Adequacy Evaluation of Distribution System Including Wind/Solar DG During Different Modes of Operation

Y. M. Atwa, *Student Member, IEEE*, E. F. El-Saadany, *Senior Member, IEEE*, M. M. A. Salama, *Fellow, IEEE*, R. Seethapathy, *Member, IEEE*, M. Assam, and S. Conti, *Member, IEEE*

***Abstract*—Keen interest in the development and utilization of renewable distributed generation (DG) has been currently observed worldwide. The reliability impact of this highly variable energy source is an important aspect that needs to be assessed as renewable power penetration becomes increasingly significant. Distribution system adequacy assessment including wind-based and solar DG units during different modes of operation is described in this paper. Monte Carlo simulation (MCS) and analytical technique are used in this work with a novel utilization of the clearness index probability density function (pdf) to model the solar irradiance using MCS. The results show that there is no significant difference between the outcomes of the two proposed techniques; however, MCS requires much longer computational time. The effect of islanding appears in the improvement of the loss of load expectation (LOLE) and loss of energy expectation (LOEE).**

***Index Terms*—Distributed generation, distribution system adequacy assessment, reliability, solar energy, wind energy.**

I. Introduction

WITH power system restructuring, continuous growth in the demand, and deregulation, small, scattered generators referred to as distributed generation (DG) are predicted to play a key role in the power distribution systems. Moreover, among the different types of DG units, it is widely accepted that renewable DG units are the key to a sustainable energy supply infrastructure since they are both inexhaustible and nonpolluting. However, the intermittent nature and the uncertainties associated with the renewable resources create special technical and economical challenges that have to be comprehensively investigated in order to facilitate the deployment of these DG units in the distribution system.

Distribution system reliability and adequacy is one of the most important challenges that the system planners encounter, especially when renewable DG units are deployed in the system. The reliability aspects of utilizing renewable resources have largely been ignored in the past due to the relatively insignificant contribution of these sources in major power systems, and also due to the lack of appropriate techniques.

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Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama, and R. Seethapathy are with the Department of Electrical and Computer Engineering, University of Waterloo, ON N2L 3G1, Canada (e-mail: ymoustaf@uwaterloo.ca).

M. Assam and S. Conti are with the Department of Electrical Engineering, University of Catania, Catania 95124, Italy.

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Currently, the global trends toward increasing the sustainable power penetration in existing power system dictate a very serious need to consider their effect on the system adequacy.

The work in [1] proposed two probabilistic techniques to model the wind generation system. The first one is in the form of a capacity outage probability table based on the Weibull probability density function (pdf) of the wind speed, while the second is a Markov model based on the detailed hourly mean speed data. In [2], a probabilistic approach to capture the uncertainty associated with the renewable sources is used. Analytical approaches are proposed in [3]–[7]. In [3], an analytical approach to model wind turbine generators as multi-state unit is used, and in [4] and [5], an analytical approach to model renewable energy sources considering the correlation between the load and the renewable sources is proposed. In [6] and [7], an approach to estimating the loss of power supply probability (LPSP) of stand-alone solar generation system is developed. Deterministic chronological simulation is proposed in [8] and [9] to estimate LPSP. Monte Carlo simulation (MCS) is extensively used in [10]–[12] to evaluate the system reliability by modeling the random output of the renewable sources, load variation, and the forced outage rate (FOR) of the system component over a sufficiently long study period. During the beginning of the 21st century, [13]–[16] make pioneering efforts to apply system well-being criteria to the Small Autonomous Power System (SAPS) including renewable energy sources. They use a sequential (MCS) approach for adequacy assessment of the SAPSs with renewable energy sources. Later [17]–[19] apply a sequential (MCS) approach to calculate the loss of load expectation (LOLE) and the loss of energy expectation (LOEE) of the renewable energy sources-based SAPSs with battery storage.

From the above discussion, it is obvious that sufficient work has been done to assess the adequacy of SAPS with renewable DG units. The system well-being approach is a relatively new concept which combines the deterministic and probabilistic methods to evaluate the system adequacy. However, only MCS method has been used for the well-being assessment of a system with renewable DG units, and analytical methods have not yet been developed.

The work in this paper is a continuation of the work presented in [20]. The work presented in [20] assessed the distribution system supply adequacy when integrated with only wind-based DG units. In this paper, analytical and MCS techniques are utilized to assess the distribution system adequacy, when integrated with wind-based and solar DG units, during different modes of operation. During the grid connected mode, from the load perspective, the substation transformers act as generating units. Therefore, the adequacy of the distribution system will be assessed based on the assumption that generating units of the distribution system are the substation transformers and the DG units. During islanding mode of operation, the island adequacy is assessed based on the assumption that the island is acting as SAPS during the islanding period that is typically short. The most important issue during the islanding mode of operation is to determine the probability of the island to be successful (the DG power output within the island matches the load) or failure (there is a deficit in power generation). Therefore, unlike SAPS, there will be only two states to assess the island adequacy: 1) *success state* which is corresponding to the healthy and marginal states in SAPS; 2) *failure state* which is corresponding to the at risk state in SAPS. The island creation probability is calculated based on the status of the system components, such as feeders, busbars, and protection devices. Moreover, this work introduces a novel technique to model the solar irradiance chronologically using MCS technique.

The following control strategies are applied in the study.

- The renewable DG units are controlled to operate at unity power factor.
- The wind speed and solar irradiance data used are the average hourly values and the variations within the hour are not considered.
- Only dispatchable DG units are allowed to supply reactive power in the island.
- There is no storage option, so renewable DG output power is regulated based on load requirement; no surplus is allowed. This strategy will be applied only during islanding mode of operation. However, during the grid connected mode, the Standard Offer Program (SOP) gives the DG owner the privilege to inject all the generated power in the system.
- Load curtailment strategy will be applied only during grid connected mode; however, any deficit in generation during islanding mode will result into islanding failure.
- All generating units rating will be considered in MW; however, the reactive power will be considered as constant percentage of the load, based on the assumption that all loads are working on constant power factor.

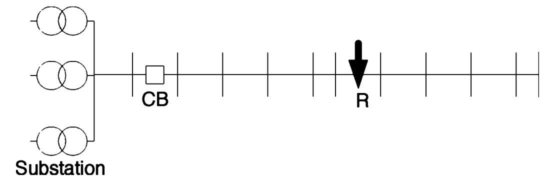

Fig. 1. Schematic diagram of a radial distribution system.

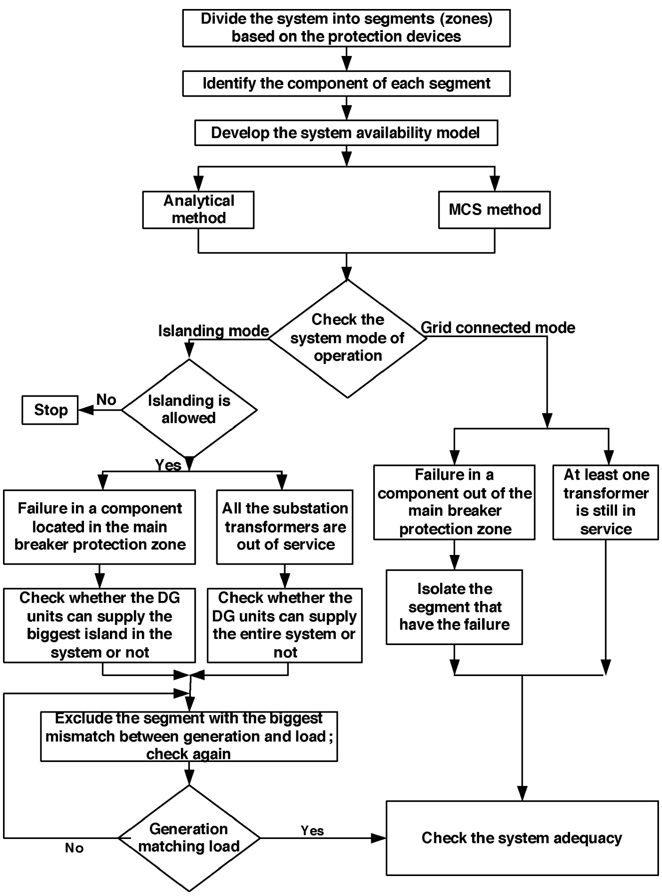

Fig. 2. Proposed adequacy assessment technique.

II. Problem Description

The ultimate goal of this work is to comprehensively assess the adequacy of radial distribution system, during different modes of operation, when integrated with different types of DG units. Particularly, the different modes of distribution system operation means grid connected mode and islanding mode. In order to proceed with this study, each transformer in the distribution substation will be considered, from the load perspective, as a generating unit. Based on that, the cases of grid connected mode and islanding mode can be defined as follows.

A. Grid Connected Mode

The system is operating in grid connected mode if:

1) *Case 1*: At least one transformer is still in service;
2) *Case 2*: A failure in any of the distribution system component out of the main breaker protection zone (i.e., any failure downstream recloser R can be isolated while the rest of the system is still connected to the grid as shown in Fig. 1).

B. Islanding Mode

Part of the system is operating in islanding mode if:

1) *Case 1*: All the transformers are out of service;
2) *Case 2*: A failure in any component of the distribution system in the main breaker (CB) protection zone (i.e., any failure upstream recloser R involves disconnecting the system from the grid as shown in Fig. 1), and the rest of the system downstream recloser R can work in the islanding mode.

In each of these modes, the system status will be checked to calculate the reliability indices of interest. In this work, LOLE is the reliability index of interest; nevertheless, more indices will be calculated. The block diagram in Fig. 2 summarizes the proposed adequacy assessment technique.

III. System Well-Being Analysis

System well-being criteria incorporate deterministic criteria in the probabilistic framework. The different well-being states associated with a generation system are healthy, marginal, and at risk. A system operates in the healthy state, when it has a sufficient amount of reserve capacity to meet a deterministic criterion as well as enough available generation capacity to serve the load. Whenever the system has enough available generation capacity, but does not have sufficient margin to meet the specified deterministic criterion, it is in the marginal state. The system is in the risk state, when the load exceeds the available capacity. The probabilities associated with healthy, marginal, and at risk states of the system are collectively recognized as well-being indices. Deterministic criteria are based on the comparison of available reserve capacity with either a fixed percentage of the total installed capacity or the capacity of largest unit or the capacity of largest unit plus a percentage of the peak load. The deterministic criterion applied in this work is presented mathematically as

$$C_R \geq C_{\mathrm{LU}} \tag{1}$$

where C_R is the available capacity reserve in MW and C_{LU} is the capacity of the largest unit in MW.

IV. Modeling of Renewable Resources and Load Data

This section explains the generation of the proposed models of renewable resources for both analytical and MCS techniques.

A. Modeling of Renewable Resources and Load Data for Analytical Technique

Unlike wind speed, there is no way to utilize a pdf to describe the random behavior of annual solar irradiance. The rationale behind that is that in order to use a pdf to model a random variable, the variable must be totally random. However, this is not the case when dealing with solar irradiance as at night time, the value of solar irradiance is certain to be zero. Therefore, in this work, the hourly wind speed and solar irradiance are modeled using proper pdfs.

In both models, the year is divided into four seasons, and a typical day is generated for each season. The day representing each season is further subdivided into 24-h segments (time segments), each referring to a particular hourly interval for the entire season. Thus, there are 96 time segments for the year (24 for each season). Considering three years of historical data, each time segment then has (270) wind speed and solar irradiance level data points (3 years × 30 days per month ×3 months per season). Then for each hour, the discrete form is created, for each continuous pdf, with a step of 1m/s for wind speed states and 0.1 for clearness index states. From the wind turbine performance curve and the PV module characteristics, the output power of the wind-based DG and the solar DG can be calculated. Hence, a complete availability model of the wind-based DG and the solar DG, for each hour, can be created.

a) Hourly Wind Speed Modeling: The hourly wind speed is modeled using Weibull pdf [21] as shown in (2):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where $f(v)$ is the distribution probability of the wind speed v, k and c are the shape parameter and scale parameter, respectively. Different methods can be used to calculate the Weibull parameters [22], [23]. Here, the parameters k and c are calculated, approximately, using the mean wind speed v_m and the standard deviation σ as follows:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \tag{3}$$

$$c = \frac{v_m}{\Gamma(1+1/k)}. \tag{4}$$

b) Hourly Solar Irradiance Modeling: In this work, the clearness index pdf [24]–[26], shown in (5), is utilized to model the hourly solar irradiance. Hourly clearness index (k_t) is defined as the ratio of the irradiance on a horizontal plane I_t (kW/m^2), to the extraterrestrial total solar irradiance I_o (kW/m^2):

$$P(k_t) = C\frac{(k_{tu} - k_t)}{k_{tu}} \exp(\lambda k_t) \tag{5}$$

where C and λ are functions of the maximum value of clearness index (k_{tu}) and the mean value of clearness index (k_{tm}) as follows:

$$C = \frac{\lambda^2 k_{tu}}{(e^{\lambda k_{tu}} - 1 - \lambda k_{tu})} \tag{6}$$

$$\lambda = \frac{(2\gamma - 17.519\exp(-1.3118\gamma) - 1062\exp(-5.0426\gamma))}{k_{tu}} \tag{7}$$

$$\gamma = \frac{k_{tu}}{k_{tu} - k_{tm}}. \tag{8}$$

Therefore, once λ is determined from (7) for a specific value of k_{tm}, the corresponding value of C can be determined from (6).

From the hourly clearness index, the solar irradiance on a surface with inclination β can be calculated as in (9):

$$I_\beta = \left[R_b + \left(\frac{1+\cos\beta}{2} - R_b\right)k + \rho\frac{1-\cos\beta}{2}\right] \cdot I_t \tag{9}$$

where

R_b	ratio of beam radiation on a tilted surface to that on a horizontal surface;
k	fraction of the hourly radiation on horizontal plan which is diffused;
ρ	reflectance of the ground.

Regarding R_b, it is calculated as in [24]. The diffuse fraction (k), the correlation between it, and the clearness index can be approximated with a piecewise linear function as follows [27]:

$$kd = p - qk_t \tag{10}$$

whereas, the reflectance of the ground (ρ) is calculated based on the nature of the ground itself [28].

Further, I_t can be expressed as a function of I_o and k_t as follows:

$$I_t = I_o k_t \tag{11}$$

$$I_o = \mathrm{SC}\left[1 + 0.33\cos\left(\frac{360n}{365}\right)\right] \times (\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi). \tag{12}$$

Hence, the final formula of I_β as a function of clearness index is as given in (13):

$$I_\beta = \left[\left(R_b + \rho \cdot \frac{1-\cos\beta}{2}\right) + \left(\frac{1+\cos\beta}{2} - R_b\right)\cdot p\right] I_o \cdot k_t - \left(\frac{1+\cos\beta}{2} - R_b\right)\cdot q \cdot I_o \cdot k_t^2. \quad (13)$$

From this formula, it can be figured out that once the clearness factor is modeled, the solar irradiance can be determined.

c) Load Modeling: In this model, the load profile is assumed to follow the IEEE-RTS system presented in [29]. This system provides weekly peak load as a percentage of the annual peak load, daily peak load cycle as a percentage of the weekly peak, and hourly peak load as a percentage of the daily peak load

B. Modeling of Renewable Resources and Load Data for MCS Technique

a) Wind Speed Modeling: Weibull cumulative density function (cdf) with its inverse (14), (15) have been utilized to simulate the wind speed chronologically using MCS:

$$F(v) = 1 - e^{[-(\frac{v}{c})^k]} \quad (14)$$

$$V = -c\ln(1-u)^{1/k} = -c\ln(u)^{1/k} \quad (15)$$

where u are the random numbers uniformly distributed on [0, 1].

b) Solar Irradiance Modeling: In order to chronologically model the solar irradiance using MCS technique, the clearness index pdf is integrated, and then inverted to get the inverse transform of the clearness index (cdf). Once the invertible cdf is created, MCS can be utilized to model the clearness index and hence the solar irradiance. The process of generating the invertible cdf is elaborated herein.

The pdf of the clearness index can be written as in (16); hence, by integrating the pdf, using integration by parts, the cdf of the clearness index is found to be as in (18):

$$P(k_t) = \left[e^{\lambda \cdot k_t} - \frac{1}{k_{tu}} \cdot k_t \cdot e^{\lambda \cdot k_t}\right] \quad (16)$$

$$\text{cdf}(k_t) = \int P(k_t)\cdot dk_t + c \quad (17)$$

$$\text{cdf}(k_t) = \frac{C}{\lambda}\left[\left(\frac{\lambda \cdot k_{tu} + 1 - \lambda \cdot k_t}{\lambda \cdot k_{tu}}\right)\cdot e^{\lambda k_t}\right] + c. \quad (18)$$

The integration constant c is found from the final value condition mentioned in (19). Based on this condition, the integration constant was found to be as shown in (20):

$$\text{cdf}(k_{tu}) = 1 \quad (19)$$

$$c = -\frac{C}{\lambda}\left(1 + \frac{1}{\lambda \cdot k_{tu}}\right). \quad (20)$$

In order to get the inverse of the cdf, the original cdf is rearranged using mathematical manipulation as in (21)–(39). Then a Lambert W function [30] is used to get the inverse of the cdf.

$$\text{cdf}(k_t) = \frac{C}{\lambda}\left[\left(\frac{\lambda \cdot k_{tu} + 1}{\lambda \cdot k_{tu}} + \frac{-1}{k_{tu}} \cdot k_t\right)\cdot e^{\lambda k_t}\right] + c \quad (21)$$

$$\text{cdf}(k_t) = \frac{C}{\lambda}[(a + b \cdot k_t)\cdot e^{\lambda k_t}] + c \quad (22)$$

where

$$a = \frac{\lambda \cdot k_{tu} + 1}{\lambda \cdot k_{tu}} \quad (23)$$

$$b = \frac{-1}{k_{tu}}. \quad (24)$$

Then, by doing the substitutions shown in (25) and (26), the cdf is changed to the form shown in (27):

$$y = a + b \cdot k_t \quad (25)$$

$$z = \frac{\lambda \cdot y}{b} \quad (26)$$

$$\begin{aligned}\text{cdf} &= \frac{C}{\lambda}\left(y \cdot e^{\lambda(\frac{y-a}{b})}\right) + c \\ &= \frac{C}{\lambda}\left(y \cdot e^{(\frac{\lambda \cdot y}{b})} \cdot e^{(\frac{-\lambda \cdot a}{b})}\right) + c \\ &= \frac{C}{\lambda} \cdot e^{(\frac{-\lambda \cdot a}{b})}\left(y \cdot e^{(\frac{\lambda \cdot y}{b})}\right) + c \end{aligned} \quad (27)$$

$$\text{cdf} = \text{const}.z \cdot e^z + c \quad (28)$$

$$\text{const} = \frac{C \cdot b}{\lambda^2} e^{(-\frac{\lambda a}{b})}. \quad (29)$$

Last, a Lambert W function is used to find the inverse of the cdf as follows:

$$z \cdot e^z = (\text{cdf} - c)/\text{const} \quad (30)$$

$$z = W((\text{cdf} - c)/\text{const}). \quad (31)$$

c) Load Modeling: The MCS also requires chronological load data. However, because the load variation is much slower than the wind speed and the solar irradiance, therefore, the load will be assumed to be constant during a given time and changes discretely for every time segment. The load value during each time segment is determined from the historical data regarding the system under study.

V. Calculation of the Output Power of PV Modules and Wind Turbines

This section describes the calculation of the output power of the PV module and the wind turbine corresponding to each state, using the characteristics of the PV module and the wind turbine power performance curve.

A. Calculation of the PV Module Output Power

The output power of the PV module is dependent on the solar irradiance and ambient temperature of the site as well as the characteristics of the module itself. Therefore, once the clearness index pdf is generated for a specific time segment, the output power during the different states is calculated for this segment using (32)–(36):

$$Tc = T_A + I_\beta\left(\frac{N_{\text{OT}} - 20}{0.8}\right) \quad (32)$$

$$I = I_\beta[I_{\text{sc}} + K_i(Tc - 25)] \quad (33)$$

$$V = V_{\text{oc}} - K_v * Tc \quad (34)$$

$$P_{I_\beta}(I_\beta) = N * \text{FF} * V * I \quad (35)$$

$$FF = \frac{V_{\text{MPP}} * I_{\text{MPP}}}{V_{\text{oc}} * I_{\text{sc}}}. \quad (36)$$

T_c is the cell temperature °C during state y. T_A is the ambient temperature °C. K_v is the voltage temperature coefficient V/°

C. K_i is the current temperature coefficient A/°C. $N_{\rm OT}$ is the nominal operating temperature of cell in °C. FF is the fill factor. $I_{\rm sc}$ is the short circuit current in A. $V_{\rm oc}$ is the open circuit voltage in V. $I_{\rm MPP}$ is the current at maximum power point in A. $V_{\rm MPP}$ is the voltage at maximum power point in V. $P_{I\beta}$ is the output power of the PV module during state y.

B. Calculation of the Output Power of a Wind Turbine

The output power of a wind turbine is dependent on the wind speed at the site as well as the parameters of the power performance curve. Therefore, once the Weibull pdf is generated for a specific time segment, the output power during the different states is calculated for this segment using the following equation [31], [32]:

$$P_V(v) = \begin{cases} 0 & 0 \le v \le v_{\rm ci} \\ P_{\rm rated} * \frac{(v-v_{\rm ci})}{(v_r-v_{\rm ci})} & v_{\rm ci} \le v \le v_r \\ P_{\rm rated} & v_r \le v \le v_{\rm co} \\ 0 & v_{\rm co} \le v \end{cases} \tag{37}$$

where $v_{\rm ci}, v_r$, and v_{co} are the cut-in speed, rated speed, and cut-off speed of the wind turbine, respectively. P_V is the output power of the wind turbine.

VI. Adequacy Assessment During Islanding Mode of Operation

The segmentation concept will be utilized to determine the island creation probability [33]. The segmentation concept means that the distribution system will be modeled in terms of segments not components. A segment is a group of components whose entry component is a switch or a protective device, and each segment will have only one switch or protective device. This means that any segment can operate in the islanding mode if and only if there is a DG, connected to the segment, with an output power matching the segment's load during the island period. The concept of segmentation is based on the fact that any fault in a component downstream of a protection device and within its zone of protection will cause an interruption of power to those customers in that zone. This means that all the customers in any zone have the same reliability level and can be treated as one customer.

A. Monte Carlo Method for Island Adequacy Assessment

Using MCS, the adequacy assessment during islanding mode of operation is straight forward from the recorded date regarding the status of the system components and the output of the generating units during each time interval.

B. Analytical Method for Island Adequacy Assessment

Analytically, the adequacy assessment during islanding mode of operation requires the following two steps.

a) Step 1: Calculating the Probability of the Island to be Created: Segmentation concept will be utilized to measure the probability of island creation as follows.

The down time of any segment depends on the set (G) which contains all segments in the series path between the main substation and the segment under study including the segment itself. This means that a failure of any component in any of these segments requires waiting for the repair time of this component in order to successfully restore power. As shown in Fig. 3, if the segment under study is seg #3, then $\text{set}G : \{\text{seg}\,\#1, \text{seg}\,\#2, \text{seg}\,\#3 \text{ and substation}\}$.

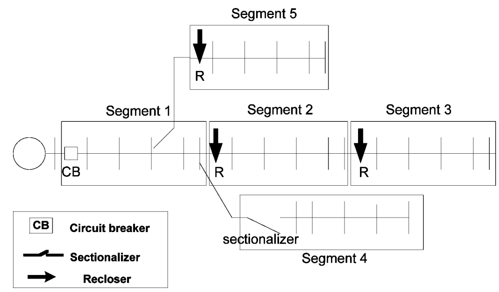

Fig. 3. Segmentation concept.

Based on this concept the down time of any segment can be calculated as follows:

$$DT_g = \left(\sum_{j \in \text{set}\, G} \sum_{i=1}^{m} \text{sfr}_i \times \text{rt}_i \right) \tag{38}$$

where

DT_g average annual outage time of segment g (hours/year);

sfr_i sustained failure rate of component i (failure/year);

rt_i repair time of component i in segment j (hour);

m number of components in segment $j \in \text{set}\, G$.

However, the island will be created when the fault has occurred in any segment of set G except the segment under study. For example, segment 3 will operate in the islanding mode if the fault occurred in the substation, segment 1, or segment 2. Hence, the probability of segment g to be working in the islanding mode $(P_g\{\text{island}\})$ in each instant of the year can be calculated as follows:

$$P_g\{\text{island}\} = \frac{\left(\sum_{\substack{j \in \text{set}\, G \\ j \neq g}} DT_j \right)}{8760}. \tag{39}$$

b) Step 2: Calculating the Probability of the Island to be Success: In the first step, the probability of creating an island is calculated, while in this step, the probability of an island to be success will be calculated. The necessary condition for an island to be successful is

$$P_G \ge P_L + P_{\rm loss} \tag{40}$$

where

P_G generated power of the DGs connected to the island;

P_L load power of the same island;

$P_{\rm loss}$ power loss in the island (assumed to be 5% [34] of the current load).

So the probability of an island to be successful $(P_g\{\text{success}\})$ depends on the probability of the DG units in the island to match the total island load and the island losses $(P_g\{\text{enoughDG}\})$ during the period of islanding. Given that the probability that the DG units match the load and the probability of creating an island are independent, therefore, the probability of success for the islanding mode can be obtained by convolving the two probabilities as shown in the following equation:

$$P_g\{\text{success}\} = P_g\{\text{island}\} \times P_g\{\text{enoughDG}\}. \tag{41}$$

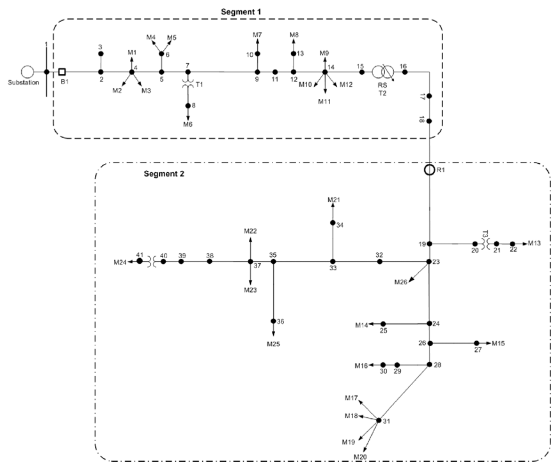

Fig. 4. System under study.

VII. Case Study

The system under study, as shown in Fig. 4, is a practical rural distribution system. The main substation at bus 1 consists of four transformers each of 5 MW with FOR of 0.02. The regulating station between buses 15 and 16 is used to boost the voltage in order to maintain the voltage drop at the end users within accepted limits. The data of the system are given in [20]. Based on the segmentation concept, this system is divided into two segments, where segment 1 has an aggregated peak load of 8.096 MW and is protected by the circuit breaker B1. Segment 2 has an aggregated peak load of 8.165 MW and is protected with the recloser R1.

If the distribution system is to rely only on the wind-based DG units to supply the load during the islanding operation, stability problems might arise. This is due to the fact that wind-based DG units are characterized by a high level of random power fluctuations that is relatively higher than load fluctuations leading to power mismatch. Conventional DG units, such as diesel generators, respond to these stability problems by changing the supply power to match the demand through either excitation or governor controls, which consequently control the island frequency and voltage. This calls for sharing the load between wind-based and conventional DGs. In this way, the useful capacity of the wind-based DGs is calculated and added to the available capacity of the conventional DGs in order to create the generation model.

Three types of DG units will be connected to the distribution system; the first one is diesel DG which consists of two diesel generators each of 2.5 MW (60% of the peak load in segment 2) [35] connected to bus 28 with FOR of 0.05; the second one is wind-based DG which consists of one wind turbine of 1 MW connected at bus; and the third one is solar DG unit of 2 MW connected to bus 39. The characteristics of the wind turbine and the PV modules are given in [20].

The failure rate and repair time of different components in the system (e.g., cables, busbars, breakers, etc.) are given in [36]. Based on the system configuration, the modes of the system operation are as follows.

A. Grid Connected Mode

1) *Case 1*: At least 1 transformer is in service. In this case, the total power from the transformers and the DG units are aggregated and compared to the total load to check the system status.
2) *Case 2*: A failure at segment 2. In this case, only the power from the transformers is compared to the load of segment 1 to check the status of this segment.

B. Islanding Mode

1) *Case 1*: The four transformers are out of service. In this case, only the power of the DG units is compared to the total load to check the system status; however, during at risk states, the power of the DG units will be compared to the loads of segment 2.
2) *Case 2*: A failure occurred in segment 1. In this case, only the power of the DG units is compared to the load of segment 2 to check the status of this segment.

VIII. Results

In this section, the MCS and analytical technique are applied to the system under study to assess its adequacy during different modes of operation.

A. Monte Carlo Technique

a) Wind Speed and Solar Irradiance Simulation: Wind speed and solar irradiance are modeled chronologically using (18) and (35), respectively.

b) Hardware Simulation: Hardware simulation includes the simulation of the up and down state of all the system components (e.g., generating units, feeders, etc.). The up and down states of all the system components have been simulated using exponential distributions [16].

c) Load Modeling: The hourly load values are based on historical data from the years 2005, 2006, and 2007. Since the reliability assessment needs to be studied over a large number of years, the hourly load are assumed to be the same every year.

d) Stopping Criterion: Let X be the reliability index of interest; $E(X)$ and $\sigma(X)$ are the mean and the standard deviation. Hence, the stopping criterion is as follows:

$$\frac{\sigma[E(X)]}{E(X)} \leq \varepsilon \tag{48}$$

where ε is the specified tolerance.

B. Analytical Technique

a) Modeling of the Passive Components: Based on (38)–(41), the probability of a failure in segment 2 is calculated to be **0.000898**. However, the probability of island creation in segment 2 is calculated to be **0.00084**.

b) Modeling of the Conventional Generating Units: The availability models of the two diesel DG units and the four transformers are given in [20].

c) Modeling of Renewable Generating Units: In this work, Weibull pdf and the clearness index pdf have been utilized to describe the hourly wind speed and solar irradiance, respectively.

d) Modeling of the Load: The load profile is assumed to follow the IEEE-RTS. From this model and three years of historical data regarding the system under study hourly load, a typical daily load profile for each season has been generated as a percentage of the annual load as shown in Table I.

e) Combining the Generation and Load Models: During the grid connected mode, the total generation model should include the power from transformers, diesel DG units, the wind-based DG, and the solar DG; however, during the islanding

TABLE I
LOAD DATA

Hour	Winter	Spring	Summer	Fall
12-1 am	0.4757	0.3969	0.64	0.3717
1--2	0.4473	0.3906	0.60	0.3658
2--3	0.4260	0.3780	0.58	0.3540
3--4	0.4189	0.3654	0.56	0.3422
4--5	0.4189	0.3717	0.56	0.3481
5--6	0.4260	0.4095	0.58	0.3835
6--7	0.5254	0.4536	0.64	0.4248
7--8	0.6106	0.5355	0.76	0.5015
8--9	0.6745	0.5985	0.87	0.5605
9--10	0.6816	0.6237	0.95	0.5841
10--11	0.6816	0.6300	0.99	0.5900
11--12pm	0.6745	0.6237	1.00	0.5841
12--1	0.6745	0.5859	0.99	0.5487
1--2	0.6745	0.5796	1.00	0.5428
2--3	0.6603	0.5670	1.00	0.5310
3--4	0.6674	0.5544	0.97	0.5192
4--5	0.7029	0.5670	0.96	0.5310
5--6	0.7100	0.5796	0.96	0.5428
6--7	0.7100	0.6048	0.93	0.5664
7--8	0.6816	0.6174	0.92	0.5782
8--9	0.6461	0.6048	0.92	0.5664
9--10	0.5893	0.5670	0.93	0.5310
10--11	0.5183	0.5040	0.87	0.4720
11--12am	0.4473	0.4410	0.72	0.4130

TABLE II
ADEQUACY INDICES IN GRID CONNECTED MODE

Grid-connected mode				
Adequacy indices	**Case 1**		**Case 2**	
	MCS	Analytical	MCS	Analytical
LOLE (hr/year)	4.166	3.7516	0.0043	0.0047
LOLP	0.0476	0.04282	4.905E-05	5.36E-05
LOEE (MWh/year)	3.08	2.9	0.0040	0.0042
Period of healthy state(hr/year)	8571.6	8592.8	7.7700	7.7594
Probability of Healthy state	97.85	98.09	0.0886	0.0885
Period of Marginal state (hr/year)	184.23	163.404	0.0920	0.1060
Probability of Marginal state	2.10	1.87	0.0011	0.0012

mode, the total generation model should only include the power from diesel DG units, the wind-based DG, and the solar DG.

The outcomes of the two techniques during different modes of operation are listed in Tables II and III, which reveal that the results of the two techniques are very close to each other.

From the availability model of the transformers, it is evident that the probability of the four transformers to be out of service is almost zero; therefore, case 1 of the islanding mode of operation (four transformers are out of service) is neglected in the study.

From Table III, it can be figured out that allowing the islanding has a notable impact on the improvement of the system adequacy.

TABLE III
ADEQUACY INDICES IN ISLANDING MODE

Islanding mode (case 2)				
Adequacy indices	**Islanding not allowed**		**Islanding allowed**	
	MCS	Analytical	MCS	Analytical
LOLE (hr/year)	7.1892	7.3584	2.1876	2.8891
LOLP	0.00081	0.00084	0.0249	0.0329
LOEE (MWh/year)	35.824	36.71	11.781	13.076

IX. CONCLUSION

In this work, the adequacy of a radial distribution system including different types of DG units has been assessed during different modes of operation. Analytical technique has been utilized to assess the system adequacy by modeling the load behavior using IEEE_RTS system and creating the multi-state availability model of all the generating units. Moreover, a novel technique for modeling solar irradiance chronologically using MCS has been proposed. MCS technique, which is the common technique for this kind of analysis, has been used for the same problem in order to check the validity of the analytical technique. The results show that there is no significant difference between the outcomes of the two proposed techniques. Moreover, it was found that integrating DG units with the system has a notable impact on the improvement of the system adequacy and allowing islanding mode of operation add more improvement to this adequacy.

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Y. M. Atwa (S'06) was born in Alexandria, Egypt, in 1975. He received the B.Sc. and M.Sc. degrees in electrical engineering from Alexandria University, Alexandria, Egypt, in 1998 and 2004, respectively. He is currently pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada.

His research interests are distribution system planning, power quality, reliability, and distributed generation.

E. F. El-Saadany (SM'05) was born in Cairo, Egypt, in 1964. He received the B.Sc. and M.Sc. degrees in electrical engineering from Ain Shams University, Cairo, Egypt, in 1986 and 1990, respectively, and the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 1998.

Currently, he is an Associate Professor in the Department of Electrical and Computer Engineering, University of Waterloo. His research interests are distribution system control and operation, power quality, distributed generation, power electronics, digital signal processing applications to power systems, and mechatronics.

M. M. A. Salama (F'02) received the B.Sc. and M.Sc. degrees in electrical engineering from Cairo University, Cairo, Egypt, in 1971 and 1973, respectively, and the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 1977.

Currently, he is a Professor in the Department of Electrical and Computer Engineering, University of Waterloo. His interests include the operation and control of distribution systems, power-quality monitoring and mitigation, asset management, and electromagnetic. He has consulted widely with government agencies and the electrical industry.

Dr. Salama is a registered Professional Engineer in the Province of Ontario.

R. Seethapathy (M'76) is currently Manager—Distributed Generation, and Advanced Grid Development, Hydro One Networks, Inc., Toronto, ON, Canada.

Mr. Seethapathy sits on several T&D/DG committees at the PES/IEEE and CIGRE. He is also a Registered Professional Engineer in the Province of Ontario.

M. Assam received the first and second electrical engineering level degrees from the University of Catania, Catania, Italy, in 2006 and 2010, respectively. He is currently pursuing the M.A.Sc. degree in the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada.

His research interests include distributed generation, renewable energy modeling, and reliability.

S. Conti (S'97–M'01) received the Five-Years Second Level Degree with honors and the Ph.D. degree in electrical engineering from the University of Catania, Catania, Italy, in 1997 and 2001, respectively.

She became a professional engineer at the University of Catania in 1997. In December 2002, she joined the Department of Electrical, Electronics and Systems Engineering, University of Catania, as a Researcher/Assistant Professor in Power Systems. At present, she is Aggregate Professor of Power Systems Dynamics and Control at the Department of Electrical, Electronics and Computer Engineering in the same university. Her research interests include power systems reliability, control and protection; integration of DG with distribution networks and SmartGrids; autonomous and non-autonomous operation of microgrids; and optimization techniques applied to electrical power systems.