Reliability assessment of distribution system with the integration of renewable distributed generation

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HIGHLIGHTS

- Addresses impacts of renewable DG on the reliability of the distribution system.
- Multi-objective formulation for maximizing the cost saving with integration of DG.
- Uses Markov model to study the stochastic characteristics of the major components.
- The investigation is done using modified RBTS bus test distribution system.
- Proposed approach is useful for electric utilities to enhance the reliability.

ARTICLE INFO

ABSTRACT

Recent studies have shown that renewable energy resources will contribute substantially to future energy generation owing to the rapid depletion of fossil fuels. Wind and solar energy resources are major sources of renewable energy that have the ability to reduce the energy crisis and the greenhouse gases emitted by the conventional power plants. Reliability assessment is one of the key indicators to measure the impact of the renewable distributed generation (DG) units in the distribution networks and to minimize the cost that is associated with power outage. This paper presents a comprehensive reliability assessment of the distribution system that satisfies the consumer load requirements with the penetration of wind turbine generator (WTG), electric storage system (ESS) and photovoltaic (PV). A Markov model is proposed to access the stochastic characteristics of the major components of the renewable DG resources as well as their influence on the reliability of a conventional distribution system. The results obtained from the case studies have demonstrated the effectiveness of using WTG, ESS and PV to enhance the reliability of the conventional distribution system.

1. Introduction

The main function of a power system is to supply electricity to its customers at optimal operating costs with the assurance of a reasonable quality and continuity at all times [1]. Reliability is the probability that a power system will perform its functions adequately without any failure within a stipulated period of time when subjected to normal operating conditions [2]. The reliability study can be utilized to assess the performance of the distribution system based on the availability of suitable input component data and the configuration of the system. The reliability assessment can also be used to identify the malfunctional components that need urgent replacement in the distribution system as well as recommending the numbers of new components that should be incorpo-

rated in order to improve the reliability of the networks [3]. Owing to these technical and economic attributes, the reliability technique has been accepted as a benchmark for power system design and operation at all phases of the power system, i.e. conceptual, design, planning and operational phases [4].

The power system is in a significant phase of shifting from a conventional distribution system to the smart grid system with the integration of renewable energy resources (RER) [5–7]. This allows more intelligent state of the art technologies and renewable DG units to be integrated into the transmission and distribution (T&D) systems as a measure to improve the reliability of the system. The integration of renewable DG units and more intelligent technologies into a power system will reduce the outage duration and the interruption cost and also increase the revenue of the utilities owing to quick power restoration and the improved utilization of the distribution system capacity. Power utilities have encouraged the integration of RERs into their networks having ana-

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lyzed the environmental, technical and economic impacts of using these resources to enhance the reliability of the distribution system. The integration of renewable DG units into a conventional distribution system depends on the power output of the DG units, availability of wind speed and solar irradiance based on the specifications of the original equipment manufacturers (OEM), repair time, configuration of the network, consumer load demand, etc. The performance of the WTG and PV can be analyzed by using the historical meteorological data of the sites where the units are to be installed, so that it will be very easy to predict the availability of the local renewable energy resources on an hourly basis.

This research work is aimed at exploring renewable energy resources to ameliorate the reliability of the distribution system and to reduce the cost that is associated with the power outage. Renewable DG units have the potential to enhance the reliability of the distribution system, to optimize greenhouse gas emissions and the fuel consumption cost of the conventional power systems [7–9]. This work focuses on developing a reliability evaluation framework for a conventional power system in the presence of WTG, ESS and PV to the reduce power outage which is one of the challenges of the distribution system. The main objective of this work is achieved by integrating renewable energy system, which consists of WTG, ESS and PV units, into a conventional distribution system at a number of bus bars within the network. The distributed energy resources (DER) at the respective bus bars are designed in such a way that their operations depend on the availability of the local RERs. This paper presents a methodology that allows multiple renewable DG and ESS units at various states to be integrated into a conventional distribution system.

It has been reported in many literatures that the distribution system contributes the greatest percentage of power outage at the consumer load points owing to the radial nature of the networks [4]. Therefore, the reliability assessment of the distribution system in the presence of WTG, ESS and PV has drawn the attention of many researchers. The impact of renewable DG and battery storage units on the reliability of a conventional distribution system has been studied in [10,11]. Arifujjaman et al. [12] have explored the characteristics of the ESS to optimize power system losses, efficiency, reliability and energy cost. Bhandari et al. [13] have presented the economical hybridization methods to estimate the impacts of PV, wind and micro hydro units on the environmental sustainability. Ogunjuyigbe et al. [14] have proposed a Genetic Algorithm (GA) to optimize the dump energy, life cycle cost and CO_2 emissions of a power system that consists of PV-wind-diesel-battery hybrid energy systems. They have explored the characteristics of the renewable energy resources to minimize the objective function of the proposed power system. Ahadi et al. [15] have presented a new approach for optimal combination of renewable energy sources in stand-alone systems with the main objective of minimizing the total cost of the system.

Duan et al. [16] have presented a network reconfiguration method to improve the reliability indices of a conventional distribution system. The method, however, depends on the availability of a power supply from the utilities and the capacity of the power system components. Souza et al. [17] have presented a pseudo-dynamic planning approach to estimate the impact of reliability assessment on the distribution system. The technique is tested on a 54-bus distribution network and the results obtained from the technique have demonstrated the effectiveness of the pseudo-dynamic planning method on a conventional distribution network. Abbasi et al. [18] have proposed distribution system expansion planning to improve the reliability of a conventional distribution system. This approach is aimed at optimizing the system's reliability indices, power system investment and operating costs. The method has demonstrated that it can be effectively used to improve the reliability of a power system. Locatelli et al. [19]

have proposed an optimal switch allocation in a conventional distribution system for reliability improvement. This technique minimizes the cost that is associated with energy not supplied in a power system. Ghajar et al. [20] have presented different methods for evaluating the reliability worth and the cost of the power system. These techniques are based on customer damage functions (CDF) and the interrupted energy assessment rates for each load point in the network. The proposed model is illustrated by an interruption cost data of the IEEE-reliability test system (IEEE-RTS). The work is aimed at optimizing the costs and benefits of using DG units to reduce power system interruption.

Monte Carlo simulation is one of the techniques for calculating the reliability indices of a conventional distribution system with the integration of the renewable DG and ESS units [21–26]. The techniques present the stochastic characteristics of the RERs and their impact on the system reliability. The simulated results from the Monte Carlo simulation methods illustrate the fact that the stochastic behaviour of the renewable energy technologies plays an important role in determining the reliability indices of the distribution system. The Monte Carlo simulation technique presented in [21–26], can be very effective in giving approximate solutions to the power system problems. The results are, however, not accurate when compared with other techniques. The computational time is lengthy, and it is not easy to implement when applied to the large electrical power networks that contain multi-objective functions. Owing to the computational time, it can be used only in small electrical systems.

The reliability indices of a conventional distribution system can also be estimated based on the analytical method that can handle numerous generating units [27]. The analytical method for estimating the reliability indices of a conventional distribution system in the presence of DG units is adopted to carry out a reliability assessment of a power system [27]. This technique is based on the fact that the conventional DG units will supply the load demand in a situation where there is a power outage from the utilities. The analytical technique can be used only to estimate the reliability indices of the generating units that have non-intermittent output power. Analytical models can be utilized only for the reliability evaluation of a small-scale power system [28]. It can provide accurate results or solutions when applied to a small-scale power system with a smaller computational effort than Monte Carlo simulation. The results obtained with the analytical technique demonstrate its effectiveness in a power system. These benefits are, however, limited to the failure of the technique to be used for stochastic characteristics of the major components of a power system at different operating states.

To achieve an accurate solution of the multi-objective functions and a more realistic reliability assessment of the distribution systems, a multi-state model that describes the stochastic characteristics of different components of the WTG, ESS and PV units in their respective states has been introduced. It is a powerful model that can be used to describe multi-states of various components of the renewable DG units [29–32]. This method yields more information on the load points and system reliability indices when compared to the analytical and Monte Carlo simulation methods. The methodology proposed in this paper aims to reduce the frequency and duration of power interruption at the consumers' load points during the grid connected mode. Many approaches have been employed to improve the reliability assessment of a conventional distribution system. Nevertheless, the stochastic characteristics of the major components of the renewable DG and ESS units, as well as their economic impact on the reliability assessment of a power system, have not been fully addressed. In view of this shortcoming, this paper addresses the reliability improvement of a conventional distribution system with the integration of WTG, ESS and PV units.

The reliability of the WTG, ESS and PV is estimated by the application of a Markov model based on the respective states of the major components of the system. The reliability assessment of the distribution system is performed by combining the power output of the WTG, PV and ESS based on the six scenarios which are discussed in Section 4. The results obtained from this study have established that renewable DG technologies can be utilized to improve the reliability of a power system.

2. Distribution system

The distribution system is the final section of the power system that provides a link between the consumer load points and the generation and transmission systems. It is utilized by the utilities for power distribution because of its low cost of installation and simplicity of design. To avert intermittent power interruption in the distribution network, it must be frequently assessed in order to reflect the impact of a power system outage, and the frequency and duration of power interruption on the reliability of the system [33]. The reliability of the distribution system depends on the environment, configuration of the system (radial and mesh), type of loads installed and location of loads [34]. An example of a distribution system with the integration of RERs is presented in Fig. 1. Since the main circuit breaker of feeder 1 is open circuited owing to the electrical faults, the system is isolated from the main grid and operates in an islanded mode. With this configuration, all the loads on the feeder will be supplied via a renewable DG unit. The second feeder is connected to the grid where the loads are supplied by the renewable DG unit and the main grid. The system will be operating at the optimal rated capacity if the correlation between the power supply and power demand is established, based on the available power output from the utilities and renewable DG units.

2.1. The hybrid system

A hybrid system that consists of WTG, ESS and PV systems, as presented in Fig. 2, is proposed in this work as a measure to enhance the reliability of a conventional distribution system. The failure of the utilities to meet the load demand of their consumers owing to technical and financial constraints has prompted power utilities to integrate RERs into their systems. The integration of a number of DER units into different sections of the power system can be utilized by the utilities in order to increase the reliability of their networks. The WTG and PV systems are adopted in this study because of their technical, environmental and economic benefits [35–37]. Owing to the fact that WTG and PV power output changes with time as a result of the intermittent nature of the RERs, part of the power generated from the WTG and PV systems must be stored in the battery banks. This will reduce the power outage time and increase the efficiency of the power system [38–42]. This section explains the modelling of the PV, WTG and ESS units briefly.

2.1.1. PV system

A PV is a system designed to generate electric power by means of converting sunlight directly into electricity. The solar PV system consists of many PV modules that are connected in series and parallel to produce the required power output based on the voltage and current ratings of the manufacturer. The PV systems can be utilized for power generation based on several configurations such as grid connected and standalone system. Numerous applications can be powered with PV system, i.e. solar street lights, a telephone exchange, solar vehicles, radio and television broadcasting, solar pumps and spacecraft. The PV system has witnessed rapid growth recently owing to the following features, i.e. low operating and maintenance costs, no greenhouse gas emissions, environmentally friendly, no noise emission and reduction of the fuel cost of hybrid system that combines PV with other generating units [43]. The output power of the PV system depends on the operating temperature and solar irradiance of the locations where PV systems are installed. The output power of the PV system can be expressed as [44–46]:

$$P_{pv}(s(t)) = \eta_{cells} * FF * V * I \tag{1}$$

$$T_{ct} = T_{at} + s(t) * \left\{ \frac{NOCT - 20}{0.8} \right\} \tag{2}$$

$$I = s(t) * \{I_{sc} + K_{ct} * (T_{ct} - 25)\} \tag{3}$$
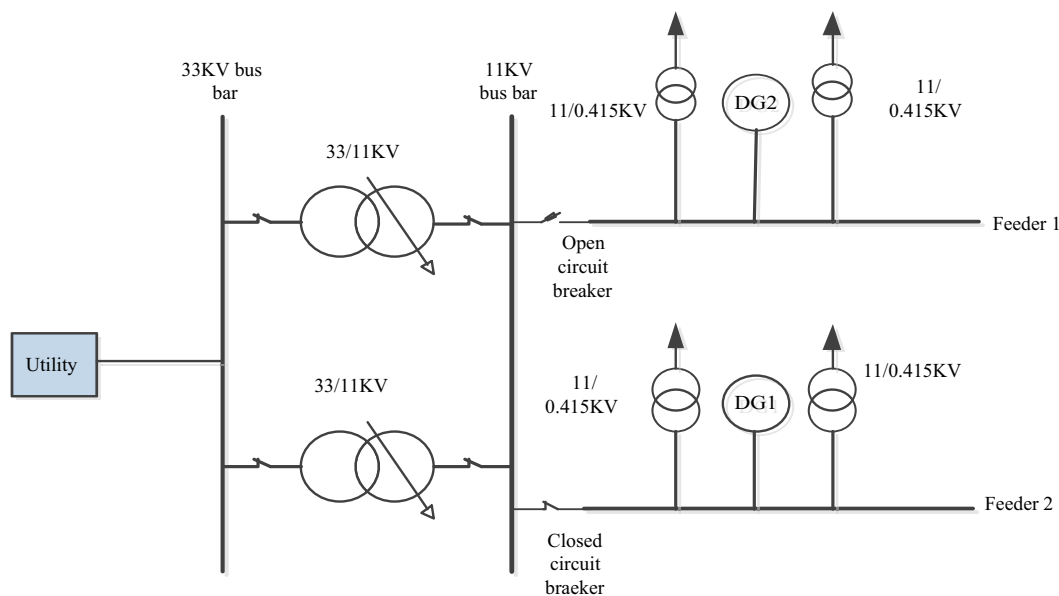
$$V = \{V_{oc} + K_{vt} * T_{ct}\} \tag{4}$$

Fig. 1. Distribution system with the renewable distributed generation units.
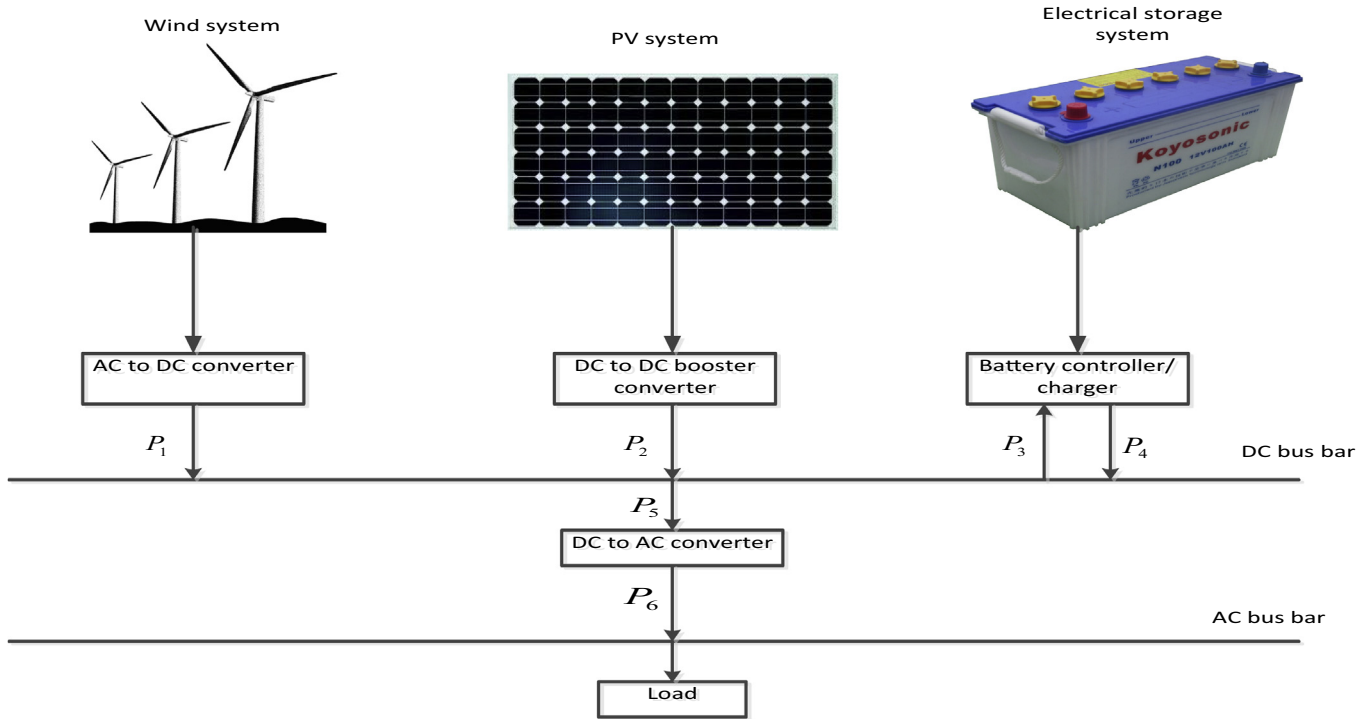
Fig. 2. A proposed hybrid unit.

$$FF = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}} \tag{5}$$

where T_{ct} = cell temperature [°C], T_{at} = ambient temperature [°C], $s(t)$ = random irradiance, NOCT = nominal operating cell temperature [°C], I_{sc} = short circuit current [A], K_{ct} = current temperature coefficient [mA/°C], V_{oc} = open circuit voltage [V], K_{vt} = voltage temperature coefficient [mV/°C], V_{mp} = voltage at maximum power [V], I_{mp} = current at maximum power [A], FF = Fill factor, V = output voltage (V), I = terminal current (A), η_{cells} = number of photovoltaic cells and $P_{pv}(s(t))$ = PV power output (W).

2.1.2. Wind system

The wind system describes the process by which the kinetic energy that is available in the wind regime is converted into the electrical energy. The wind system can be installed in an area that has a wind regime which falls within the operating limits of the specifications of the manufacturer [47]. The wind system is one of the renewable energy resources that can offer a good power solution because of being cost effective, with zero emissions and low operation and maintenance (O&M) costs. A wind system can be tied to the national grid through the available power provider or it can operate as a stand-alone system. The power produced from the wind system can be used for several applications, such as water pumps, security systems, telemetry, boats and yachts, and signage and signalling. The output power of WTG depends on the characteristics of the wind regime, wind speed, air density, swept area of rotor, tower height, aero-turbine performance and efficiency of gearbox and generator, etc. The relationship between the power output of the wind turbine and wind speed can be expressed as [46,47]:

$$P_{wtg}(v(t)) = \begin{cases} 0 & v(t) < v_{ci} \\ \frac{v(t)-v_{ci}}{v_r-v_{ci}} P_r & v_{ci} \leqslant v(t) \leqslant v_r \\ P_r & v_r \leqslant v(t) \leqslant v_{co} \\ 0 & v(t) > v_{co} \end{cases} \tag{6}$$

where P_r = rated power (kW), v_{ci} = cut-in speed (m/s), v_r = rated speed (m/s), v_{co} = cut-out speed (m/s) and P_{wtg} = power output of WTG (kW).

2.1.3. Electric storage system

The ESS is utilized in a power system as a strategic measure to reduce the uncertainity that is associated with the local renewable energy resources. This will ultimately enhance the reliability and effiecncy of the power system. The state of charge of a battery at time t can be determined by using the following expression [48]:

$$SOC(t) = SOC(O) + \eta_c \sum_{t=1}^{t} P_3(t) - \eta_d \sum_{t=1}^{t} P_4(t) \tag{7}$$

2.2. Problem formulation

The main objective of this paper is to minimize the cost that is associated with the power outage in the distribution system while satisfying the system requirements. In order to evaluate the impact of renewable DG units on the reliability of the distribution system, two objective functions are formulated. The first objective function is to minimize the expected energy not supplied (EENS) while the second objective function is to reduce the expected interruption cost index (ECOST) in the distribution system. The two objective functions are combined to assess the impact of renewable DG and ESS units in the conventional distribution system. The renewable DG units are incorporated into the distribution system to maximize the improved cost saving of the power system as presented in equations [8–10]. This objective can be accomplished by comparing the objective function before and after incorporating the DG units into the power system.

The objective function can be formulated as follows:

$$F_g^{obj} = \max(F_{WDG}^{obj} - F_{DG}^{obj}) \tag{8}$$

$$F_{WDG}^{obj} = \sum_{i=1}^{n}(k_e EENS_{WDG} + ECOST_{WDG})\$/\text{yr} \qquad (9)$$

$$F_{DG}^{obj} = \sum_{i=1}^{n}(k_e EENS_{DG} + ECOST_{DG})\$/\text{yr} \qquad (10)$$

where F_{WDG}^{obj} is the total costs associated with the power outage without the integration of DG into the system, F_{DG}^{obj} is the total costs associated with the power outage with the integration of renewable DGs into the system and k_e is the cost of energy not supplied (CENS, \$/MW h) that is applied to convert the unit of EENS from MW h/yr to \$/yr.

The objective function is subject to the following constraints based on Fig. 2:

    i. Power balance constraints

$$\sum_{i=1}^{n}P_{6,i}(t) + P_{utility} = \sum_{i=1}^{n}LP_i \qquad (11)$$

where $\sum_{i=1}^{n}P_{6,i}(t)$ is the sum of the power supplied by the renewable energy and ESS units, $\sum_{i=1}^{n}LP_i$ is the sum of the power demands at the load points and $P_{utility}$ is the power supplied by the power utilities.

    ii. Load constraints

$$P_{1(t)} + P_{2(t)} + P_{3(t)} - P_{4(t)} = P_{5(t)} \qquad (12)$$

$$P_{1(t)} \geqslant 0, P_{2(t)} \geqslant 0, P_{3(t)} \geqslant 0, P_{4(t)} \geqslant 0 \qquad (13)$$

where $P_{1(t)}$ = power output of the WTG system, $P_{2(t)}$ = power output of the PV system, $P_{3(t)}$ = power that flows from the bus bar to the battery for charging process, $P_{4(t)}$ = power that flows from the battery to the load and $P_{5(t)}$ = sum of power generated from WTG.

    iii. Constraints of battery storage system
    State of charge (SOC) limits

$$SOC^{min} \leqslant \left(SOC(O) + \eta_c\sum_{t=1}^{t}P_3(t) - \eta_d\sum_{t=1}^{t}P_4(t)\right) \leqslant SOC^{max} \qquad (14)$$

$$SOC^{min} = (1 - DOD)SOC^{max} \qquad (15)$$

where DOD = depth of charge, η_c = battery charge efficiency and η_d = Battery discharge efficiency.

The flow chart that illustrates how to estimate the benefit of the WTG, ESS and PV units on the reliability of a conventional distribution power system is presented in Fig. 3.

2.3. Operational states of wind and PV system

The wind and PV systems are designed in such a way that their operation depends on the availability of the renewable energy resources that enable them to provide reliable power at the load points. The system has five states of operation which are illustrated in Fig. 4.

First state: The wind and solar systems will be in up states and they will be operating effectively if the local renewable resources are within the operating limits specified by the wind turbine manufacturers. In addition to this, the wind and PV systems must be in the healthy states.

Second state: The wind system will be in the up state when it is healthy and the wind speed is between the cut-in and cut-out speed specified by the wind turbine manufacturers. The PV system on other hand will be in down state when there is no availability of solar insolation to operate it.

Third state: The PV system will be in the up state owing to the availability of the solar insolation, and the PV system must also be in a healthy state. The wind system will be in the down state due to the non-availability of the wind speed that meets the manufacturer's specifications.

Fourth state: The wind and PV systems are in the down state when there is no solar irradiance and the wind speed does not fall within the operating limits specified by the manufacturers. The output power of the wind and PV systems is, therefore, zero. At this critical junction, some strategic measures must be put in place to maintain continuous power at the load points. The power that has already been stored in the battery will be used to supply the power demanded by the consumers.

Fifth state: When the wind and PV systems, together with the ESS which is acting as a standby unit, are faulty owing to the failure of their respective components simultaneously, the output power of the renewable DG units is zero, since the wind system, ESS and PV are in the failure states. The power to the load points is, however, met from the power utilities.

2.4. Stochastic models for the wind system, ESS and PV system

In this section, the reliability of the distribution system that consists of WTG, AC/DC rectifier, battery bank, battery controller/charger, PV system, DC/DC boost converter and DC/AC inverter is assessed. These components are integrated into a radial distribution system to reduce the frequency and duration of power interruption caused by momentary and sustained outages while improving the overall performance of the distribution system. The performance of the distribution system with the integration of multiple sources of renewable energy resources and ESS depends on the individual components that constitute the system. To analyze the reliability assessment of the whole system, several components that make up the system must be analyzed separately. The performance of each component is one of the key factors that can determine the state of reliability of the entire network. In view of this, the stochastic model for each component that constitutes the system is done separately.

2.4.1. Stochastic models for the WTG, AC/DC rectifier and DC/AC inverter system

The output power of the WTG is intermittent due to the variation of the wind speed. The system can be represented by a three state model such as: an up state that represents the full operation of each component of the system; a derated state that represents the partial operation of each component of the system; and a down state that represents down or non-operational state of the major components of the system [49]. The stochastic model for WTG, AC/DC rectifier and DC/AC inverter systems is presented in Fig. 5. The reliability assessment of the system can be effectively carried out if the effects of other components are negligible. The operational states of the entire system depend on the stochastic characteristics of the major components that constitute the system. This system will be in an operating state in a situation where the wind resource is within the operating limits set by the manufactures and when the major components are in the healthy states. The system can be in a full operating state only if the WTG, AC/DC rectifier and DC/AC inverter system are in state 1. The failure of any components among the three major constituents of the system will render the system non-operational. As a result of this, the system is considered to be a series configuration. The stochastic transitional probability matrix of the system establishes the fact that the system will operate only if it is in state 1; otherwise the system will be in the down state. The states 2–8 have been observed to be in the failure states due to the series configuration of the system. The transition matrix of the entire system can be represented by
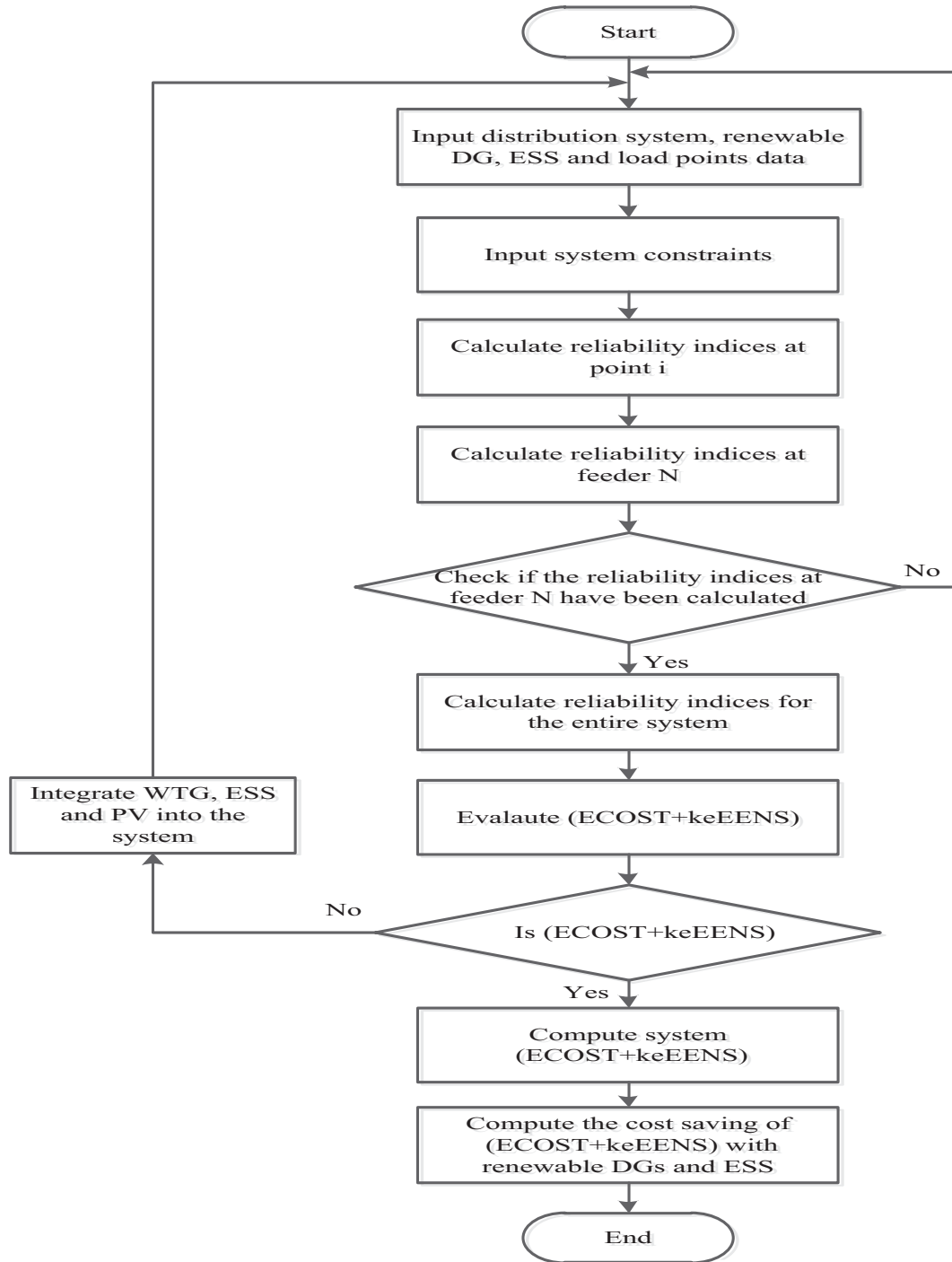
Fig. 3. Estimation and improvement of the reliability of a convention distribution system with DG and ESS units.

$$P_1 = \begin{bmatrix} (1-\lambda_{wtg}-\lambda_{rec}-\lambda_{inv}) & \lambda_{wtg} & \lambda_{rec} & \lambda_{inv} & 0 & 0 & 0 & 0 \\ \mu_{wtg} & (1-\mu_{wtg}-\lambda_{rec}-\lambda_{inv}) & 0 & 0 & \lambda_{rec} & 0 & \lambda_{inv} & 0 \\ \mu_{rec} & 0 & (1-\mu_{rec}-\lambda_{wtg}-\lambda_{rec}) & 0 & \lambda_{wtg} & \lambda_{inv} & 0 & 0 \\ \mu_{inv} & 0 & 0 & (1-\mu_{inv}-\lambda_{wtg}-\lambda_{rec}) & 0 & \lambda_{rec} & \lambda_{wtg} & 0 \\ 0 & \mu_{rec} & \mu_{wtg} & 0 & (1-\mu_{rec}-\mu_{wtg}-\lambda_{inv}) & 0 & 0 & \lambda_{inv} \\ 0 & 0 & \mu_{inv} & \mu_{rec} & 0 & (1-\mu_{rec}-\mu_{inv}-\lambda_{wtg}) & 0 & \lambda_{rec} \\ 0 & \mu_{inv} & 0 & \mu_{wtg} & 0 & 0 & (1-\mu_{wtg}-\mu_{inv}-\lambda_{inv}) & \lambda_{wtg} \\ 0 & 0 & 0 & 0 & \mu_{inv} & \mu_{wtg} & \mu_{rec} & (1-\mu_{wtg}-\mu_{rec}-\mu_{inv}) \end{bmatrix}$$
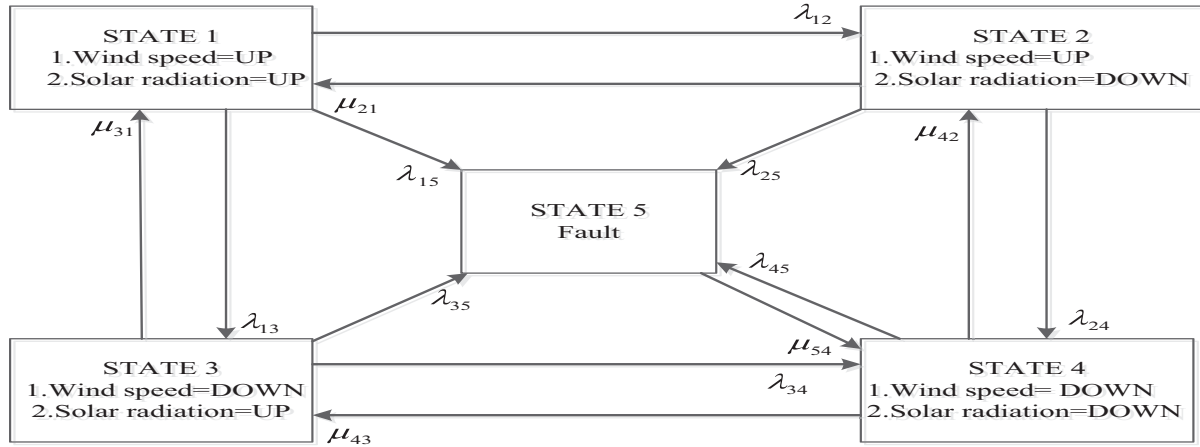
(16)

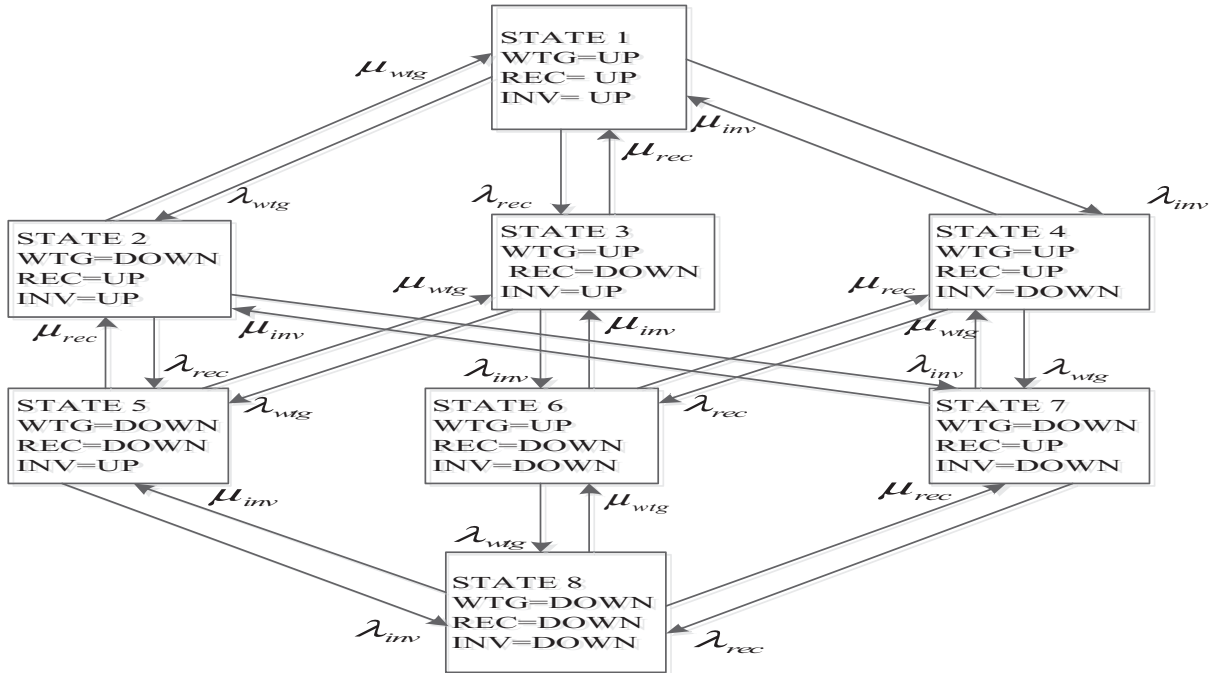Fig. 4. Five operational states of wind and PV system.

Fig. 5. Stochastic model for wind system.

absorbing states which resulted in a truncated matrix Q having eliminated the number of states that have a low probability of occurrence [49]. In this study, the failure rate and repair rate for the WTG, AC/DC rectifier and DC/AC inverter system are represented by $\lambda_{wtg}, \mu_{wtg}, \lambda_{rec}, \mu_{rec}, \lambda_{inv}$ and μ_{inv} respectively.

The transition matrix of the system for the entire network is represented in Eq. (16).

$$Q = [1 - \lambda_{wtg} - \lambda_{rec} - \lambda_{inv}] \qquad (17)$$

The mean time to failure (MTTF) of the WTG, AC/DC rectifier and DC/AC inverter system can be obtained by using the following equations [49,50]:

$$MTTF = [[I] - [Q]]^{-1} \qquad (18)$$

where I = identify matrix.

$$MTTF = [[I] - [1 - \lambda_{wtg} - \lambda_{rec} - \lambda_{inv}]]^{-1} = [\lambda_{wtg} + \lambda_{rec} + \lambda_{inv}]^{-1}$$

$$= \frac{1}{\lambda_{wtg} + \lambda_{rec} + \lambda_{inv}} \qquad (19)$$

The total failure of the WTG, AC/DC rectifier and DC/AC inverter can be estimated by using Eq. (20).

$$\lambda_1 = \lambda_{wtg} + \lambda_{rec} + \lambda_{inv} \qquad (20)$$

The Markov state transition diagram is shown in Fig. 4 where λ and μ represent the system failure rate and repair rate respectively. The probability of the system in the up and down states can be expressed as follows:

$$P_{UP} = \frac{\mu}{\lambda + \mu} \qquad (21)$$

$$P_{DOWN} = \frac{\lambda}{\lambda + \mu} \qquad (22)$$

The probability of the series components in up state is denoted by a subscript P_{s-UP} which is the product of the probability of WTG, AC/DC rectifier and DC/AC inverter in up states [49,50].

$$P_{s-UP} = \frac{\mu_{wtg}}{\lambda_{wtg} + \mu_{wtg}} \frac{\mu_{rec}}{\lambda_{rec} + \mu_{rec}} \frac{\mu_{inv}}{\lambda_{inv} + \mu_{inv}} \qquad (23)$$

The equivalent repair rate (μ_s) can be derived as follows:

$$P_{s-UP} = \frac{\mu_s}{\lambda_s + \mu_s} \tag{24}$$

$$\mu_s = \frac{P_{s-UP}\lambda_s}{1 - P_{s-UP}} = \frac{\lambda_s}{\left[\left(1 + \frac{\lambda_{wtg}}{\mu_{wtg}}\right)\left(1 + \frac{\lambda_{rec}}{\mu_{rec}}\right)\left(1 + \frac{\lambda_{inv}}{\mu_{inv}}\right) - 1\right]} \tag{25}$$

$$\lambda_1 = \lambda_s = \lambda_{wtg} + \lambda_{rec} + \lambda_{inv} \tag{26}$$

$$\mu_1 = \mu_s = \frac{\lambda_{wtg} + \lambda_{rec} + \lambda_{inv}}{\left[\left(1 + \frac{\lambda_{wtg}}{\mu_{wtg}}\right)\left(1 + \frac{\lambda_{rec}}{\mu_{rec}}\right)\left(1 + \frac{\lambda_{inv}}{\mu_{inv}}\right) - 1\right]} \tag{27}$$

2.4.2. Stochastic model of the PV array, DC/DC booster converter and inverter system

The system consists of three paramount components, such as an array of PV, DC/DC booster converter and DC/AC inverter as shown in Fig. 6. The system can be represented by a three state model, such as up state, down state and derated state of each component of the system. In this study, subscripts $\lambda_{pvc}, \mu_{pvc}, \lambda_{conv}, \mu_{conv}, \lambda_{inv}$ and μ_{inv} denote the failure rate and repair rate for each component of the system as presented by the Markov model. The failure of any constituent of the system will lead to the total failure of the entire system since the three components are connected in series. With this configuration, the system has a similar operation and a Markov model with the WTG, AC/DC rectifier and DC/AC inverter system as discussed in Section 2.4.1.

Having analyzed the failure rate and repair rate with a different combination of components that make up the system, the failure rate and repair rate for the entire network are obtained by using the following equations:

$$\lambda_2 = \lambda_{pvc} + \lambda_{conv} + \lambda_{inv} \tag{28}$$

$$\mu_2 = \mu_s = \frac{\lambda_{pvc} + \lambda_{conv} + \lambda_{inv}}{\left[\left(1 + \frac{\lambda_{pvc}}{\mu_{pvc}}\right)\left(1 + \frac{\lambda_{conv}}{\mu_{conv}}\right)\left(1 + \frac{\lambda_{inv}}{\mu_{inv}}\right) - 1\right]} \tag{29}$$

2.4.3. Stochastic model for battery, battery controller/charger and inverter system

The system has three major components, viz. battery, battery controller/charger and inverter system. The failure of any components that constitute the system will cause the failure of the entire system since they are connected in series. The system will function effectively only if it is in state 1, otherwise it will be in down states 2–8 as presented in Fig. 7. The failure rate and repair rate for each component that constitutes the battery, battery controller/charger and inverter systems are denoted by $\lambda_{bat}, \mu_{bat}, \lambda_{bc}, \mu_{bc}, \lambda_{inv}$ and μ_{inv} as presented by the Markov model in Fig. 7. The system has a similar operation with the WTG, AC/DC rectifier and DC/AC inverter system as discussed in Section 2.4.1. The Markov model for the battery, battery controller/charger and DC/AC inverter system is presented in Fig. 7 to illustrate the mode of operation of the system.

Hence, the total failure rate and repair rate of the battery, battery controller/charger and inverter system can be estimated by using the following equations:

$$\lambda_3 = \lambda_{bat} + \lambda_{bc} + \lambda_{inv} \tag{30}$$

$$\mu_3 = \mu_s = \frac{\lambda_{bat} + \lambda_{bc} + \lambda_{inv}}{\left[\left(1 + \frac{\lambda_{bat}}{\mu_{bat}}\right)\left(1 + \frac{\lambda_{bc}}{\mu_{bc}}\right)\left(1 + \frac{\lambda_{inv}}{\mu_{inv}}\right) - 1\right]} \tag{31}$$

3. Distribution system reliability

This section introduces a modified Roy Billinton Test System (RBTS) with the integration of the DER 1 (PV + boost converter + inverter), DER 2 (WTG + converter + inverter) and DER 3 (Bat-
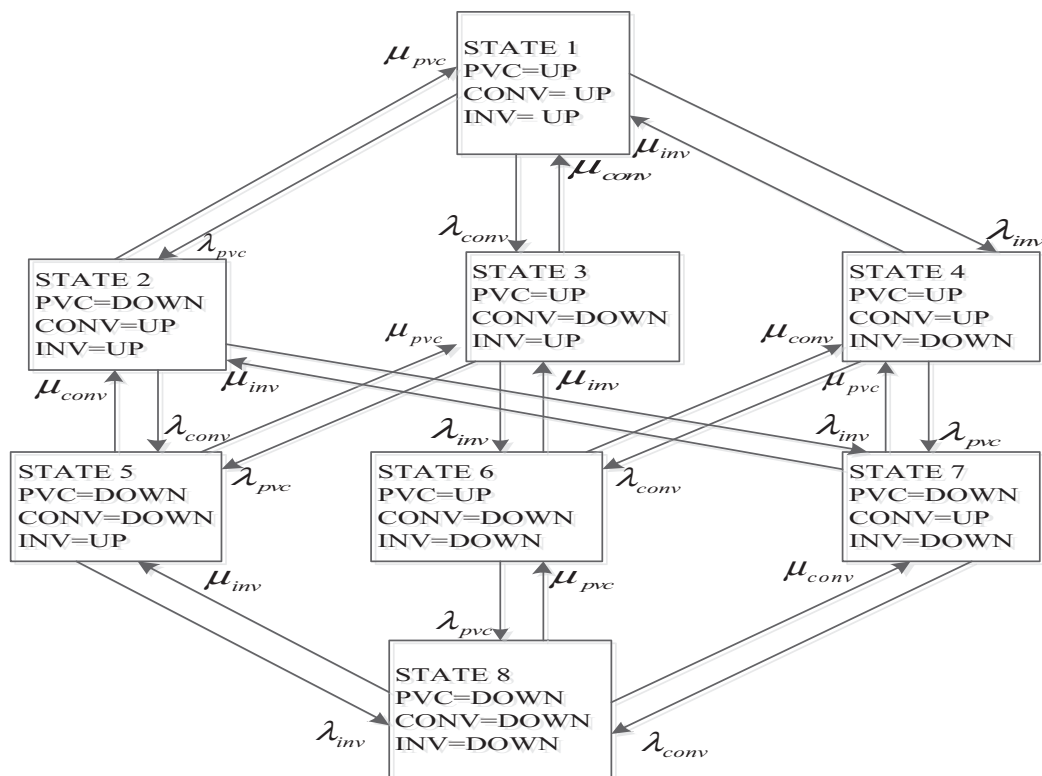
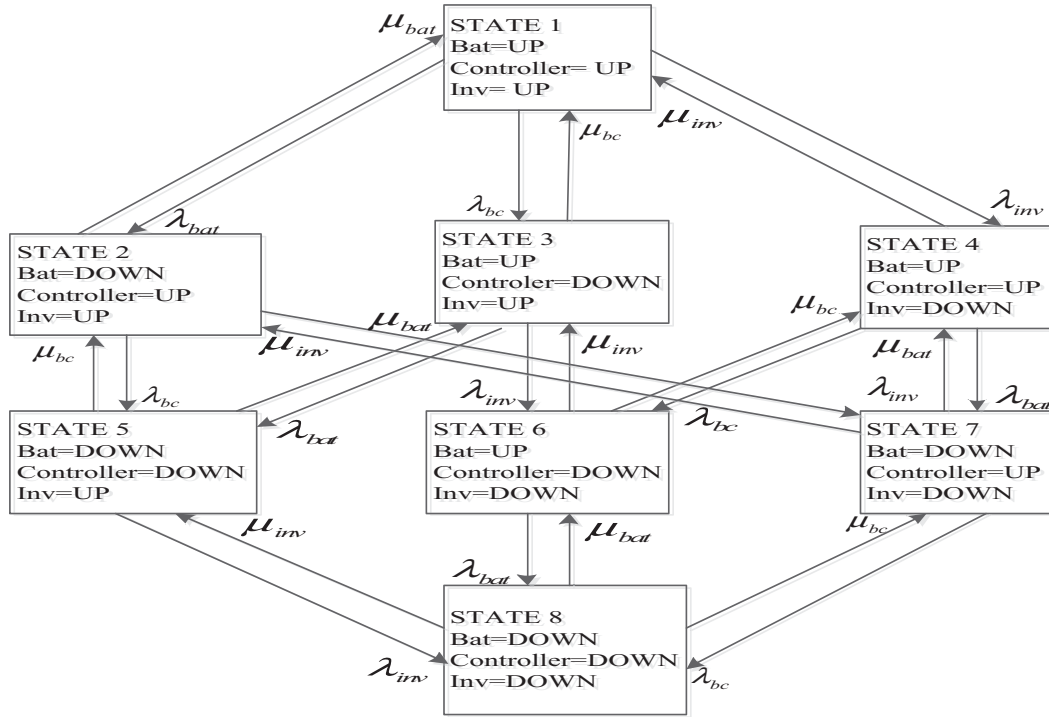**Fig. 6.** Stochastic model for PV system.

Fig. 7. Stochastic model for electric storage system.

tery + controller + inverter) at different sections of the distribution system. The main objective of this paper can be validated by using modified RBTS bus distribution test system as shown in Fig. 8. The ratings of the DER units are presented in Table 1. The customer and feeder data used for this work are available in references [51,52]. In this study, the following assumptions are made:

- Only overhead lines from the supply point bus to the load points at 11 kV for the lateral and main feeders are considered for this study;
- The supply point, main feeder bus bars and circuit breakers are assumed to have their respective failure and repair rates as indicated in the references [51,52]; and
- In an event of any fault, the loads on the transformer attached to each DER will be automatically transferred to the standby transformer instead of repairing it. This will reduce the power outage duration.

3.1. Cost of energy not supplied

The cost of energy not supplied (CENS) in a power system represents the average cost over the interruption interval. It can be estimated by modelling the interruption cost as a function of the unsupplied energy irrespective of the interruption duration and frequency [53,54]. The CENS captures the financial damage that consumers experience during the power outage or load shedding. In order to estimate the CENS in the distribution system, the following details must be supplied: i. economic direct costs; ii. social indirect costs; and iii. statistical data on the energy not supplied, etc. [55]. The CENS for the South African power system, which is estimated to be $ 5.5/kW h, is used for this paper [56,57]. CENS can be estimated according to [55].

$$CENS = \frac{\sum_{i=0}^{n} F_i D_i + \sum_{j=0}^{n} I_j}{\sum_{t=0}^{T} EENS} \quad (\$/MW\,h) \tag{32}$$

$$= \frac{(F_{res}D_{res} + F_{ind}D_{ind} + F_{com}D_{com} + F_{g\&i}D_{g\&i} + F_{other}D_{other}) + (\sum_j I_{jx} - \sum_j I_{jy})}{\sum_{t=0}^{T} EENS} \quad (\$/MW\,h) \tag{33}$$

where F_i = vulnerability factor of consumer at the load point, i = type of consumers such as industrial (ind), commercial (comm), government and institution (g&i), residential (res) and other (others), D_i = economic direct costs of consumers i, I_j = indirect social costs, I_{jx} = total indirect cost brought about during the time of investigation, I_{jy} = indirect costs that had no association with the investigation and n = number of customers in the system.

3.2. Expected energy not supplied

The expected energy not supplied (EENS) is the expected amount of the energy that is not delivered at the consumer load points owing to an unexpected power outage or power interruption. The EENS can be utilized by the power utilities to carry out an economic and reliability assessment of a power system. The EENS can be expressed mathematically as:

$$EENS_i = P_i U_i \quad ((MW\,h/yr) \tag{34}$$

$$= \sum_{i=0}^{n} \lambda_i r_i L_i \tag{35}$$

$$= \lambda_x r_x L_x + \{\lambda_x r_x + \lambda_y r_y\}L_y + \lambda_x r_x + \lambda_y r_y + \lambda_z r_z\}L_z \tag{36}$$

$$= \{L_x + L_y + L_z\}\lambda_x r_x + \{L_x + L_y\}\lambda_y r_y + L_z\lambda_z r_z \tag{37}$$

$$PF_1\lambda_x r_x + PF_2\lambda_y r_y + PF_3\lambda_z r_z \tag{38}$$

$$= \sum_{i=0}^{n} \lambda_i r_i PF_i \tag{39}$$

where PF_x, PF_y, and PF_z are the power that flow in the line sections x, y, and z as presented in Fig. 9.

3.3. Expected interruption cost

The practical method that can be used to estimate the reliability worth of a power system is based on the evaluation of the expected interruption cost (ECOST) owing to power interruption at the load points. The ECOST can be estimated by using the customer inter-

Legend

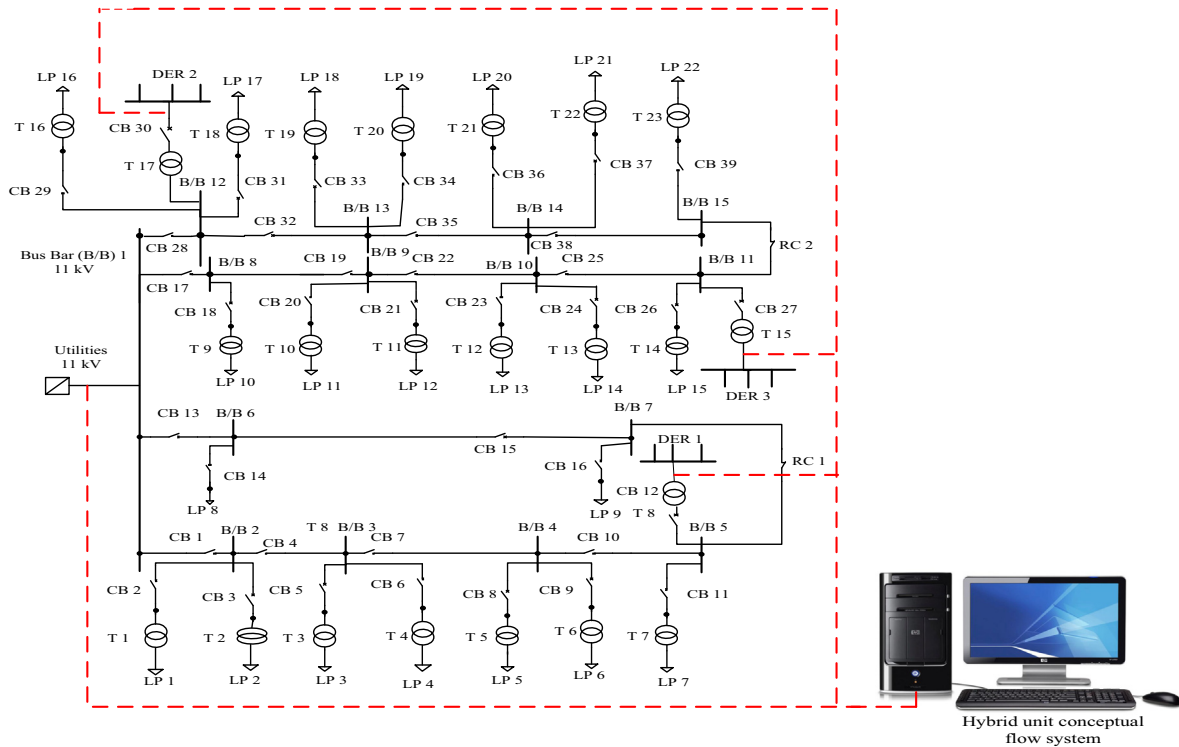| Description	Symbol	Power rating	Voltage rating
Transformers	T1-T5,T9-T10, T12-T13 and T21-T22	1.2 MVA	11/0.415 kV
	T6-T7,T11,T14,T18-T20 and T23	1 MVA	
	T8	3 MVA	0.415/11 kV
	T15	0.75 MVA	
	T17	4.5 MVA	
Load points	LP1-LP3 and LP10-LP11	0.535 MW	0.415 kV
	LP12 and LP17-LP19	0.45 MW	
	LP8	1 MW	
	LP9	1.15 MW	
	LP4-LP5, LP13-LP14 and LP-21	0.566 MW	
	LP6-LP7, LP15-LP16 and LP22	0.454 MW	

Fig. 8. Modified RBTS bus distribution system [51,52].

Table 1
Ratings of the renewable WTG, ESS and PV units.

Case studies	Location of DER 1–3 units	Capacity of DER 1–3 units (MW)	Total Capacity of DER 1–3 units (MW)
1	–	–	–
2	5	2	2
3	12	3	3.0
4	11, 12	3, 0.5	3.5
5	5, 11	2, 0.5	2.5
6	5, 11,12	3, 0.5, 2	5.5

Fig. 9. A distribution system with the section lines.

ruption costs and load point reliability indices. The ECOST can be expressed as:

$$\text{ECOST} = L_i \sum N_e f_{r,j} \lambda_i (\text{K\$/yr})$$
$$= L_x N_e f_{x,j} \lambda_x + L_y N_e f_{y,j} \lambda_y + L_z N_e f_{z,j} \lambda_z \qquad (40)$$

where λ_i = average failure rate at load points, N_e = number of components whose fault will interrupt the power system, $f_{r,j}$ = cost of interruption, L_i = average load at load point and r_i = failure duration.

3.4. Study cases

The operations of various numbers of the DER units depend on the correlation between the power supply from the utilities and the power demand at the load points. The reliability indices, such as SAIDI, customer average interruption index (CAIDI), customer average interruption frequency index (CAIFI), system interrupted energy assessment rate index (IEAR), average energy not supplied (*AENS*) and expected interruption cost index (ECOST) are selected to estimate the impact of renewable DG units in the distribution system. The total improved cost saving from EENS and ECOST is
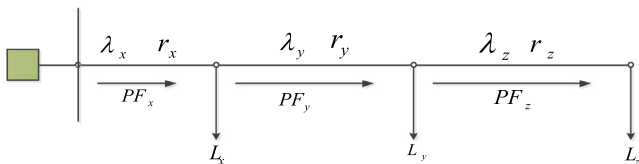
also used to study the performance of renewable DG units in the distribution system. The different combinations of the DER units are utilized in order to study their effects on the reliability of the distribution system. The reliability evaluation is performed on the distribution system based on the following six cases:

1. Conventional distribution system without DER unit;
2. Conventional distribution system with DER 1 unit;
3. Conventional distribution system with DER 2 unit;
4. Conventional distribution system with DER 2 and DER 3 units;
5. Conventional distribution system with DER 1 and DER 3 units; and
6. Conventional distribution system with DER 1, DER 2 and DER 3 units.

4. Results and analysis

The reliability assessment technique applied in this paper is one of the key performance indicators to assess the impact of using the WTG, PV and ESS in the conventional distribution system. The detailed information about the system reliability indices and the specifications of the components that constitute the system are presented in Tables 2 and 3. The Table 3 also shows different configurations of the renewable DER units using Markov models to analyze the scholastic characteristics of the components that constitute the systems. The six case studies are used in this work to estimate the reliability indices of the DER units based on different configurations. The values of several reliability indices and cost saving parameters for six case studies are also presented in Table 4.

Case study 1: In this case study, the reliability assessment is carried out on the modified RBTS bus distribution system without the application of DER units. The results in Table 4 reveal that the utilization of the conventional distribution power system without DER units will increase both the frequency and duration of power outages experienced by the consumers at the load points. The total cost of energy not supplied at the consumer load points is 50,633 $/yr.

Case study 2: The second case study is a conventional distribution system with the integration of the DER 1 unit. The integration of the DER 1 unit into the conventional distribution system has improved the values of the reliability indices and cost saving parameters as shown in Table 4. The values of the distribution system reliability indices, such as SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS and ECOST, are improved by 3.84%, 2.59%, 1.29%, 2.08%, 0.48%, 4.21% and 3.53% as shown in Figs. 10a–10d, respectively. The total improved cost saving of the system is increased by 3.91% as presented in Fig. 10d. The DER 1 unit has a better impact on reducing the system interruption frequency and interruption duration than a conventional distribution system without renewable DG technologies. The reliability of the distribution system is

significantly improved with the penetration of the DER 1 unit just as it reflected in Figs. 10a–10d.

Case study 3: The third case study is a conventional distribution system with the penetration of the DER 2 unit. The values of the reliability indices and the cost saving parameters for case study 3 are presented in Table 4. The integration of the DER 2 unit into the system has improved the values of SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS and ECOST by 8.27%, 5.59%, 2.90%, 4.17%, 1.40%, 4.87% and 4.19% as shown in Figs. 10a–10d respectively. The total improved cost saving of the system is further improved by the integration of the DER 2 unit by 4.57 % as presented in Fig. 10d.

Case study 4: The fourth case study is a conventional distribution system with the DER 2 and DER 3 units. This arrangement optimizes the interruption frequency and duration at the load points. The integration of the DER 2 and DER 3 units into a conventional distribution system has improved the reliability of the distribution system based on the scholastic characteristic of the system. The values of the reliability indices and the cost-saving parameters for case study 4 are presented in Table 4. The values of SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS and ECOST of the system with the integration of the DER 2 and DER 3 units are improved by 10.70%, 7.26%, 3.79%, 6.25%, 2.01%, 6.20% and 4.30% as presented in Figs. 10a–10d respectively. Compared with the case study 1, the total improved cost saving of the system is increased by 5.36 % as shown in Fig. 10d. From the above analysis, the integration of the DER 1 and DER 3 units into a conventional distribution system has improved the reliability of the system.

Case study 5: The fifth case study is a conventional distribution system with the integration of the DER 1 and DER 3 units in a conventional distribution power system. From the results obtained in Table 4, it can be seen that the reliability of the system has improved with the integration of the DER 1 and DER 3 units. The values of the system reliability indices such as SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS and ECOST have increased marginally by 14.98%,

Table 3
Reliability indices of different components of the WTG, ESS and PV units and their combinations based on the Markov model [61,62].

Description	Failure rate (f/yr)	Repair rate (repair/year)
WTG	0.05	20
PV	0.04	18.25
Battery	0.0312	51.9571
Battery controller/charger	0.125	45.213
Inverter	0.143	52.143
Boost converter	0.0657	62.5
Converter AC/DC	0.152	55.232
DER 1 (PV + converter + inverter)	0.2487	41.473
DER 2 (WTG + boost converter + inverter)	0.345	43.040
DER 3 (Battery + controller + inverter)	0.2992	48.9

Table 2
Specifications of WTG, battery and PV units [58–60].

Description	PV	WTG	Battery
Installed capacity	2 MW	3 MW	0.5 MW
Nominal rating	200 W	3 MW	200Ah
Efficiency	18.70%	45%	80–95%
Life time	20 years	25 years	4 years
Unit price	3000 $/kW	2290 $/kW	219 $/kW
Maintenance cost (% of the capital cost)	3%	1%	3%
Other technical parameters	Voc = 22.30 V, Ta = 30 °C, NOCT = 43 °C, I_{sc} = 11.89 A, V_{mp} = 18.0 V, I_{mp} = 11.12 A, K_v = 0.38%/°C, K_i = 0.1%/°C and Panel Area = 1580 x 808 mm^2	v_{ci}=3 m/s, v_r=10 m/s, v_{co} = 25 m/s and Swept area = 6362 m^2	

Table 4
Simulation results for WTG, ESS and PV units.

| Case studies	1	2	3	4	5	6
SAIFI (f/customer yr)	0.1355	0.1303	0.1243	0.121	0.1152	0.1132
SAIDI (h/customer yr)	0.7766	0.7565	0.7332	0.7202	0.6975	0.6895
CAIDI (h/customer interruption)	5.733	5.807	5.899	5.95	6.055	6.091
AENS (MW h/customer yr)	0.0048	0.0047	0.0046	0.0045	0.0043	0.0042
IEAR ($/kW h)	4.37	4.391	4.431	4.458	4.463	4.476
Total EENS (MW h/yr)	9.206	8.818	8.758	8.635	8.225	8.104
Total ECOST ($/yr)	40230.17	38809.01	38544.99	38498.33	36709.3	36272.54
Total cost of EENS ($/yr)	50633	48499	48169	47492.5	45237.5	44572
Total outage cost ($/yr)	90863.17	87308.01	86713.99	85990.83	81946.8	80844.54
Total cost saving of EENS ($/yr)	–	2134	2464	3140.5	5395.5	6061
Total cost saving of ECOST ($/yr	–	1421.16	1685.18	1731.84	3520.87	3957.63
Total cost saving ($/yr)	–	3555.16	4149.18	4872.34	8916.37	10018.63
Total improved cost saving (%)	–	3.9126524	4.5664046	5.3622826	9.8129638	11.02606259
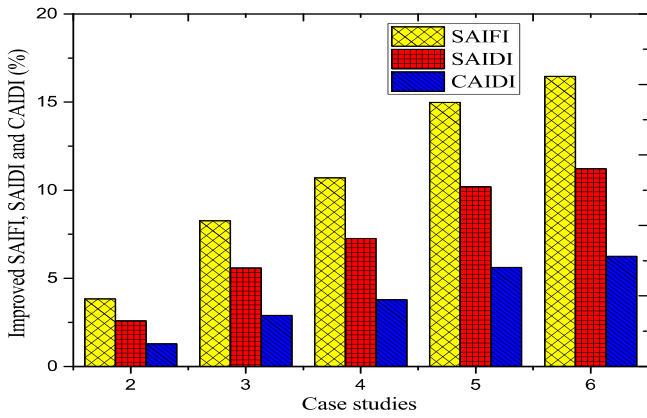
Fig. 10a. Improved SAIFI, CAIDI and SAIDI with the application of distributed energy resources.
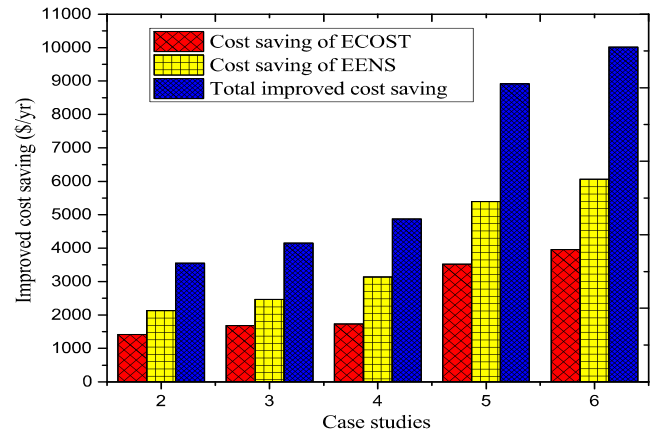
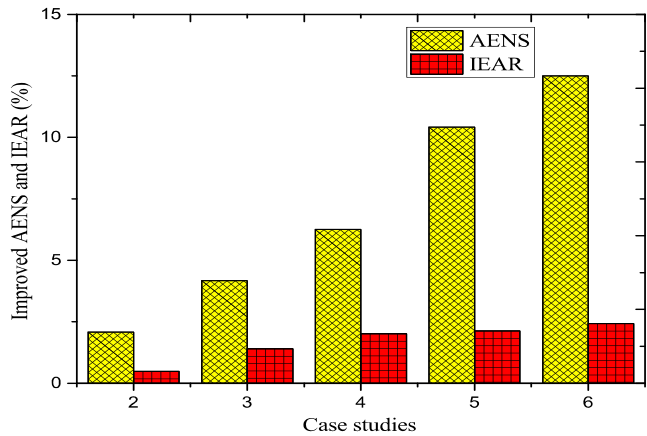**Fig. 10c.** Improved cost saving with the application of distributed energy resources.

Fig. 10b. Improved AENS and IEAR with the application of distributed energy resources.
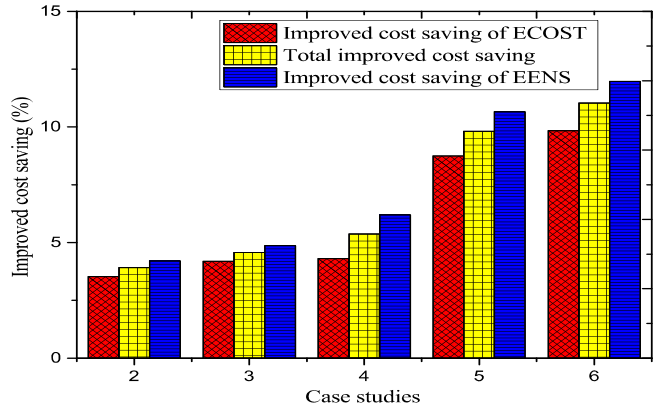
Fig. 10d. Precentage of the improved cost saving with the application of distributed energy resources.

10.19%, 5.62%, 10.42%, 2.13%, 10.66% and 8.75% as presented in Figs. 10a–10d respectively. The system's total improved cost saving is increased significantly by 9.81% as shown in Fig. 10d. The results obtained from this analysis have shown that the overall performance and monetary worth of the system have been increased with the incorporation of the DER 1 and DER 3 units.

Case study 6: The sixth case study is the application of the DER 1, DER 2 and DER 3 units in a conventional power distribution system. The penetration the DER 1, DER 2 and DER 3 units in the distribution system has a great effect on system reliability. This is, however, limited to the availability of the local renewable energy

resources and the capacity of the battery storage system. The values of reliability indices and the cost saving parameters for case study 6 are presented in Table 4. With this configuration, there is a significant increase in the reliability indices of the system. This is noticeable in the values of the system SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS and ECOST that are improved by 16.46%, 11.22%, 6.24%, 12.5%, 2.43%, 11.97% and 9.84% as presented in Figs. 10a–10d respectively. The system's total improved cost saving is increased significantly by 11.03% as shown in Fig. 10d. By comparing the six case studies, it can be established that an increase in the capacity of the renewable energy DG units in the conventional distribu-

tion system can make the system to be more reliable, and, at the same time, reduce consumer interruption costs.

5. Conclusion

Reliability technique is one of the key performance indicators to measure the impact of renewable DG resources in the conventional power distribution system. A reliability assessment method in the presence of the DER 1, DER 2 and DER 3 units is proposed in this paper to optimize the cost that is associated with the power outage. Based on the results of simulation, it is obvious that renewable DG resources and ESS have a great effect on the reliability of the distribution system. There is a considerable reduction in the cost that is associated with the power outage with the application of renewable DG resources. It can be deduced from the results obtained from the simulation that the power utilities should encourage the integration of renewable energy into their distribution systems as an alternative way to increase the reliability of their networks. This work can be extended to evaluate the effect of renewable energy resources on a large distribution system. In addition, reliability assessment can assist the power system operators, planners, designers and engineers to optimize the power outage cost in a conventional distribution system with the application of renewable energy resources. The analyzed results have established a fact that the incorporation of DER 1, DER 2 and DER 3 units into a conventional distribution system can not only increase the cost saving, but also improve the reliability of the distribution system.

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