obtained by using a standard PV model [16]:

$$P_t^{pv} = \frac{H_t^{pv}}{H_r^{pv}} P_r^{pv} \quad (11)$$

where H_r^{pv} is the rated solar radiation of the PV array, and P_r^{pv} is the rated power output of the PV array.

III. Proposed Approach

In this paper, the probability distributions of system state variables is evaluated by using Monte Carlo based probabilistic load flow analysis. Monte Carlo simulation is a stochastic

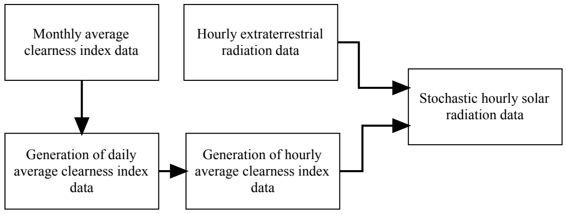

Fig. 1. Procedure for generating synthetic solar radiation data

technique that relies on iterative evaluation of a system by using randomly generated numbers [12]. For power distribution systems involving uncertain changes in load demand as well as in the renewable power output, Monte Carlo simulation can be used as an effective tool to analyse probability distributions of system state variables, such as nodal voltage, feeder current, power loss and reliability. The traditional Newton-Raphson power flow is performed in each loop of the Monte Carlo simulation, wherein the substation bus is modelled as a slack bus with specified fixed voltage. The system loads are modelled as PQ buses with specified real and reactive load demand and the renewable distributed generation units are modelled as negative loads. The convergence of probabilistic load flow can be verified by comparing the old and updated values of the estimated state variables. The flowchart of Monte Carlo simulation is shown in Fig. 2. The general equation for checking the convergence is given as:

$$\overline{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \tag{12}$$

where N is total number of evaluations, X_i is the state variables (could be nodal voltage, branch current, system losses and system reliability), and $\overline{X}$ is the average value of all X_i.

IV. Simulations and Results

A. Simulation Data

The available historical measured data including the hourly wind speed, the hourly solar radiation and the hourly load demand is used to build the probabilistic models by applying the approaches developed in Section II.

1) The Distribution Feeder under Study: The distribution feeder to be investigated is a remote 11kV radial feeder from NSW, Australia that consists of 86 system nodes including 62 load points. The topology of the feeder is shown in Fig. 3. The voltage regulation of the feeder has been achieved through a tap changing transformer at the zone substation. The hourly average load demand for each month in the annual observation period of 01/07/2007 - 30/06/2008 is shown in Fig. 4. It is assumed that all the loads are residential loads and they vary with the same trend in hourly time frames. In this paper, distributed wind and solar generation support is evaluated for the distribution feeder with a load growth of 20% over a planning period of 20 years.

2) Wind Speed Pattern: The hourly wind speed data measured at a height of 10 meters above the surface at Richmond RAAF station from year 1998 to year 2008 is obtained from Bureau of Meteorology, Australia [17]. The wind speed at hub height v_{hub} could be estimated by applying the logarithmic profile and the surface roughness length [18]:

$$\frac{v_{hub}}{v_{anem}} = \frac{\ln(m_{hub}/m_0)}{\ln(m_{anem}/m_0)} \tag{13}$$

where m_{hub} is the hub height of the wind turbine, m_{anem} is the anemometer height, m_0 is the surface roughness length, and v_{anem} is the wind speed at anemometer height.

In this paper, it is assumed that the hub height of the WTG is 50m and the surface roughness length is 0.25m. It is also assumed that the availability of wind will remain the same in

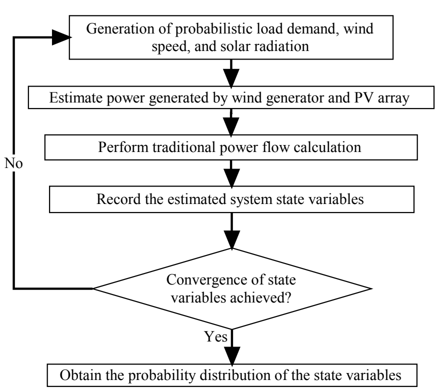

Fig. 2. Flowchart of Monte Carlo simulation

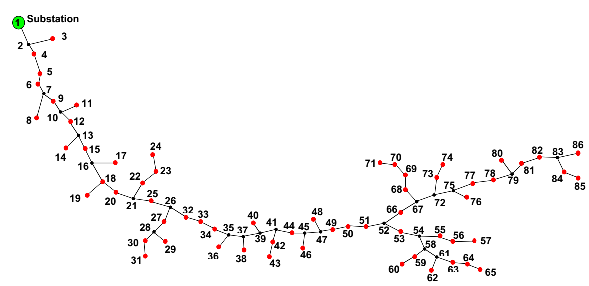

Fig. 3. Topology of the distribution feeder

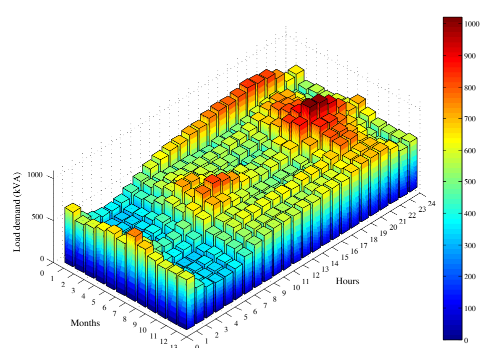

Fig. 4. Hourly average load demand

the zone involving the distribution feeder. The hourly average wind speed for each month over the observation period is shown in Fig. 5.

3) Solar Radiation: The monthly average of clearness index data from 22 years is obtained from NASA Atmospheric Science Data Centre, USA [19] and shown diagrammatically in Fig. 6. The hourly average solar radiation can be obtained by using the monthly clearness index and the extra-terrestrial radiation data, derived based on the latitude and the longitude of the investigated area. It is assumed that the solar radiation data remains the same in the proposed zone. The average hourly solar radiation is shown in Fig. 7.

B. Scenario Studies

In this section, Monte Carlo simulations with four different scenarios are performed. The probability distributions of system state variables with wind generation system and PV system are evaluated.

1) Scenario-1: Distribution System without DG Support: In this scenario, the probability distributions of system states are evaluated without the integration of DG units. The hourly average power loss for the distribution system over the planning period is around 6.265kW. The probability distributions of lowest system voltage and real power loss in the hourly time frames are shown in Fig. 8 and Fig. 9 respectively.

It can be observed from Fig. 8 that the lowest system voltage varies from 0.95 pu to 0.97 pu for more than 90% of the time in a day. It has been also seen that the lowest system voltage may stay between 0.94 pu - 0.95 pu during 18hrs - 21hrs with an average probability of 35%. In Fig. 9, it can be seen that the system real power loss is within the range of 0kW - 5kW during 2hrs - 7hrs with an average probability of 89%. For the other hours between 8hrs - 17hrs, the losses may vary between 5kW to 10kW with an average probability of 53%. During the peak hours from 18hrs - 21hrs, the losses vary between 10kW to 20kW with 45% of probability. The power losses exceed 20kW for a probability of 0%.

2) Scenario-2: Distribution System with 500kW PV System: It has been identified in the previous work [20] that the DG could be installed at node 78 to minimise the overall system investment cost. Moreover, the hourly average load demand for the distribution feeder from 7hrs to 18hrs over the planning period is 588kW. Accordingly, it is assumed in this paper that the 500kW of PV system will be installed at the node 78 and

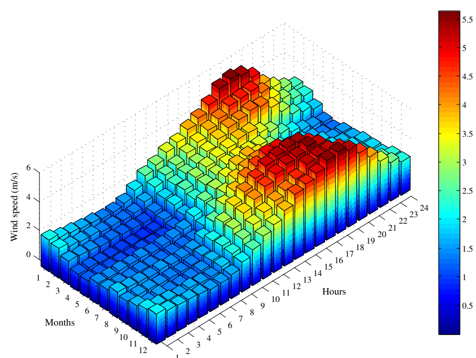

Fig. 5. Hourly average wind speed

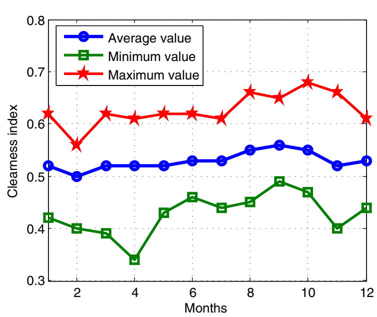

Fig. 6. Monthly average clearness index

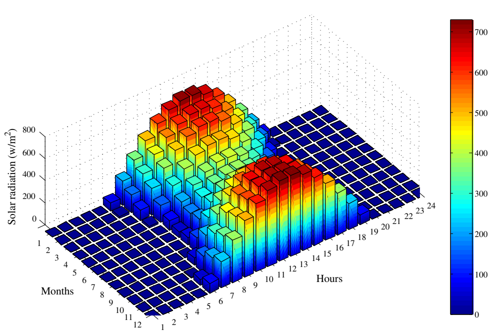

Fig. 7. Hourly average solar radiation

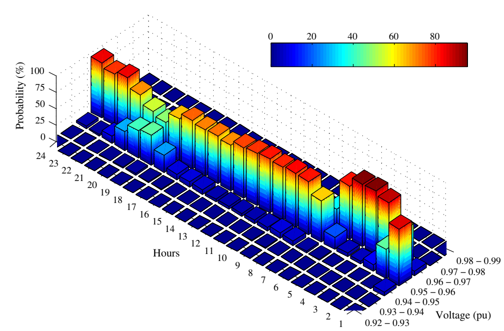

Fig. 8. Probability distribution of hourly lowest system voltage (without DG units)

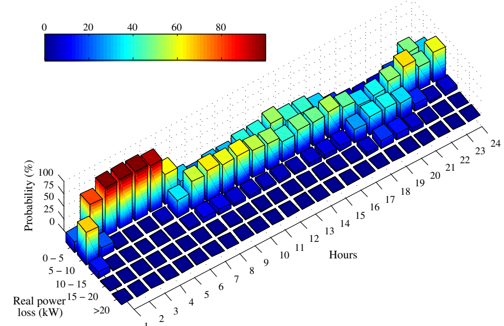

Fig. 9. Probability distribution of hourly real power loss(without DG units)

operated at unity power factor without any explicit control mechanism for output power. The probability distributions of the lowest system voltage and real power loss are shown in Fig. 10 and Fig. 11 respectively.

It can be seen that probability of the lowest system voltage in the range of 0.96 pu - 0.97 pu is significantly increased to 61% during 9hrs to 16hrs due to the real power injection from the PV system. The hourly average power loss over the planning period is around 5.193kW, which is 17.2% less than the system without DG units. It can be observed in Fig. 11 that the probability of losses in the range of 0kW - 5kW is increased significantly to 81.5% during 9hrs to 16hrs due to the availability of solar radiation. However, there is no improvement in system voltage and loss reduction during 18hrs - 21hrs due to the absence of solar radiation.

3) Scenario-3: Distribution System with 500kW Wind Generation System: It is assumed that the size of 500kW of wind generation system is installed at node 78. The wind generation system is assumed to be operated at unity power factor without any explicit control methodology for output power. In this paper, the active power generated by WTG is evaluated based on the assumptions that the cut-in wind speed is 3.5 m/s, the cut-out wind speed is 25 m/s, and the rated wind speed is 12.5 m/s. The probability distributions of the hourly lowest system voltage and the hourly real power loss are shown in Fig. 12 and Fig. 13 respectively. Due to the low hourly average wind speed, the probability distributions of lowest system voltage and system power loss are almost the same as those without DG integration. The probability of lowest system voltage in the range of 0.94 pu - 0.95 pu during 18hrs to 21hrs is slightly reduced to 32%. The hourly average power loss over the planning period is around 5.991kW, which is 4.37% less than the system without DG units.

4) Scenario-4: Distribution System with Hybrid Generation System: It is assumed that a 250kW wind generation system and a 250kW PV system are installed at node 78. It is obtained by the simulation that the hourly average system loss over the planning period has been reduced to 5.33kW, which has 15% reduction in comparison with the system without DG units. The probability distributions of system state variables are shown in Fig. 14 and Fig. 15 respectively. It can be observed that the improvement in system voltage and loss reduction are less than the system with standalone 500kW PV system due to the uncertainties associated with the availability of wind power.

V. Conclusion

This paper presents a probabilistic approach for evaluating the system performance with the integration of renewable DG units. The probabilistic models for solar radiation, wind speed and load demand have been built based on the historical measured data. The probability distributions of system states in terms of lowest system voltage and real power loss have been

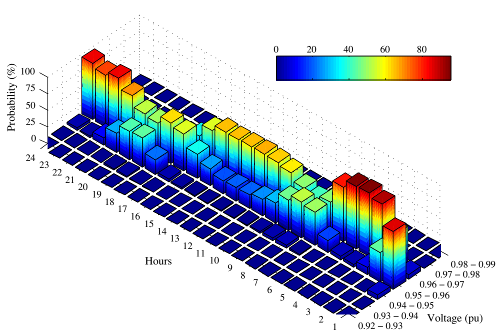

Fig. 10. Probability distribution of hourly lowest system voltage (with 500kW PV System)

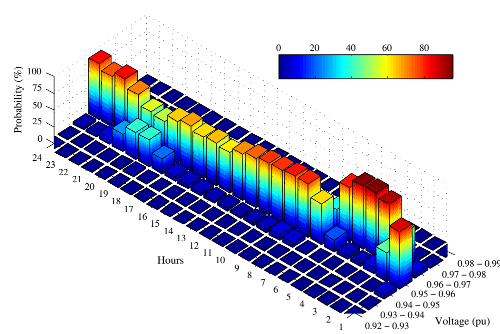

Fig. 12. Probability distribution of hourly lowest system voltage (with 500kW WTG)

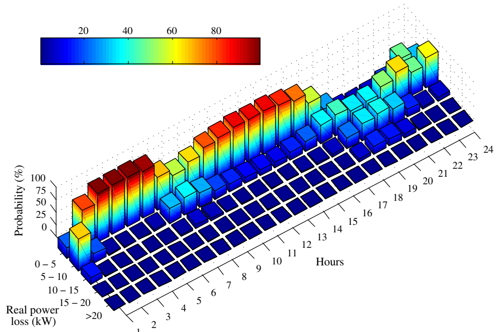

Fig. 11. Probability distribution of hourly real power loss (with 500kW PV System)

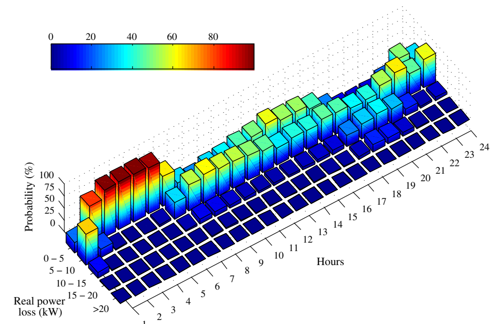

Fig. 13. Probability distribution of hourly real power loss (with 500kW WTG)

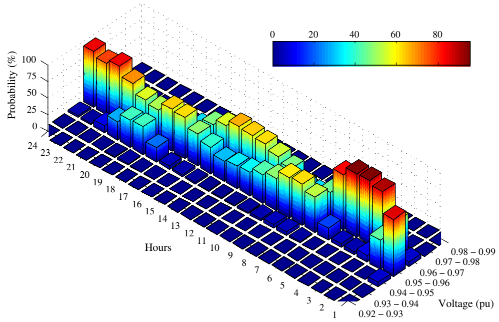

Fig. 14. Probability distribution of hourly lowest system voltage (with hybrid system)

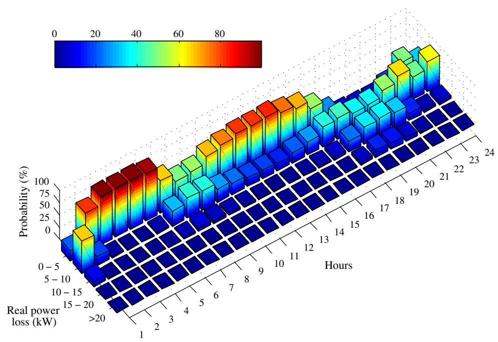

Fig. 15. Probability distribution of hourly real power loss (with hybrid system)

obtained using Monte Carlo based probabilistic load flow. The use of probabilistic load flow can obtain extra information in terms of the probability distributions of different system states. The simulation results indicate that the integration of concentrated PV system with proper size can improve voltage profile and reduce energy loss significantly. The concentrated wind generation system cannot effectively support the system due to the uncertainty in availability.

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