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Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources

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HIGHLIGHTS

- Employs renewable energy resources (RES) to improve the reliability of power system.
- Stochastic characteristics of wind, PV and BSS are modelled using Markov technique.
- Presents a technique to reduce the annualised maintenance, emission and fuel costs.
- Proposed method can be used in the real time to improve reliability and reduce costs.

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Renewable energy sources
Reliability
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ABSTRACT

The reliability assessment of a power system has become a significant subject in the power sector for both utilities and customers due to sudden increase in demand of a reliable power supply at minimal frequency and duration of power outages. This has prompted the utilities to use the accessible renewable energy resources (RERs) as measures to increase the reliability of a power system as well as reduction of over dependence on fossil fuels. The incorporation of renewable energy technologies into a radial distribution system has changed the single power source to bidirectional and multiple power sources. This improves the reliability of the system as well as reducing the power outages that associated with the radial distribution networks. In this work, wind turbine generator (WTG), photovoltaic (PV) and battery storage system (BSS) are utilized with the aim of improving the reliability of the existing microgrid power system and reducing the cost of energy (COE) and annualised cost of the system (ACS). The objective of the research work is accomplished by using the total outage cost (TOC), COE, ACS, annualized capital cost (ACC), annualized maintenance cost (AMC), annualized fuel cost (AFC), annualized emission cost (AEC), annualized replacement cost (ARC) and net present cost (NPC) of the power system. An fmincon optimization tool is utilized in this paper to investigate the effects of RERs in a microgrid system. The stochastic characteristics of the major components of RERs and their influences on the reliability of a power system are studied by using a Markov model. The proposed method is applied on the modified Roy Billinton Test System (RBTS) to establish the fact that RERs can be used to enhance the reliability and reduce the COE and ACS of the system. A comparative analysis of RERs is also carried out by studying the effects of interest rates on the COE, NPC and ACS of a power system. The results obtained from the research work demonstrate that the application of renewable energy distributed generation technologies has achieved better results.

1. Introduction

The high rate of world energy consumption caused by a growing population and global economic expansion coupled with a rapid industrialization has necessitated a massive investment in reliable power supply. With the global power system restructuring, rapid growth in power demand, concerns about climate change, high prices of fossil fuels and the depletion of fossil fuels, RERs have been playing proactive roles in a sustainable energy development due to their inexhaustible and non-polluting characteristics [1]. These attributes have increased the global installed capacity of renewable energy technologies. The function of a power system is to meet the power demand of the numerous customers economically and efficiently with an affirmation of adequate level of reliability and quality [2]. To meet this objective, several countries in the world have considered the possibility of integrating RERs into their power systems. The recent surveys conducted by the World Energy Council (WEC) have projected that the power output from RERs would increase from 23.7% as it is presently to about

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34% in 2030. The power demand is increasing daily on the global note due to a rapid growth in population, industrialization and high standard of living. Owing to this, the need for a reliable power system has always been very important because of the role electric power plays in the economic growth, development and social well-being of a nation. The economic development of a nation entirely corresponds to the reliability of its power system since the greater part of its financial segment depends on this type of energy to boost their economic activities [3].

Reliability is a key performance indicator in planning, design and operation of a power system. It can be used by the power utilities to measure the performance of the power system at conceptual and operating stages. It has been reported in different literatures that failures in the distribution system contribute as much as 80% towards the unavailability of power supply at the load points when compared with other segments of electric power system [4]. This has a localized effect and a severe economic loss on the consumers due to the sensitivity and sophisticated characteristics of their equipment. For this reason, the reliability of the distribution system has been considered to be a major issue in the power sector. The analysis of customer failure surveys conducted by the distribution network operators has demonstrated the need to frequently perform the reliability assessment of the distribution system. The persistent power interruptions on this section of the power system will have socioeconomic impacts on the consumers and power utilities such as loss of production, loss of sales, spoilage of raw materials and loss of revenues. Many customers have been subjected to poor power supply from the distribution system in the presence of a reliable generation and transmission system [3]. This has indicated that more attentions should be focused on the reliability assessment of the distribution power system. Any improvement in this section of a power system will bring about a significant reduction in the duration and frequency of power outages at the consumer load points [4]. Moreover, the reliability assessment is an important and effective way to furnish the power regulatory bodies with significant information that can be used as a benchmark in the deregulated power environment.

The traditional distribution system is radial in nature and it has only one power source. Any power failure or a short-circuit fault on the network can cause a severe power interrupt that will affect the entire system. This leads to power outages at the load points since there is no alternative path to supply consumers [3]. Owing to the serial configuration of a radial distribution system, the faults must be cleared as a prerequisite to restore electric power supply back into the system. The optimal operation of a radial distribution system depends on the maximum power demand, total length of the system and voltage regulation. The reliability of a radial distribution system is very low since any fault at the main feeders will cause service interruptions for all the consumers that are connected to the lateral feeders [4]. The consumers at the end of the distribution system would also be subjected to persistent voltage fluctuation when the loads on the system change. The reliability of the power system has witnessed some benefits due to adoption of microgrid system that allows multiple power sources and communication facilities. The renewable energy distributed generation units are located close to the load points for reduction of the COE, NPC and ACS and provide uninterrupted power supply in a microgrid system configuration. This will invariably improve the reliability of a microgrid system and protect a number of consumers from unexpected power outages.

The high cost of the transmission and distribution (T & D) systems, coupled with the high power demand without a corresponding increase in generation capacity has increased the application of RERs in the remote areas. The RERs are considered to be the most cost effective power solutions to meet the load requirements of the rural dwellers owing to the complex characteristics of the terrains and the extensive costs required to extend the T & D lines to such locations [5]. About 17% of the global population have been reported by different international organizations to be living without electricity supply [6]. The 22% of the people without electricity are living in the rural areas of the developing countries where the national grid connection is problematic due to some constraints and remoteness of a number of communities from the transmission lines [6]. In such locations, RERs are incorporated into a power system in order to meet the load requirements of the consumers at the load points. This will not only increase the reserve margin of the power system but also enhance the reliability and reduce the operating costs that associated with the system. One of the key strategies to meet the global energy sustainability is to promote the utilization of a microgrid system that consists of the diesel generator, WTG, PV and BSS. This will reduce over dependence on fossil fuel by using the available solar and wind resources for power generation applications.

The penetration of the RERs into a power system has gotten extensive worldwide considerable attention because of its significant impacts such as the improved reliability of a power system and reduction of fuel cost, operation and maintenance (O & M) cost and emission cost [7]. These unique characteristics have facilitated many power utilities in the world to encourage utilization of RERs as measures to increase global electric power generation. The sudden increase in the power demand and the public concerns over the environmental impacts of utilizing fossil fuels for power generation have created global awareness for exploitation of RERs. Solar and wind are one of the potential renewable energy sources that have recently received global attention because of their economic and technical benefits [8]. The potential alternative for climate change mitigation and greenhouse gas emission (GHG) reduction have motivated the distribution network operators to harness the solar and wind sources for power generation application. The issue brought about by the stochastic characteristics of solar and wind systems can be reduced to a specific degree with the incorporation of various power sources in a power system [9]. The strength of one resource can be used by the power utilities to overcome the weakness of other renewable energy sources. The effects of the intermittent natures of the local RERs on a microgrid power system can also be smoothed out with the application of the BSS. The energy stored in the battery system can be utilized during the deficit power supply or peak period.

Several methodologies have been proposed to study the effects of RERs and BSS on the reliability and economic analysis of a power system. Thapa et al. [10] have proposed a time dependence model and BSS to minimize the uncertainty that is related to the wind system. However, the proposed technique failed to capture the impacts of PV modules on the reliability of a power system. Hussain et al. [11] have presented an iterative filter selection method to evaluate the benefits of utilizing an array of PV modules, WTG and BSS in a hybrid power system. This is achieved by considering a situation where some constraints are enforced on a hybrid system for improvement of reliability and minimization of total project cost and unutilized surplus power. Khaledian et al. [12] have exploited particle swarm optimization (PSO) algorithm to minimize the operating cost and emission cost of a microgrid power system. The impact of RERs is also investigated on the frequency deviation of a power system. Khare et al. [13] have determined the optimum operation of a PV-wind-battery-diesel hybrid system with the application of the Hybrid Optimisation Model of Electric Renewable (HOMER) software. The cost of the hybrid power system is minimized by using different variables and constraints. Govardhan et al. [14] have also presented a unit commitment technique to obtain the suitable on/off decision among the numerous generating units to accomplish minimum generation cost while meeting the power demand requirements of the consumers, power reserve merging and other essential requirements over a planned time horizon. While Iqbal et al. [15] have performed techno-economic evaluation of a PV, battery and diesel generator hybrid power system by using HOMER software. The results obtained from the study showed that the diesel generator could be replaced by the proposed renewable energy sources.

Gonzalez et al. [16] have performed the optimal sizing of a grid-connected hybrid system that consists of the PV and wind systems for minimization of the life cycle cost (LCC) of the system. The sensitivity analysis of the system is also carried out by studying the input variables that can affect the PV and wind configurations. Ayodele et al. [17] have carried out feasibility study of a stand-alone hybrid energy system for remote Ala-Ajagbusi community in Nigeria. The simulation results proved that a wind/diesel/battery hybrid system is the most suitable power alternative for the community. Similarly, Caballero et al. [18] have introduced a technique for the optimal operations and design of a grid-connected PV/Wind hybrid power system. The objective of the study is to reduce the LCC of the power system as well as to improve the reliability of the system by using loss of power supply probability (LPSP). Ramli et al. [19] have performed techno-economic evaluation of wind and solar hybrid power system by utilizing energy generation cost and cost of energy as the benchmarks to assess the impacts of wind and solar resources in a hybrid power system. Moreover, Notton et al. [20] have evaluated the potential of solar and wind resources for power generation application in Corsica Island. The results obtained from the study demonstrate that PV/wind/BSS hybrid power system is a potential power application that could offer a highly reliable power solution for the rural dwellers that live in a remote area. Saheb-koussa et al. [21] have carried out an investigation on a grid connected hybrid RERs system that consists of solar and wind energy resources. In this research, the impacts of PV and WTG systems on a grid connected power system is carried out by focusing on environmental and economic benefits of renewable energy resources.

Kherfane et al. [22] have applied a novel meta-heuristic with a harmony search algorithm (HAS) on a hybrid system that consists of a diesel generator, wind system and PV system. The proposed technique is used to minimize the fuel cost and emission cost of the diesel generator. Bilil et al. [23] have presented a multi-objective genetic algorithm for optimization of the annualized renewable energy cost and the reliability indices of a power system. The optimization is achieved by incorporating various RERs into the proposed hybrid system. Ren et al. [24] have developed a model for optimization of annual running cost, annual CO_2 emissions and reliability of the PV/Fuel Cell/BSS for a residential power system. Moreover, Bilil et al. [25] have presented a probabilistic approach and cumulative density function (CDF) of RERs to optimize the costs that associated with the economic and environmental power dispatch of a power system. The simulation results obtained from the study show that the operating cost and GHG emissions of the proposed hybrid power system can be reduced to the optimum level with the integration of RERs. Kumar et al. [26] have assessed the impact of RERs by utilizing the portfolio theory to optimize the fuel cost and CO2 emissions of the diesel generator. An optimization structure utilizing a dynamic multi-objective evolutionary algorithm is developed to get optimal power solutions. Musau et al. [27] have proposed a multi objective function to solve the dynamic economic emission dispatch problem with thermal, wind, solar, line losses and emissions. The results obtained from the simulation reveal that the proposed technique can be used to optimize fuel cost and emissions simultaneously.

In summary, the literature review of the previous work presented above and the data presented in Table 1 show that little work has been done in integrating RERs into a microgrid system to enhance the reliability of the power system and reduce the COE, ACS and NPC. The aforementioned body of literature has failed to carry out the reliability assessment of a power system with the COE, ACS and NPC. The previous works have dealt with the reliability evaluation of a power system without considering the listed operating parameters. The main weakness of the models proposed in the aforementioned body of literature is their failure to consider the stochastic characteristics of the major components of the power system. The stochastic information about the components of the power systems can be used to assess the performance of a power system. However, this research work aims at exploring the RERs in conjunction with the stochastic characteristics of the major components of a microgrid power system to enhance the reliability of the proposed power system. In this study, the reliability assessment of the power system is carried out by using the proposed model to estimate the expected interruption cost (ECOST) index, expected energy not served (EENS) and TOC of the system since about 80% of the power interruptions occur in the distribution system due to the radial natures of the network. The research work is focussed on the incorporation of RERs in a power system for economic, environmental and reliability benefits by using a number of case studies. The comparative analysis of RERs in a power system is also carried out to study the influences of interest rates on the COE, NPC and ACS. This sheds more light on a number of research questions that have not been fully addressed in the previous research works. Therefore, the main contributions of this work are highlighted as follows:

i. Development of a model that will assess the reliability of a power system with integration of RERs and a baseline from which improvements in the reliability of a power system can be achieved with the incorporation of renewable energy distributed generation units.
ii. Assessment of the environmental and economic benefits of using RERs in a power system.
iii. Development of a model that will minimize the COE, ACS and NPC of a power system and maximize the utilization of RERs.
iv. Application of a Markov model in a microgrid power system by considering the stochastic characteristics of RERs and the cost that is associated with the power outage.
v. Incorporation of the model that can be used to monitor the performance of a power system with the application of RERs based on the design, specifications and government policies.
vi. Utilization of a model that will assist the power utilities to estimate the cost that associated with the power outages and measures to improve the reliability of the system with the integration of RERs.

The key performance indicators like NPC, COE, ACS and reliability indices for several configurations are utilized in this study based on the available RERs to evaluate their economic impacts on a microgrid power system. The results obtained from this research work demonstrate the fact that the wind system, PV system and BSS can be utilized to enhance the reliability and reduce the AEC, AFC, AMC, ACS, COE and NPC of a power system. The approach adopted in this study emerges with some significant improvements based on results obtained that give detailed information on the cost effectiveness of using RERs in a microgrid system. The results obtained from the simulation can be used as a benchmark to make a reasonable managerial decision on renewable energy investment. This paper is organized as follows: In Section 1, the concept of the research work is introduced. In Section 2, a microgrid system and its components such as diesel generator, PV, WTG and BSS are discussed. Moreover, the mathematical modelling for each component of a microgrid system is also presented. In Section 3, the problem is formulated with the objective function and the power system constraints. In Section 4, the reliability indices and economic evaluation parameters are presented. In Section 5, the model is applied on the proposed power system and simulation results are conducted by using some case studies. The results are also presented and discussed in Section 5. Finally, the conclusions are summarized and presented in Section 6.

2. Microgrid power system

By definition, a microgrid system is an electric distribution system that can operate within or independent of the entire power network. It can be used in the remote areas where accessibility to the national grid is difficult due to some barriers [45]. A microgrid system can also be used as a grid connected power system with a specific goal of achieving the financial results when the generating units develop faults. This depends on the technical and financial constraints that associated with the possibility of connecting the affected areas to the national grid. It consists of the loads, diesel generators, battery storage units, WTG, PV, micro gas turbine, hydro and power control units. A microgrid system has been adopted for power application owing to the following reasons: It can be used to improve the reliability of a power system at minimal operating costs and GHG emissions. It has economic benefits owing to

Table 1
Literature review of RERs with different configurations.

Type of power systems	Power generating units	CHP	Battery systems	Modelling parameters	Technique adopted
Standalone	Hydro + wind + thermal [28]	No	No	Profit and risk	PIO
Microgrid	FCG + ICE + SE [29]	Yes	No	GWP, AP, cost and heat dump	MILP
Standalone	PV + wind + hydro [30]	No	No	LPSP	GA
Microgrid	PV + BSS + WTG + FC [31]	No	Typical	COE	PMC
Standalone	PV + BSS + ICE + MGT [6]	No	Typical	COE, LPSP, LCE and waste heat	GA
Microgrid	PV + wind + BSS [32]	No	Typical	COE and TCB	PCAO
Microgrid	PV [33]	No	No	COE and TCB	PCAO
Hybrid	PV + wind + BSS + WH [34]	No	Typical	LCOE, LCC and WHR	GA
Microgrid	CHP + PV + ICE + wood biomass [35]	Yes	No	LCOE	MILP
Hybrid	DG + PV + wind + BSS [36]	No	Typical	TC	AE
Hybrid	DG + PV + BSS [37]	No	Typical	FC, CC and GHG emissions	IOM
Hybrid	DG + BG + PV + wind + BSS [38]	No	Typical	COE, emission and PP	HOMER
District heating system	Waste heater + heat pumps + CHP + HOBs + wind [39]	Yes	No	TOCHG	MILP
Distribution network	DG + BSS [40]	No	Typical	OC	PSO
Microgrid	PV + wind + BSS [41]	No	Typical	OC	MILP
Smart distribution system	RDG and CDG [42]	No	No	Reliability	SMS
Grid system	CHP + MGT [43]	Yes	No	Electricity tariff and financial benefits	DP
Grid system	PV + PHTs + pump [44]	No	No	Electricity cost and WFR	PSO

Key: - AE = Analytical equations, AP = Acidification potential, BG = Biogas generator, CC = Capital cost, CDG = Controllable distributed generation, DG = Diesel generator, DP = Dynamic programming, FC = Fuel cost, FCG = Fuel cell generator, GA = Genetic algorithm, GWP = Global warm potential, HVAC = Heat, ventilation and air conditioning, ICE = Internal combustion engine, IOM = Internal optimization method, LCC = life cycle cost, LCE = Life cycle emissions, MGT = Micro gas turbine, MILP = Mixed integer linear programming, OC = Operating cost, PHTs = Pico hydro turbines, PP = Payback period, PIO = Probability internal optimization, RDG = Renewable based distributed generation, SE = Sterling engines, SMS = sequential Monte-Carlo simulation, TC = Total cost, TOCHG = Total operating cost of heat generation, WFR = Water flow rate, WH = Water harvester and WHR = Water harvesting reliability.

low O & M costs and low emission cost. It is located near the end users, which means the costs that associated with the extension of T & D lines are reduced [45]. The economic and environmental benefits derived from using microgrid system have compelled the development of many algorithms for optimization of a power system.

In this work, the proposed microgrid system that consists of WTG system, PV system, diesel generator and BSS is designed to meet the consumers' load requirements and system constraints. The renewable energy DGs are configured in such a way to supply the consumers' load points based on the availability of the local RERs [46]. The microgrid power system is the most economical and well suited solution for supplying electricity to the remote areas or standalone system that are not tied to the national grid due to some barriers as well as grid connected power system. It can be used by the power utilities to improve the reliability and reduce the AFC, AEC, AMC, ACS, COE and NPC of a power system. The capability of the proposed methodology is validated in a number of case studies by using the meteorological data of De Aar, a town situated in the Northern Cape Province of South Africa with the geographical coordinates of 30.6766° latitude south and 24.0131° longitude east having a population of 42000 residents. The models applied in this research work are based on the average daily ambient temperature, solar irradiance and wind speed recorded by South African weather services. The schematic diagram of a microgrid power system with its major components is presented in Fig. 1. This section briefly presents modelling of renewable DG technologies, BSS and diesel generator.

The power generated by the proposed power system as presented in Fig. 1 can be expressed as:

$$P_G(i,t) = P_{DGEN}(i,t) + P_{PV}(i,t) + P_{WTG}(i,t) \quad (1)$$

The energy balance of the proposed power system is presented in Eq. (2) as:

$$P_D(i,t) = P_G(i,t) \pm P_{BSS}(i,t) \quad (2)$$

where $P_G(i,t)$ is the total power generated from the PV, diesel generator and WTG, $P_{DGEN}(i,t)$ is the power generated from the diesel generator, $P_{PV}(i,t)$ is the power generated from the PV, $P_{WTG}(i,t)$ is the power generated from the WTG, $P_D(i,t)$ is the load demand at the consumers load points and $P_{BSS}(i,t)$ is the charge and discharge power in the BSS.

2.1. Diesel generator

The diesel generator uses the principle of internal combustion for power generation. It can be used for prime, continuous and standby applications in the rural areas or standalone systems that have no access to the main grid supply system and grid connected power system. The diesel generator has the following features: quick start up, mobility, fuel flexibility, high reliability and high efficiency [47]. However, the O & M costs of the diesel generator are highly expensive when compared with RERs. The diesel generator is also a source of GHG emission. The diesel generator is designed by the original equipment manufacturer (OEM) in such a way that it can operate at the 30%–80% of its nominal rating. It utilizes the electronic control module (EDM) to regulate the fuel consumption based on the load demand as well as to increase the efficiency of the system. The fuel cost of the diesel generator with the model number CAT 3516 is used in this study together with some operating parameters such as fuel consumption and power output. The power generation cost function of the diesel generator can be determined by using polynomial fits of the diesel generator operating characteristics that are made available by the manufacturer in L/h at 1/4, 1/2, 3/4 and full loads. The fuel consumption of the diesel generator depends on the power output, type of the diesel generator, the quality of the fuel, humidity and the ambient temperature [6]. The fuel cost of the diesel generator with its output power at time t can be expressed as:

$$FC_i = a_i P_{gen}^2(i,t) + b_i P_{gen}(i,t) + c_i \quad (3)$$

where FC_i is the fuel cost of the diesel generator, $P_{gen}(i,t)$ is the power generated by the diesel generator and a, b and c are the cost coefficient of the diesel generator i.

The fuel cost of the diesel generator also depends on the rating of the diesel generator. The power ratings of the diesel generators should be 20% more than the power demand by the consumers at the load points. This prevents overloading of the diesel generator during the starting and switching operations of some equipment. The power generated by the diesel generator can be estimated by using Eq. (4):

$$P_{gen} = P_n \times N_{gen} \times \eta_{gen} \quad (4)$$

where N_{gen} is the number of the diesel generators, P_{gen} is the power generated (kW), P_n is the nominal power generated by diesel generator

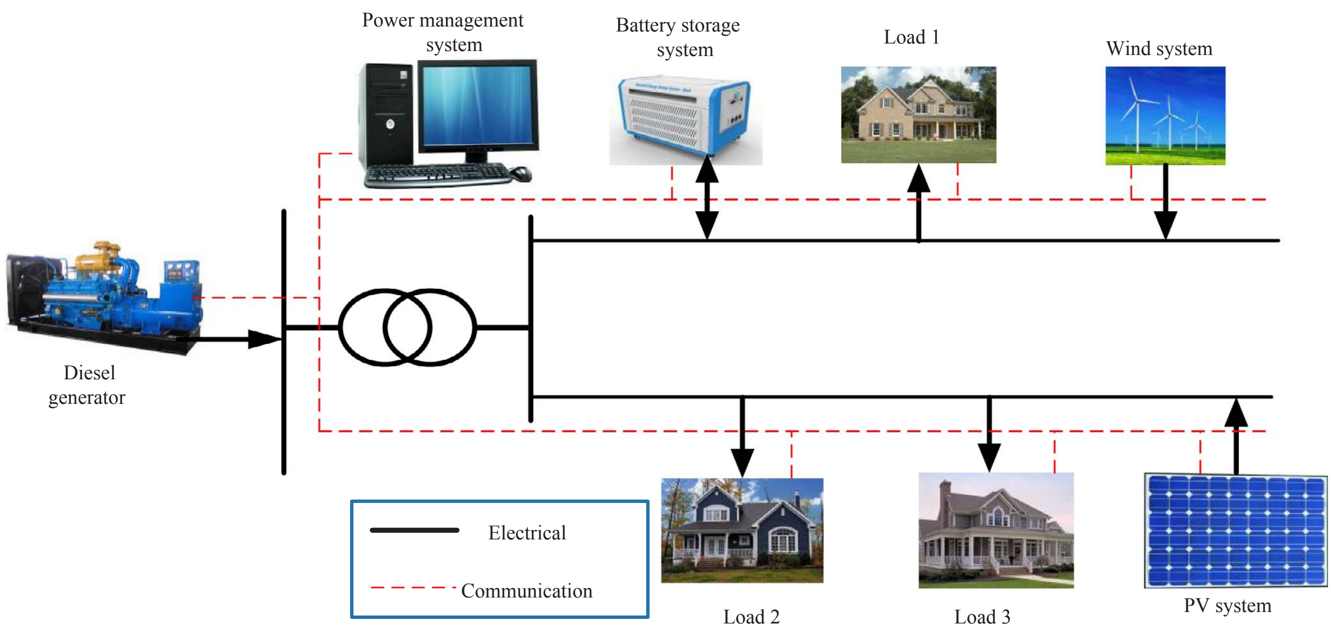

Fig. 1. The schematic diagram of the proposed power system.

(kW) and η_{gen} is the efficiency of the diesel generator.

The diesel generator is designed to operate within the maximum and minimum rated capacity specified by the manufacturers. This will limit the thermal effects on the winding of the diesel generator as well as for stability of the output power of the generating unit. The power constraints of the diesel generator are represented as follows:

$$P_{gen}^{min}(i,t) \leqslant P_{gen}(i,t) \leqslant P_{gen}^{max}(i,t) \tag{5}$$

Table 2
Emission externality costs and emission factors of the diesel generator [48,49].

Type of emission	Emission externality costs ($/kg)	Emission factor for diesel generator (kg/kW h)
NOx	1.086	0.0066911
SO_2	1.8	0.0003595
CO_2	0.017	0.6569395

2.1.1. Emission externality costs

The emissions produced by the conventional power plants due to combustion of fossil fuels has a negative impact on the environment. The emission externality costs (EECs) are introduced by the governmental agencies in the form of un-priced costs to curb the effects of GHG emissions on the climate, human health, crops, structures and biodiversity. The EECs are utilized by the environmental regulators to control the amount of carbon oxide (CO_2), sulphur oxide (SO_2), nitrous oxide (NOx), mercury and particulate emissions from the fossil fuels based power generating units. These emissions are penalized because they can damage the public health and cause asthma, chronic bronchitis, air pollution, water pollution and global warming. The EECs can be used as the economic benchmark to estimate the damage caused by each kg/hr of GHG pollutant emitted into the atmosphere. The conventional power plant's emissions, which adversely affect the environment can be reduced to a certain level with the application of the EECs. This technique is in the form of taxes that are added to the sale of energy that emanates from the conventional power plants that produce a large amount of the GHG emissions. This approach will increase the capital base of the government agencies to provide incentives for the construction of new low emissions generating power plants. The EECs and emission factors of the diesel that are used in this study are presented in Table 2 [48,49].

2.2. Battery storage system

The battery storage system is utilized in conjunction with the WTG and PV systems to reduce the uncertainty that is associated with the local renewable energy sources [50]. The unstable power supply caused by the intermittent characteristics of the local renewable energy sources can be smoothed out with the application of the BSS. The stored energy in the battery banks can be utilized to cover the deficit power during the peak period [50]. This configuration will smooth out the effects of power fluctuation of the local renewable energy sources and thereby enhance the reliability of a microgrid power system. The battery performance depends on the following parameters: ambient temperature, state of charge, voltage effects, rate of charging and rate of discharging. The listed factors also determine the lifetime of a battery. For a battery to be durable, it must not be over charged because overcharging will affect the performance and overall life of the battery. The battery must not be over discharged because this will create a very high internal heat that can damage the battery. The general requirements for the longevity of the battery is to set the maximum state of charge of the battery to its nominal capacity. In addition to this, the minimum state of charge (SOC) of the battery should not be less than 20% [6]. The SOC of the battery can be expressed as:

$$SOC^{min} \leqslant (SOC(O) + \eta_c \sum_{t=1}^{k} P_i(t) - \eta_d \sum_{t=1}^{k} P_i(t)) \leqslant SOC^{max}, \text{ for } 1 \leqslant t \leqslant k \tag{6}$$

The battery bank capacity is constrained within the minimum allowable capacity and the maximum allowable capacity. The battery bank most operate between the minimum and maximum allowable capacity for optimal performance of the system.

$$SOC^{min} \leqslant SOC(t) \leqslant SOC^{max} \tag{7}$$

$$SOC^{min} = (1-DOD)SOC^{max} \tag{8}$$

where DOD is the depth of discharge, η_c is the battery charging efficiency, η_d is the battery discharging efficiency, SOC^{min} is the minimum allowable capacity and SOC^{max} is the maximum allowable capacity.

2.3. PV system

The PV arrays contain several solar cells that are interconnected to provide the required terminal voltage and current ratings based on the manufacturer's specifications [51]. The PV system has emerged as one of the highly acceptable power generating resources because of low O & M cost, no direct carbon emission and no fuel cost. With every one of these qualities, the PV system will stabilize the costs expended for expansion of power generation in the long run [8]. On the basis of the renewables 2017 global status report (REN21) of global PV installations, the installed capacity of PV system was estimated to be 303 GW at the end of 2016 and it is projected to reach 872 GW by 2030 [52,53]. Moreover, the power output of a PV system depends on the location of the sun in the sky, solar irradiance and operating temperature [54]. The MonoXTH PV module with the model number LG250SIk-G3 is used in this study with some technical parameters at standard test conditions (STC). The power output of the PV system can be estimated by using the following expressions [55]:

$$T_{cell} = T_{amb} + s(t) \times \left\{\frac{NOCT-20}{0.8}\right\} \tag{9}$$

$$I = s(t) \times \{I_{sc} + K_{ct} \times (T_{ct}-25)\} \tag{10}$$

$$V = \{V_{oc} + K_{vt} \times T_{ct}\} \tag{11}$$

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \tag{12}$$

$$P_{pv}(s(t)) = \eta_{cells} \times FF \times V \times I \tag{13}$$

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

2.4. Wind system

The application of wind energy in a power system has witnessed a rapid growth in the recent years due to environmental impact and high prices of the fossil fuels. The fast growth of the wind system in the last few decades has been attributed to the following features, i.e. low O & M costs, cost effective, sustainable source of energy, clean fuel source, no direct GHG emission and no fuel cost [8]. These characteristics have increased the global wind energy capacity for over a decade. The worldwide installed capacity of wind system was estimated to be 487 GW at the end of 2016 and this figure has been projected to reach around 2000 GW by 2030 [53]. This indicates that the wind system is projected to supply between 16.7% and 18.8% of the global electric power by 2030 [56].

The power output of the WTG depends on the characteristics of wind regime, swept area of the rotor, aero-turbine performance, efficiency of the wind turbine, the nature of the load being supplied and the characteristics of the WTG [57]. The output power of the wind system is more intermittent when compared with the conventional generating units. The wind system will start to generate electrical power at just above the cut-in speed that is determined by the respective manufacturers and is typically between 2.5 m/s and 4 m/s. As the wind speed increases above the cut- in wind speed, the output power will continue to increase until it reaches the rated power output at a wind speed called the rated speed, which is typically between 12 m/s and 20 m/s. At the rated wind speed, the wind turbine is designed to maintain a constant electrical output by using appropriate blade pitch control technique. The system will be shut down completely for safety reasons and to reduce the possibility of damaging the wind turbine rotor if the wind speed is beyond the cut-out speed. The Vestas wind turbines with the model number V80-2.0MW and some operating parameters are used in this study. The wind turbine power output is estimated based on the daily average wind speed of the site used as a case study. The mathematical expression for estimation of the power output of the wind system is presented in Eq. (14) as [55]:

$$P_{wtg} = \begin{cases} 0 & if \ \ v < v_{ci} \\ P_r \cdot \frac{(v^k - v_{co}^k)}{(v_{co}^k - v_r^k)} & if \ \ v_{ci} \leqslant v \leqslant v_r \\ P_r & if \ \ v_r \leqslant v \leqslant v_{co} \\ 0 & if \ \ v > v_{co} \end{cases} \tag{14}$$

where P_r is the rated power output of the wind turbine, v_{ci} is the cut-in wind speed, v_r is the rated wind speed, v_{co} is the cut -out wind speed, v is the actual wind speed and P_{wtg} is the power output of the wind system respectively.

3. Objective function

The main objective function of this research work is to improve the reliability of a power system as well as to minimize the ACS and COE while satisfying the consumer power requirements and the system constraints. The ACS consists of AEC, AMC, AFC, annualized replacement cost (ARC) and annualized capital cost (ACC) of the system. This can be achieved with the integration of the BSS units and RERs such as WTG and PV systems into a power system so that consumer load requirements are shared among the diesel generator, BSS and RERs. The improvement of the power system reliability and minimization of the COE and ACS of the system are the significant objectives when designing a power system. These key operating parameters are considered in this study in order to reach the optimal operation of the proposed microgrid power system. This is accomplished by limiting the control variables of the diesel generator and increasing the control variables of RERs at reduced COE and ACS. The non-linearity of the renewable energy resources, load demand and fuel consumption pattern are considered in this study. The objective function consists of three parts: TOC, ACS and COE. The configuration of the proposed microgrid power system is presented in Fig. 2.

Mathematically, the objective function of the proposed power system can be expressed as follows:

$$\text{F}= \min \sum_{i=1}^{n} (TOC + ACS + COE)\text{"\$"/yr} \tag{15}$$

$$= \min \sum_{i=1}^{n} [ECOST + k_e EENS] + [ACC + ARC + AMC + AFC + AEC] + COE] \text{ "\$"/yr} \tag{16}$$

The first component of the objective function contains the reliability indices such as ECOST and EENS that are presented in Eq. (17) as:

$$\text{TOC} = \sum_{i=1}^{n} (ECOST + k_e EENS) \text{ ("\$"/yr)} \tag{17}$$

where k_e is the value of lost load ($/kW h), EENS is the expected energy not supplied (MW hr/yr) and ECOST is the expected interruption cost index ($/yr).

The second element of the objective function is the ACS, which is the sum of the AMC, AFC, AEC, annualized ARC and ACC of the generating unit i.

$$\text{ACS} = \sum_{i=1}^{n} [ACC + ARC + AMC + AFC + AEC] \tag{18}$$

The third component of the objective function is the cost of energy generated by the proposed power system.

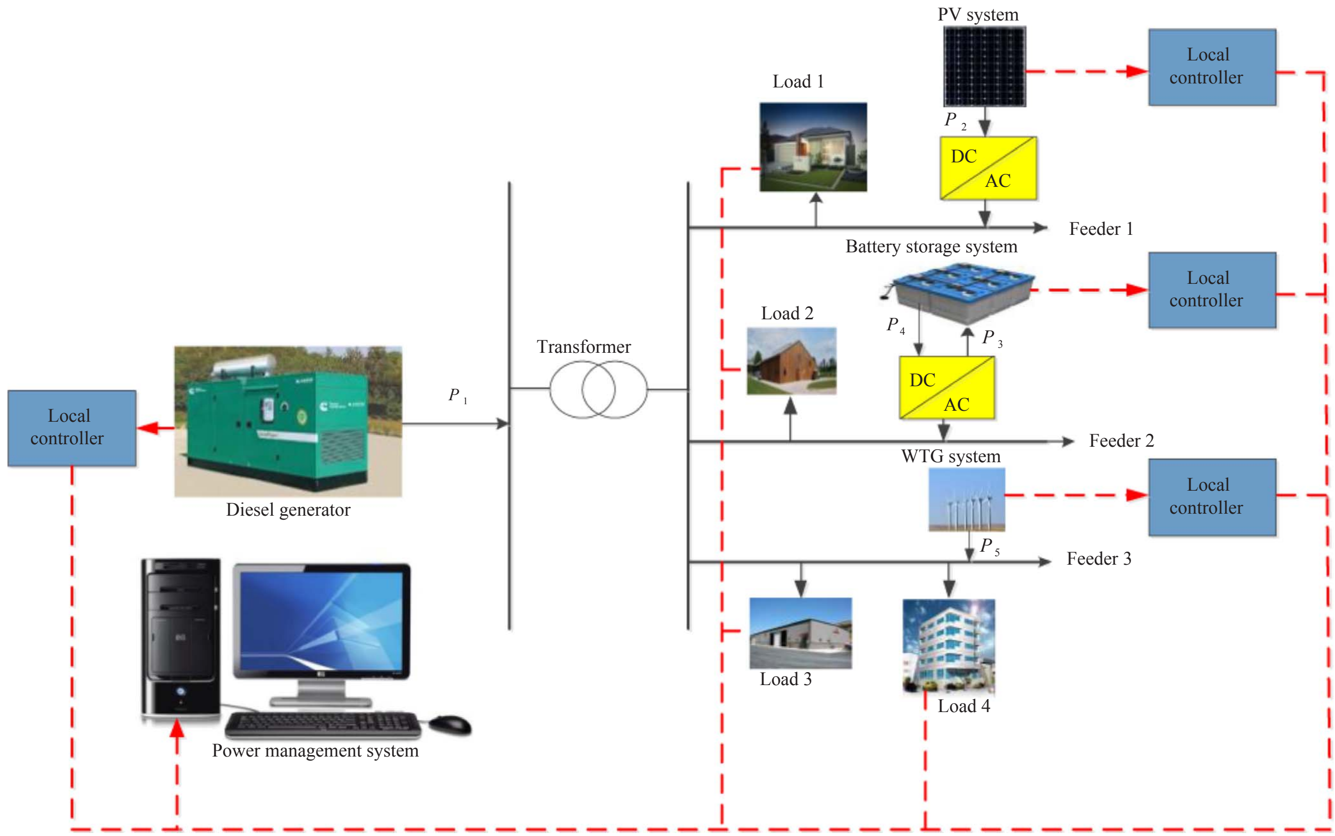

Fig. 2. The studied microgrid system configuration.

$$COE = \frac{ACS}{AEP} \tag{19}$$

where AEP is the annual energy production (kW h) and COE is the cost of the energy ($/kW h)

3.1. Objective constraints

The multi objective function of the research work is subject to the following operational constraints:

3.1.1. Power system balance constraints

The system load requirements are met when the power generated from the diesel generator, WTG system, PV system and BSS are within the operating limits of the system. The power generated from the listed generating units must meet the load demand at the load points. The power system is limited by the constraints presented in Eq. (20) as:

$$\sum_{i=1}^{N_{gen}} P_1(i,t) + \sum_{j=1}^{N_{pv}} P_2(j,t) - \sum_{k=1}^{N_{bss}} P_3(k,t) + \sum_{m=1}^{N_{bss}} P_4(m,t) + \sum_{n=1}^{N_{wtg}} P_5(n,t) = \sum_{z=1}^{N_D} P_D(z,t) \tag{20}$$

3.1.2. Power generating output constraints

The power output of each generating unit is restricted to the minimum and maximum power generating limits specified by each original equipment manufacturer. The limits of the power generated by each generating unit as shown in Fig. 2 can be expressed in Eq. (21) as:

$$\begin{cases} P_1^{\min}(i,t) \leqslant P_i(i,t) \leqslant P_1^{\max}(i,t), \\ P_2^{\min} \leqslant P_2(j,t) \leqslant P_2^{\max}(j,t), \\ P_3^{\min}(k,t) \leqslant P_i(k,t) \leqslant P_3^{\max}(k,t), \\ P_4^{\min}(m,t) \leqslant P_i(m,t) \leqslant P_4^{\max}(m,t) \text{ and} \\ P_5^{\min}(n,t) \leqslant P_i(n,t) \leqslant P_1^{\max}(n,t) \end{cases} \tag{21}$$

3.1.3. Power balance limits

The positive value of the power balance indicates the battery charging operation and a negative value indicates the battery discharging operation.

$$P_{balance} = \left[\sum_{z=1}^{N_D} P_D(z,t) - \left(\sum_{j=1}^{N_{pv}} P_2(j,t) + \sum_{n=1}^{N_{wtg}} P_5(n,t) \right) \right] \tag{22}$$

where $P_1(i,t)$ is the power generated by the diesel generator, $P_2(j,t)$ is the power generated by the PV system, $P_3(k,t)$ is the charge power at the BSS, $P_4(m,t)$ is the discharge power at the BSS, $P_5(n,t)$ is the power generated by the wind system, $P_D(z,t)$ is the power demand at the consumer load points and N_{gen}, N_{pv}, N_{wtg} and N_{bss} denote number of diesel generator, PV, WTG and BSS respectively during time t. ND depicts the number of load points in the proposed microgrid.

The main objective function of this work can be achieved with the application of an fmincon as presented by Eq. (23):

$$F = \min \sum_{i=1}^{n} f(x) \tag{23}$$

Subject to the following constraints:

$$\begin{cases} C(x) \leqslant 0 \\ Ceq(x) = 0 \\ A.\,x \leqslant b \\ Aeq.\,x = beq \\ Ib \leqslant x \leqslant ub \end{cases} \quad (24)$$

where $C(x)$ and $Ceq\ (x)$ are functions that return vectors; x, b, beq, lb and ub are vectors, A and Aeq are matrices, $f\ (x)$ is a function that returns a scalar, $f(x)$, $C(x)$ and $Ceq\ (x)$ are non-linear functions.

4. Reliability and economic analysis of a microgrid power system

A microgrid can operate as a standalone or grid connected system based on the economic, reliability and environmental benefits that the utilities obtain from utilizing the system. Based on this, it is mandatory to carry out a feasibility study on a microgrid power system as a prerequisite to analyze the level of its economic and technical proficiency. In this context, some key performance indicators are used for economic and reliability assessment of the proposed power system. This research work is centred on the investment and operating costs that have to do with the operation of a microgrid system. The application of RERs in the proposed power system has been explored to enhance the reliability and reduce the fuel cost, maintenance cost and GHG emissions of the power system. The microgrid used in this research work is islanded.

The most important benchmark to determine if the RERs that have been integrated into a power system are financially viable can be analyzed by using the following parameters: ECOST, EENS, TOC, ACS, COE and NPC. The economic approach based on the listed parameters will be used to determine the most viable combination after RERs and BSS have been incorporated into a power system. The optimum combination of a power system that consists of the WTG system, PV system, BSS and diesel generator can be determined based on the reliability and operating costs of a microgrid power system. The ACS and COE can be used to estimate the economic feasibility of different combination of the RERs and diesel generator. The ACS, NPC and COE are conducted to compare different combinations of the diesel generator, WTG system, PV system and BSS in a microgrid system. If a number of options are being considered among the numerous combination of power generating units, then the option with the lowest ACS, COE and NPC will be the most favourable financial choice. The aforementioned parameters are used in this study to find the most feasible and cost effective option among the numerous configurations of the power system. The impacts of RERs on costs, emissions and reliability of the proposed power are compared by using different case studies.

4.1. Reliability assessment of the power systems

Reliability is the probability that a power system will meet the consumers' load requirements at any time [4,58]. This objective can be achieved with the utilization of RERs, if the relationship between the economic and reliability benefits have been established. A reliable power supply must be designed by the utilities in such a way that it will have a sufficient power to meet the load demand at minimum investment and operating costs. The reinforcement of the distribution system with the integration of RERs should be based on the economic and technical considerations of the system. The power outage that occurs in the distribution system has been reported to be about 80% of the total outages in the power system. The distribution system is an important section in the power system that has a large number of consumers. For this reason, frequent reliability assessment of this section of the power system is more important due to high demand of a reliable power supply by the end users at a minimum frequency and duration of power outages.

The power requirements of the consumers can only be met by shifting the distribution power system from a single power source to a multiple power sources. This will not only enhance the reliability of the system, but also reduce the cost of energy, annualised fuel cost, annualised emission cost, annualised maintenance cost and net present cost of the system. The effect of utilizing RERs in a microgrid power system is studied and analyzed in this research work. The performance of the distribution system with the integration of RERs can be measured by using the reliability indices. It is important to state categorically that the reliability study can be utilized by the power utilities to predict the future performance of the distribution system based on the past performance of the system. The study can also be used to evaluate the impacts of adding new generating units and components in a power system. The performance metrics used for assessment of the proposed power system include EENS and ECOST. The indices are briefly explained as presented below.

4.1.1. Expectation energy not supplied

The expected energy not supplied (EENS) is the total energy that is not delivered at the system load points. The EENS is the expectation of energy shortage in a period of time when the load demanded exceeds the available generating capacity. It is an important index that is utilized by the utilities for the reliability assessment of a power system. The capacity of the unmet load demand can be measured in MW h over a specific period with the EENS index. The EENS of a power distribution system as presented in Fig. 3 can be calculated by using the following mathematical expressions [4,7,59]:

$$\begin{aligned} \text{EENS} &= P_i U_i (\text{MW hr/yr}) \\ &= \sum_{i=0}^{n} \lambda_i r_i L_i \\ &= \lambda_a r_a L_a + (\lambda_a r_a + \lambda_b r_b) L_b + (\lambda_a r_a + \lambda_b r_b + \lambda_c r_c) L_c \\ &= (L_a + L_b + L_c)\lambda_a r_a + (L_a + L_b)\lambda_b r_b + L_c \lambda_c r_c \\ &= PF_a \lambda_a r_a + PF_b \lambda_b r_b + PF_c \lambda_c r_c \\ &= \sum_{i=0}^{n} \lambda_i r_i PF_i \end{aligned} \quad (25)$$

where λ_i is the average failure rate at load point i, n is the number of outages at load point i, r_i is the failure duration at load point i, U_i is the annual outage duration at load point i and PF_a, PF_b and PF_c depict the power flow in the line sections a, b and c respectively.

4.1.2. Expectation interruption cost

Expected interruption cost (ECOST) index is the cost of not supplying the consumers at the load points due to the power outage that is associated with faulty components in a power system. ECOST depends

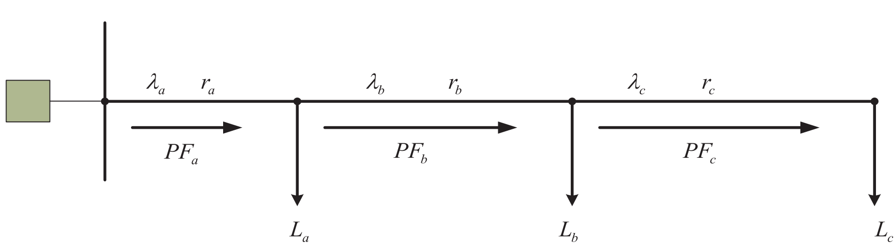

Fig. 3. A distribution system with the section lines.

on the characteristics of consumers [4,7,59].

$$\text{ECOST}{=}P_i\sum N_e f_{r,j}\lambda_i\ (\text{k"\$"/yr}) = P_a N_e f_{a,j}\lambda_a + P_b N_e f_{b,j}\lambda_b + P_c N_e f_{c,j}\lambda_c \tag{26}$$

where N_e is the number of components on which faults will interrupt the load point i, $f_{r,j}$ is the cost of interruption/composite customer damaged function (CCDF) and P_i is the average load (MW).

4.1.3. Total outage cost

The EENS and ECOST can be used by the power utility to monetize the effect of power outage in a power system. The monetary value of EENS can be estimated by multiplying it with the value of the lost load (k_e). The values of k_e are in the range of 5–40 $/kW h for industrial applications and 2–12 $/kW h for residential consumers [60]. In this study, the monetary value of the loss of load caused by the power outage is assumed to be 5.5 $/kW h or R75/kW h based on South Africa standard [59]. This approach can be used to estimate the reliability worth of a power system by focusing on the cost of loss load that results from the power outages. The total outage cost of a power system can be estimated as presented in Eq. (27) [4,7,59].

$$\text{TOC} = \sum_{i=1}^{n} (ECOST + k_e EENS)\ (\text{"\$"/yr}) \tag{27}$$

4.2. Stochastic characteristics of the generating units

The stochastic characteristics of the diesel generator, RERs and battery and their influence on the reliability of the system are studied and analyzed in this research work by using a Markov model. A Markov model is presented in this work to assess the reliability of a microgrid system, including the PV system, WTG system, BSS and diesel generator. The impact of the generating units on the reliability of a power system can be evaluated by incorporating the failure rate and repair rate of the components into the reliability model. The reliability of the proposed power system can be evaluated by using the reliability indices of the major components that constitute the power system. This can be achieved by analyzing the major components that make up the power system separately. The results obtained from analyzing the key reliability indices of the major components can be used to estimate the state of reliability of the entire power system.

4.2.1. Reliability modelling of the diesel generator

The diesel generator has three models: the electrical model, the mechanical model and fuel supply model as represented in Fig. 4. The fuel supply model can be used to study the availability of the diesel during the operating time of the diesel generator. The diesel supply is assumed to be 100% reliable due its availability at all time and other structures that have been put in place to ensure the availability of fuel supply at all time. The electrical model of the system is indicated by the capability of the electrical part of the diesel generator to be in upstate or operating state when needed without any failure. The mechanical model of the system also represents the ability of the diesel generator to be in upstate or operating state at all time without any failure. The mechanical and electrical models are considered for the reliability assessment of the diesel generator since the supply of the fuel is assumed 100% reliable. The output power of the diesel generator is also assumed to be zero or full capacity based on the stochastic characteristics of the electrical and mechanical components of the diesel generator.

The electrical model of the diesel generator can be denoted in two states, i.e. upstate and downstate. The upstate represents the operating state of the electrical part of the diesel generator and the downstate represents the failure states of the electrical part of the diesel generator. The mechanical model of the diesel generator can as well be represented in two states, i.e. upstate and downstate. The upstate represents the operating state of the mechanical part of the diesel generator and the downstate represents the failure states of the mechanical part of the diesel generator. The output power of the diesel generator will be zero if the mechanical or electrical part of the engine is in the downstate. Having analyzed the reliability assessment of the diesel generator, it is assumed that the diesel generator will produce the rated power if it is operational or in upstate. A transition matrix for the diesel generator is constructed by using the diagram represented in Fig. 4. The failure rate and repair rate for mechanical and electrical components of the diesel generator can be denoted by λ_m, λ_e, μ_m and μ_e respectively.

The system has four states that are denoted as:

State 1 (11): The mechanical and electrical components are in the operating states.
State 2 (01): The mechanical component is in the failed state and the electrical component is operational.
State 3 (10): The mechanical component is operational and the electrical component is in the failed state.
State 4 (00): Both mechanical and electrical components are failed in the failed states.

The Markov model for the mechanical and electrical components of the diesel generator is represented in Fig. 5. The diesel generator is denoted by two operating states, i.e. upstate and downstate. The mechanical and electrical components of the diesel generator are connected in series. This signifies that the diesel generator will only be in the upstate if the aforementioned components are in the successful operating states.

The transition probability matrix for the proposed system is shown below.

$$P_{gen} = \begin{bmatrix} 1{-}\lambda_m{-}\lambda_e & \lambda_e & \lambda_m & 0 \\ \mu_e & 1{-}\lambda_m{-}\mu_e & 0 & \lambda_m \\ \mu_m & 0 & 1{-}\mu_m{-}\lambda_e & \lambda_e \\ 0 & \mu_m & \mu_e & 1{-}\mu_m{-}\mu_e \end{bmatrix} \tag{28}$$

The diesel generator will only operate successfully in the state 1 as presented in Fig. 5, otherwise the system will be in failure states, i.e. states 2–4. The failure states of the system are represented by the absorbing states, this result in a truncated matrix.

$$Q = [1{-}\lambda_m{-}\lambda_e] \tag{29}$$

The mean time to failure (MTTF) of the system can be assessed by utilizing the accompanying following steps:

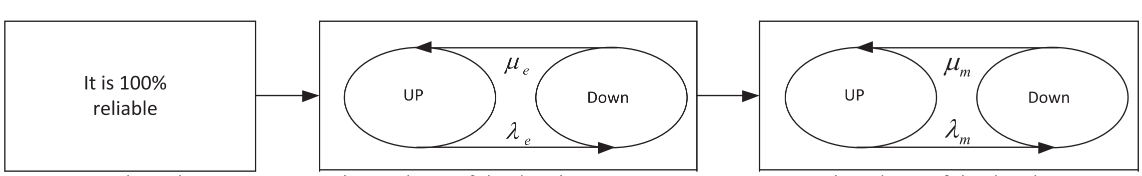

Fig. 4. Reliability model of diesel generator.

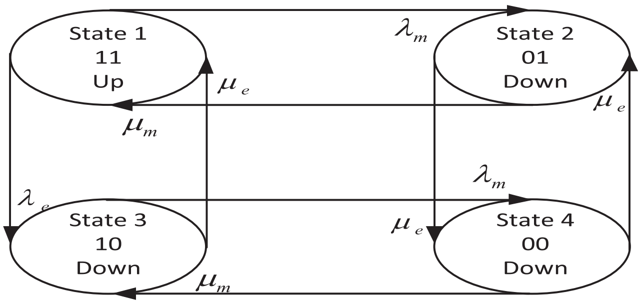

Fig. 5. Stochastic model of the diesel generator.

$$\begin{aligned}\text{MTTF} &= [I-Q]^{-1}\\ &= [[1]-[1-\lambda_m-\lambda_e]]^{-1}\\ &= [\lambda_m-\lambda_e]^{-1}\\ &= \frac{1}{\lambda_m+\lambda_e}\end{aligned} \tag{30}$$

Therefore, the equivalent failure rate for the diesel generator can be expressed as:

$$\lambda_{gen} = \lambda_m + \lambda_e \tag{31}$$

where I is the identity matrix and λ_{gen} is the equivalent failure rate for the diesel generator.

The Markov state transition diagram is presented in Fig. 5 where the failure rate and repair rates are represented by λ and μ respectively. The transition from the up state to down state and from the down state to up state of the system can be assessed by using a Markov model. The probability that the system is in the up state and down state can be expressed in Eq. (32) as:

$$P_{up} = \frac{\mu}{\lambda+\mu} \text{ and } P_{down} = \frac{\lambda}{\lambda+\mu} \tag{32}$$

The probability of the mechanical and electrical components in the up states can be denoted as:

$$P_{s-up} = \frac{\mu_m}{\lambda_m+\mu_m}\frac{\mu_e}{\lambda_e+\mu_e} \tag{33}$$

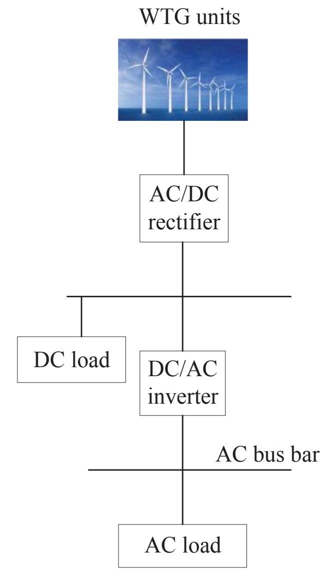

Fig. 6. Components of the wind system.

4.2.2. Reliability model of the WTG, AC/DC rectifier and DC/AC inverter systems

The WTG is utilized in this study to enhance the reliability of the power system. The benefits of using the WTG and its ancillaries can be improved by carrying out the stochastic analysis of the system. This is achieved by modelling and studying the stochastic characteristics of the RERs and their influence on the reliability of the power system. The presence of the wind system in a power system will reduce the duration and frequency of interruptions experienced by the consumers at the load points. The stochastic characteristics of the WTG, AC/DC rectifier and DC/AC inverter systems as presented in Fig. 6 can be modelled by using the Markov approach. The system may exist in any state presented in Fig. 7 based on the stochastic characteristics of the WTG, AC/DC rectifier and DC/AC inverter system. In this study, the failure rate and repair rate of the WTG, AC/DC rectifier and DC/AC inverter systems are represented by λ_{wtg},μ_{wtg},λ_{rec},μ_{rec},λ_{inv} and μ_{inv} respectively.

$$\text{P}_\text{i} = \begin{bmatrix} (1-\lambda_{wtg}-\lambda_{rec}-\lambda_{inv}) & \lambda_{wtg} & \lambda_{rec} & \lambda_{inv} & 0 & 0 & 0 & 0\\ \mu_{wtg} & (1-\mu_{wtg}-\lambda_{rec}-\lambda_{inv}) & 0 & 0 & \lambda_{rec} & 0 & \lambda_{inv} & 0\\ \mu_{rec} & 0 & (1-\mu_{rec}-\lambda_{wtg}-\lambda_{inv}) & 0 & \lambda_{wtg} & \lambda_{inv} & 0 & 0\\ \mu_{inv} & 0 & 0 & (1-\mu_{inv}-\lambda_{wtg}-\lambda_{rec}) & 0 & \lambda_{rec} & \lambda_{wtg} & 0\\ 0 & \mu_{rec} & \mu_{wtg} & 0 & (1-\mu_{rec}-\mu_{wtg}-\lambda_{rec}) & 0 & 0 & \lambda_{rec}\\ 0 & 0 & \mu_{inv} & \mu_{rec} & 0 & (1-\mu_{inv}-\mu_{rec}-\lambda_{wtg}) & 0 & \lambda_{wtg}\\ 0 & \mu_{inv} & 0 & \mu_{wtg} & 0 & 0 & (1-\mu_{inv}-\mu_{wtg}-\lambda_{rec}) & \lambda_{rec}\\ 0 & 0 & 0 & 0 & \mu_{inv} & \mu_{wtg} & \mu_{rec} & (1-\mu_{inv}-\mu_{wtg}-\mu_{rec}) \end{bmatrix} \tag{36}$$

The repair rate (μ_{gen}) for the diesel generator can be obtained by using Eqs. (34) and (35)

$$P_{s-up} = \frac{\mu_{gen}}{\lambda_{gen}+\mu_{gen}} \tag{34}$$

$$\mu_{gen} = \frac{P_{s-up}\lambda_{gen}}{1-P_{s-up}} \tag{35}$$

$$= \frac{(\lambda_m+\lambda_e)(\lambda_m\mu_e)}{\lambda_m\mu_e+\lambda_m\mu_e+\lambda_e\mu_m}$$

The transition matrix of the entire system is presented in Eq. (36).

$$\text{Q} = [1-\lambda_{wtg}-\lambda_{rec}-\lambda_{inv}] \tag{37}$$

The mean time to failure (MTTF) for the entire system as presented in Fig. 7 can be expressed as [59]:

$$\text{MTTF} = [[I]-[Q]]^{-1} \tag{38}$$

$$= \frac{1}{\lambda_{wtg}+\lambda_{rec}+\lambda_{inv}} \tag{39}$$

The total failure rate for the entire system can be expressed as:

$$\lambda_{ws} = \lambda_s = \lambda_{wtg}+\lambda_{rec}+\lambda_{inv} \tag{40}$$

The probability of the series components in the upstate is denoted

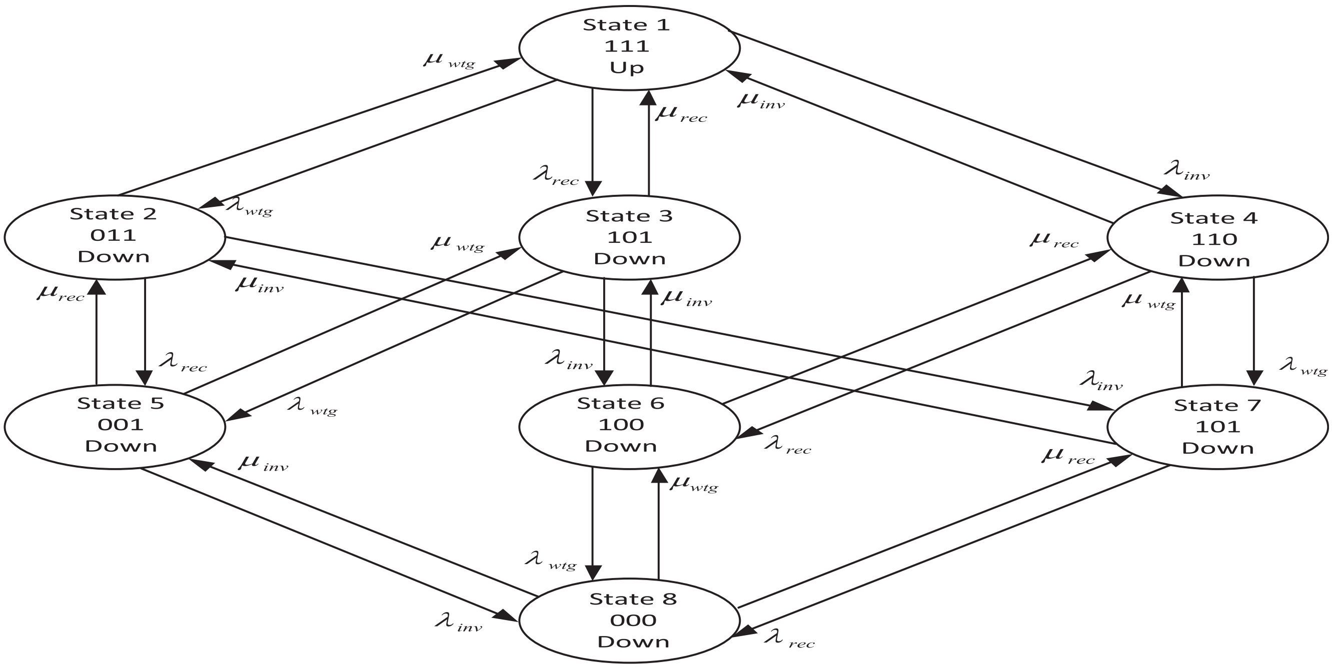

Fig. 7. Stochastic model for wind system.

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 [3,61]:

$$P_{s-up} = \frac{\mu_{wtg}}{\lambda_{wtg} + \mu_{wtg}} \frac{\mu_{rec}}{\lambda_{rec} + \mu_{rec}} \frac{\mu_{inv}}{\lambda_{inv} + \mu_{inv}} \tag{41}$$

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

$$P_{s-up} = \frac{\mu_s}{\lambda_s + \mu_s} \tag{42}$$

The equivalent repair rate (μ_{eq}) for the entire system that consists of WTG, AC/DC rectifier and DC/AC inverter can be determined by using Eq. (43) [3,59,61]:

$$\mu_{ws} = \mu_s = \frac{P_{s-up}\lambda_s}{1-P_{s-up}} \tag{43}$$

$$\mu_{ws} = \frac{(\lambda_{wtg} + \lambda_{rec} + \lambda_{inv})(\mu_{wtg}\mu_{rec}\mu_{inv})}{\lambda_{wtg}\lambda_{rec}\lambda_{inv} + \lambda_{wtg}\lambda_{rec}\mu_{inv} + \lambda_{wtg}\lambda_{inv}\mu_{rec} + \lambda_{rec}\lambda_{inv}\mu_{wtg} + \lambda_{wtg}\mu_{rec}\mu_{inv} + \lambda_{rec}\mu_{wtg}\mu_{inv} + \lambda_{inv}\mu_{wtg}\mu_{rec}} \tag{44}$$

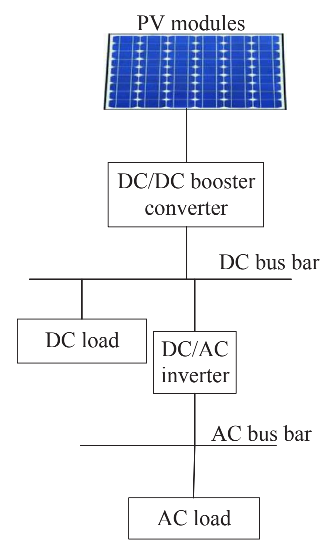

Fig. 8. Components of the PV system.

4.2.3. Reliability model of the PV array, DC/DC booster converter and DC/AC inverter systems

The PV system comprises of an array of PV modules, a DC/DC booster converter and a DC/AC inverter as shown in Fig. 8. The application of the PV system has become a potential alternative for the utilities to improve the reliability of their systems rather than to construct a new distribution network. The effect of RERs on the reliability of a power system is investigated with the PV system as one of the main sources of power supply. With the integration of the PV system in a power system, the cost that associated with the power outages will be reduced by a significant value. The continuity of power supply during the major power outages can be maintained with the application of RERs. The stochastic characteristics of the major components of the PV system are used in this research work to investigate their impacts on the reliability performance of a power system. The system is modelled to exist in any of the states as presented in Fig. 9. In this study, subscripts λ_{pv},μ_{pv},λ_{conv},μ_{conv},λ_{inv} and μ_{inv} represent the failure rate and repair rate for each component of the system as presented by the Markov model. A Markov model of the WTG, AC/DC rectifier and DC/AC inverter system described in Section 4.2.2 has a similar operation with the PV array, DC/DC booster converter and DC/AC inverter systems. The technique can be applied in this section for individual generating subsystems to obtain the generating model for a PV system.

The failure rate and repair rate of the PV array, DC/DC booster converter and DC/AC inverter systems can be analyzed by using the following equations:

$$\lambda_{pvs} = \lambda_{pv} + \lambda_{conv} + \lambda_{inv} \tag{45}$$

$$\mu_{pvs} = \frac{(\lambda_{pv} + \lambda_{conv} + \lambda_{inv})(\mu_{pv}\mu_{conv}\mu_{inv})}{\lambda_{pv}\lambda_{conv}\lambda_{inv} + \lambda_{pv}\lambda_{conv}\mu_{inv} + \lambda_{pv}\lambda_{inv}\mu_{conv} + \lambda_{conv}\lambda_{inv}\mu_{pv} + \lambda_{pv}\mu_{conv}\mu_{inv} + \lambda_{conv}\mu_{pvc}\mu_{inv} + \lambda_{inv}\mu_{pv}\mu_{conv}} \tag{46}$$

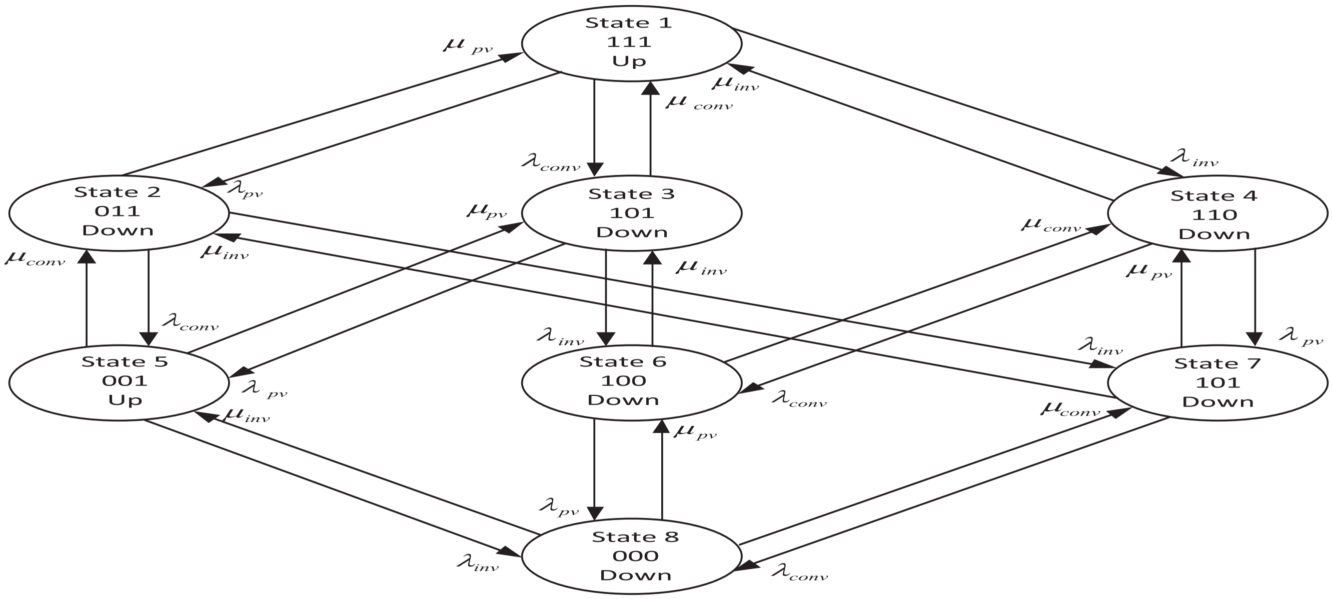

Fig. 9. Stochastic model for PV system.

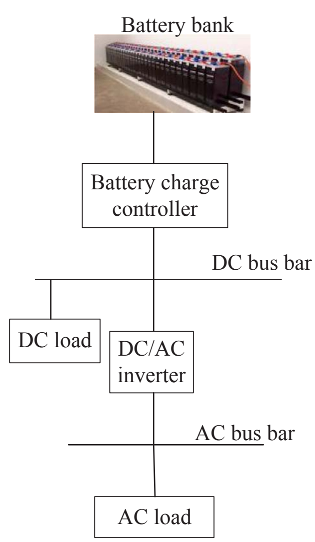

Fig. 10. Components of battery storage system.

4.2.4. Reliability model of the battery, battery controller/charger and inverter system

The battery storage system consists of the battery, battery controller/charger and inverter system as presented in Fig. 10. The battery system can be used to smooth out the effect of the intermittent nature of local RERs. This will improve the reliability of a power system with a substantial value. A battery charge controller is introduced in a power system as a measure to control the rate at which electric current is being drawn from the battery banks. This will prevent overcharging as well as enhance the performance and life span of the battery. It can be utilized by the utilities to prevent the battery from being completely drained. The battery storage system can exist in any of the states as presented in Fig. 11. The failure rate and repair rate for each component that constitutes the battery storage system are denoted by λ_{bat},μ_{bat},λ_{bc},μ_{bc},λ_{inv} and μ_{inv} as presented by the Markov model in Fig. 11. A Markov method is proposed in this study to study the major characteristics battery storage system and its ancillary on the reliability of a power system. The system has a similar operation with the WTG, AC/DC rectifier and DC/AC inverter system as discussed in Section 4.2.2.

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

$$\lambda_{bss} = \lambda_{bat} + \lambda_{bc} + \lambda_{inv} \quad (47)$$

$$\mu_{bss} = \frac{(\lambda_{bat} + \lambda_{bc} + \lambda_{inv})(\mu_{bat}\mu_{bc}\mu_{inv})}{\lambda_{bat}\lambda_{bc}\lambda_{inv} + \lambda_{bat}\lambda_{bc}\mu_{inv} + \lambda_{bat}\lambda_{inv}\mu_{bc} + \lambda_{bc}\lambda_{inv}\mu_{bat} + \lambda_{bat}\mu_{bc}\mu_{inv} + \lambda_{bc}\mu_{bat}\mu_{inv} + \lambda_{inv}\mu_{bat}\mu_{bc}} \quad (48)$$

4.3. Economic analysis of renewable energy resources

The most important benchmark to determine if the RERs that have been integrated into a power system are financially worthwhile can be analyzed by using the following parameters: ACS, NPC and COE. The application of RERs in a microgrid power system is influenced by the techno-economic feasibility of each component of the system. The optimum combination of a microgrid system that consists of the WTG, PV, BSS and diesel generator (DGEN) can be determined based on the reliability and investment costs of a power system. The economic approach that is based on the listed parameters will be used to determine the most viable combination after RERs have been incorporated into a power system.

4.3.1. Annualized cost of the system

The ACS can be utilized to evaluate the economic performance of a power system that is incorporated with RERs. The ACS is calculated by using the following operating parameters, i.e. ACC, AFC, ARC, AEC, AMC and capital recovery factor (CRF) respectively. The capital recovery factor of a power system is estimated with the aid of life span and interest rate of the system. The ACS can be expressed as:

$$\text{ACS} = \sum_{i=1}^{n} [ACC + ARC + AMC + AFC + AEC] \quad (49)$$

4.3.2. Annualized capital cost

The cost model of the various components of the microgrid power system is developed by using the capital cost per kW for the capacity of the unit. The ACC for a microgrid system that consists of DGEN, WTG, PV, BSS and converter (Conv) can be estimated by using Eqs. (50)–(53):

$$\text{ACC} = C_{acap,i} \sum_{i=1}^{n} [DGEN + WTG + PV + BSS + Conv] \quad (50)$$

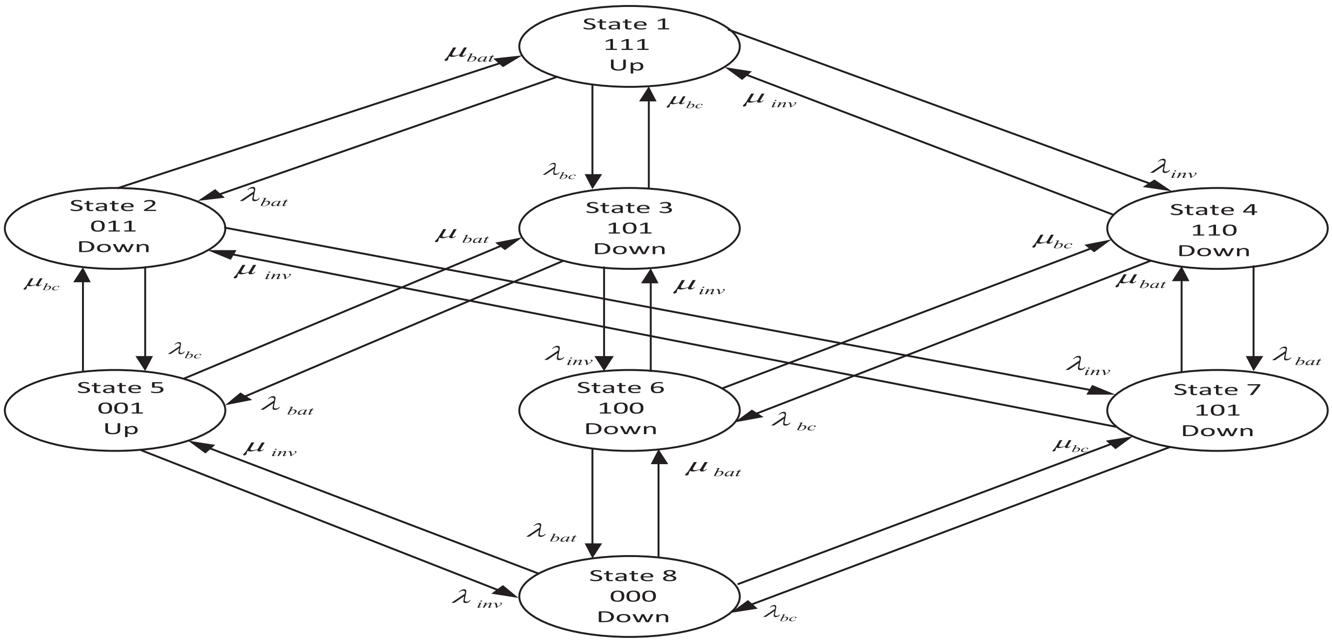

Fig. 11. Stochastic model for battery storage system.

The capital recovery factor for each component of a microgrid system can be expressed as [38]:

$$CRF(i,P_{proj}) = \frac{i.\,(1+i)^{P_{proj}}}{(1+i)^{P_{proj}}-1} \tag{51}$$

where i is the annual interest rate (%), P_{proj} is the lifetime of each component of the microgrid system and $CRF(i,P_{proj})$ is the capital recovery factor.

The annualized capital cost of nth year for each component of a microgrid system can be expressed as [38]:

$$C_{acap,i} = C_{cap} \times CRF(i,P_{proj}) \tag{52}$$

where C_{cap} is the capital cost for each component of a microgrid system and $C_{acap,i}$ is the annualized capital cost of nth year for each component of a microgrid system.

The annual interest rate can be estimated by using the following equation [38]:

$$i = \frac{(i^{nom}-f)}{(1+f)} \tag{53}$$

where f is the annual inflation rate and i^{nom} is the nominal interest rate.

4.3.3. Annualized replacement cost

The annualized replacement cost (ARC) is the cost of replacing any component during the life time of the project. The annualized replacement cost of a microgrid power system can be estimated as:

$$\text{ARC} = C_{arep,i}\sum_{i=1}^{n}[DGEN + WTG + PV + BSS + Conv] \tag{54}$$

The annualized replacement cost of nth year for each component of a microgrid system can be mathematically represented in Eq. (55) as [38]:

$$C_{arep,i} = C_{rep} \times SFF(i,P_{proj}) \tag{55}$$

where $C_{arep,i}$ is the annualized replacement cost of each component of a microgrid system, SFF is the sinking factor and C_{rep} is the replacement cost of replacing each component.

The sinking fund factor (SFF) can be expressed as [38]:

$$SFF(i,P_{proj}) = \frac{i}{(1+i)^{P_{proj}}-1} \tag{56}$$

4.3.4. Annualized maintenance cost

The annualized maintenance cost of a microgrid power system can be calculated having considered the annual inflation rate. The annualized maintenance cost of nth year can be estimated as follows [62]:

$$\text{AMC} = C_{amain,i}\sum_{i=1}^{n}[DGEN + WTG + PV + BSS + Conv] \tag{57}$$

The maintenance cost for the diesel generator are assumed to be proportional to the power generated by unit i. The maintenance proportionately factors (C_i^{om}) for the diesel generator used as a case is 0.01258 $/kW h [63]. The maintenance cost for PV, WTG, BSS and converter can be estimated by using the capacity rating (CR) of the equipment and maintenance fixed charge rate (FCR).

$$\text{MC} = \sum_{i=1}^{n} C_i^{om}P_i + CR_i \times FCR_i \ (\text{"\$"/hr}) \tag{58}$$

The annualized maintenance cost of nth year each component of a micro grid system is expressed in Eq. (59) as:

$$C_{amain} = MC(1+f)^{P_{proj}} \tag{59}$$

where C_i^{om} is the maintenance proportionality factor, IC_i is the installed capacity, FCR_i is the maintenance fixed charge rate, C_{amain} is the annualized maintenance cost of nth year each component of the hybrid system, CR is the capacity rating and MC is the maintenance cost for each component of a microgrid system.

4.3.5. Annualized fuel cost

The annualized fuel cost is the fuel cost of running the diesel generator throughout the lifetime of a power system. It can be estimated by:

$$AFC = C_{afuel,i}\sum_{i=1}^{n}[DGEN] \tag{60}$$

The fuel cost for nth year can be estimated as follows [62]:

$$C_{afuel,i} = FC(1+f)^{P_{proj}} \tag{61}$$

where is $C_{afuel,i}$ is the fuel cost for nth year.

The fuel cost (FC) of the diesel generator can be expressed as:

$$FC = \sum_{i=1}^{n} [(a_i + b_i P_i + c_i P_i^2)] \text{ "\$"/hr} \tag{62}$$

where is FC the fuel cost and a, b and c are cost coefficients of the diesel generator.

4.3.6. Annualized emission cost

The amount of GHG emissions from the diesel generator can be measured by using AEC. This depends on the characteristics of the diesel generator and type and characteristics of fuels utilized by the distribution network operators. The AEC for the diesel generator can be calculated by using:

$$\text{AEC} = C_{aemission,i} \sum_{i=1}^{n} [DGEN] \tag{63}$$

The emission cost for nth year can be estimated as follows [62]:

$$C_{aemission,i} = EC_i (1 + f_p)^{P_{proj}} \tag{64}$$

where $C_{aemission,i}$ is the annualized emission cost of the diesel generator.

The emission for the diesel generator can be expressed as:

$$EC_i = (\alpha_i EF_{CO_{2,i}} P_i + \alpha_j EF_{SO_{2,i}} P_i + \alpha_k EF_{NO_{x,i}} P_i) \tag{65}$$

where $EF_{CO_{2,i}}$, $EF_{SO_{2,i}}$ and $EF_{NO_{x,i}}$ denote CO_2, SO_2 and NOx emission factors of the diesel generator unit i (kg/kW h), α_i, α_j and α_k depict externality emission costs for each type of emission ($/kg) and EC_i is the emission cost for generating unit i.

4.3.7. Net present cost

The NPC of a project is based on the summation of the net present cost of capital cost, maintenance cost, fuel costs, emission costs and replacement costs of each component of the hybrid system. The power investors and utilities can utilize the NPC to determine the costs and benefits of any capital investment on a renewable energy project. The NPC is a useful tool that can be used to determine whether the money expended on a renewable energy project will result to a net profit or a loss. If a number of options are being considered among the numerous configurations of the microgrid power systems, then the option with the lowest NPC will be the most favourable financial option. The NPC is used in this study to find the most feasible option among the numerous configurations of the power systems. It can be expressed in Eq. (66) as [64]:

$$NPC = \frac{ACS}{CFR} \text{ ("\$"/yr)} \tag{66}$$

4.3.8. Cost of energy

The COE is the monetary value of the energy produced per kW h by the power generating units. The COE is primarily derived from the annualised cost of the system and the annual energy production. It can be expressed in Eq. (67) as [64]:

$$COE = \frac{ACS}{AEP} \text{ ("\$"/kW h)} \tag{67}$$

where AEP is the annual energy production (kW h).

4.4. Technical specifications

The technical specifications and cost data details for each component of the proposed power system are presented in Table 3. The developed evaluation technique is applied based on the technical specifications and cost data to estimate the TOC, COE and ACS, which consists of AFC, AMC, ARC, AEC, AMC and ACC of the power system. These performance indicators are utilized to select the optimal solution among the numerous configurations.

5. Results and discussions

This section describes the economic and reliability benefits of using RERs in a power system. A modified RBTS distribution system is selected to investigate the impacts of using RERs in a power system. The RBTS has been used in different research work because of the availability of the necessary data for the reliability studies and manageable size of the network. This study considers the failure and repair rates of the main feeder, lateral feeder, circuit breakers and transformers of the distribution system. The system consists of 26 load points, 26 distribution transformers, 3 transformers for the PV system, WTG system and battery storage system and 40 circuit breakers as presented in Fig. 12. The feeder and customer details, failure rates and repair rates of the major components of the system can be found in [68]. The reliability indices can be used by the power utilities to measure the performance of their networks as a prerequisite to provide uninterrupted power supply at the load points. The RERs are integrated into a microgrid system to improve the reliability of the consumer power supply as well as to reduce the COE, NPC and ACS of the power system. The technique described in Section 4 is applied in the proposed power system to meet the objective of this paper as shown in Table 4. The model developed in this research work is applied on the modified RBTS bus system that has a load demand that varies from 13 MW to 20 MW. The hourly chronological load shape of the IEEE-RTS is used in this study with the peak load of 20 MW. To get a clear insight of the impacts of renewable energy in a power system, a number of case studies are investigated and analyzed. Hence, the impacts of renewable energy DG technologies on the power system can be investigated by using the following case studies:

- Case study 1: Microgrid power system with only the diesel generator,
- Case study 2: Microgrid power system with the diesel generator and PV system,
- Case study 3: Microgrid power system with the diesel generator, PV system and BSS,
- Case study 4: Microgrid power system with the diesel generator and WTG system,
- Case study 5: Microgrid power system with the diesel generator, WTG system and BSS and
- Case study 6: Microgrid power system with the diesel generator, PV system, WTG and BSS.

Case study 1

This case study captures the economic and reliability study of a microgrid system without the application of RERs. The diesel generator is a non-renewable energy resources that operates with a very high GHG emissions, fuel cost and maintenance cost. The operation of the diesel generator is limited owing to the aforementioned setbacks. This case study illustrates a situation where all the loads are supplied via only the diesel generator with the installed capacity of 24.32 MW. The results obtained from using the diesel generator alone to meet the load requirements show that the values of ACS, AFC, AMC, AEC, COE and NPC are very high based on the operating parameters of the diesel generator as shown in Table 5. The AFC, AEC and AMC that carry the largest percentage of the ACS based on the results presented in Figs. 13a–13c can be minimized with the application of RERs.

The annual CO_2, SO_2 and NOx emissions produced and the quantity of fuel consumed by the diesel generator to meet the power requirements in this case study are presented in Table 6. The quantity of emissions produced and the fuel consumed by the diesel generator can be reduced to a certain level with the integration of renewable energy resources in order to minimize the ACS of the system as depicted in Figs. 14a–14d respectively. The values of EENS, ECOST and TOC

Table 3
Technical and cost parameters of the proposed microgrid system [65–67].

Description	Diesel generator	Wind turbine	PV	Battery	Converter
Installed capacity	24.32 MW	12 MW	12 MW	2 MW	2–15 MW
Nominal rating	1280 kW	2 MW	250 W	200 A h	2–15 MW
Replacement cost	1521 $/kW	651 $/kW	550 $/kW	300 $/battery	300 $/kW
Capital cost	1521 $/kW	651 $/kW	550 $/kW	300 $/battery	300 $/kW
Maintenance cost	0.01258 $/kW h	20 $/kW/year	10 $/kW/year	10 $/battery/year	3 $/kW
Lifetime	25000 h	25 yr	25 yr	5 yr	15 yr
Other technical parameters	Model = CAT 3516, diesel generator parameters: a = 2.4438, b = 208.21, c = 35.968 Efficiency = 80% and diesel fuel price = $0.91/L	Model number V80-2.0MW Wind speed: v_{ci} = 4 m/s, v_r = 16 m/s and v_{co} = 25 m/s Swept area = 5027 m^2, rotor diameter = 80 m, nominal revolutions = 16.7 rpm, frequency = 50/60 HZ, generator type: 4 pole doubly fed generator, slip ring and Blade dimension: Length = 39 m Max. chord = 3.5 m	Model number = LG250SIK-G3 Maximum power point voltage = 30.8 V, maximum power point current = 8.13 A, nominal cell operating temperature (NOCT) = 45 ± 2 °C, voltage temperature coefficient = −0.325%/k, current temperature coefficient = 0.050%/k, short circuit current = 8.62 A, open circuit voltage = 38.3 V, dimensions = 16,400 × 1000 × 35 (mm), weight = 16.8 ± 0.5 kg, cells = 6 × 10, cell type = monocrystalline and frame = anodized aluminium	Battery max SOC = 95%, battery min SOC = 40%, battery discharging efficiency = 100% and battery charge efficiency = 85%	Converter efficiency = 85%, rectifier relative capacity = 100% and rectifier efficiency = 85%

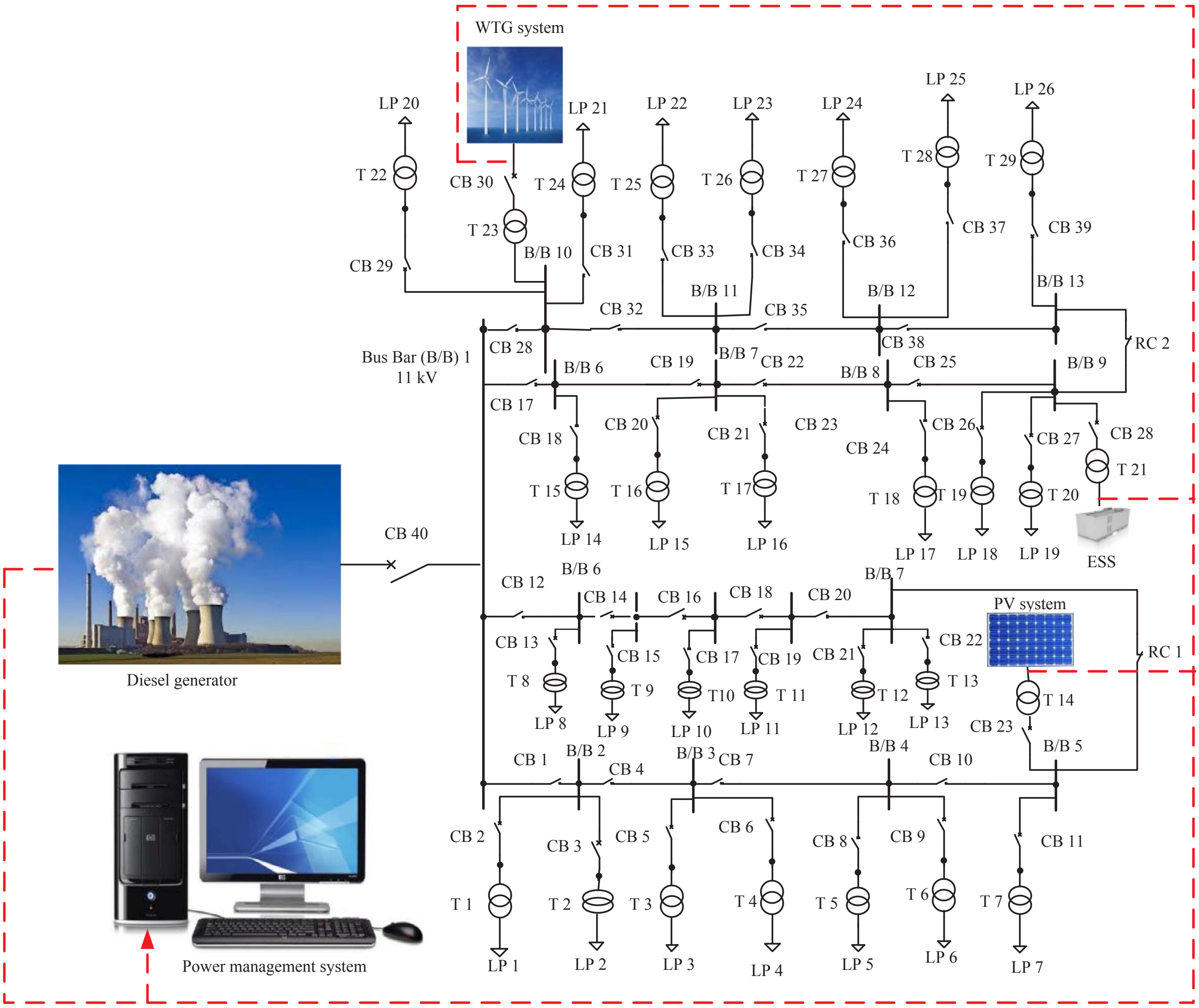

Fig. 12. Modified RBTS distribution system [68].

Table 4
Reliability indices of different components of the WTG system, PV system and ESS and their combinations [59,69].

Description	Failure rate (f/yr)	Repair rate (repair/year)
WTG	0.05	20
PV	0.04	18.25
Battery	0.0312	51.9571
DC/AC inverter	0.143	52.143
AC/DC rectifier	0.152	55.253
Battery controller/charger	0.125	45.203
Diesel generator mechanical part	0.016	21.9
Diesel generator electrical part	0.016	21.9
PV system (PV + DC/DC boost converter + DC/AC inverter)	0.2487	41.473
Diesel generator (electrical + mechanical)	0.032	21.8920
WTG system (WTG + AC/DC rectifier + DC/AC inverter)	0.345	43.040
Battery storage system (Battery + battery controller + DC/AC inverter)	0.2992	48.9

obtained from using the diesel generator alone to meet the load demand as presented in Table 7 are observed to be very high due to the duration and frequency of the power outage experienced by the consumers. The reliability of the system can be increased with the incorporation of RERs based on the results presented in Figs. 15a–15d.

Case study 2

The load demand at the consumers' load points are met with the diesel generator and PV system with the installed capacities of 24.32 MW and 12 MW respectively. The results that are presented in Table 5 and Figs. 13a and 13b show that there is a significant change in the values of ACS, AFC, AMC, AEC, COE and NPC when the PV system is integrated into the existing system. This shows that the system is more economically viable when compared with using only the diesel generator to meet the power demand at the consumer's load points. It is established from Fig. 13c that the incorporation of PV units into the base power system has improved the cost savings of ACS, AFC, AMC and AEC by 20.78%, 33.26%, 29.56% and 30.98% respectively. This is based on a significant improved cost savings that is recorded with the application of RERs. The impacts of PV system on the annual CO_2, SO_2 and NOx emissions are presented in Table 6. It is clearly seen that incorporation of the PV system in a microgrid system has reduced the energy share of the diesel generator. The amount of CO_2, SO_2 and NOx emissions and the fuel consumption of the diesel generator that are reduced per annum with the application of the PV system are presented in Figs. 14a–14d. The utilization of the PV system in a microgrid power system has reduced the fuel consumption of the diesel generator by 33.26%. Hence, the PV system has a positive impact on the CO_2, SO_2 and NOx emissions and the fuel consumption of the diesel generator.

The reliability indices are enhanced by reducing the outage duration and number of customers affected by power outages. This is achieved

Table 5
Impacts of incorporating numbers of WTG, PV and ESS on the annual operating costs.

Description	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
ACS ($/yr)	69,527,000	55,079,000	54,768,000	50,151,000	49,877,000	37,320,000
ACC ($/yr)	11,665,000	12,552,000	12,756,000	12,646,000	12,851,000	13,737,000
ARC ($/yr)	9,793,800	10,069,000	10,201,000	10,091,000	10,223,000	10,498,000
AFC ($/yr)	36,803,000	24,562,000	24,020,000	20,542,000	20,035,000	9,612,900
AMC ($/yr)	8,476,468	5,970,700	5,897,300	5,230,000	5,156,700	2,706,000
AEC ($/yr)	2,788,700	1,924,800	1,894,100	1,641,700	1,611,000	765,240
NPC ($/yr)	993,230,000	786,830,000	782,410,000	71,640,0000	712,520,000	533,140,000
COE ($/kW h)	0.4757	0.3769	0.3747	0.3431	0.3413	0.2554

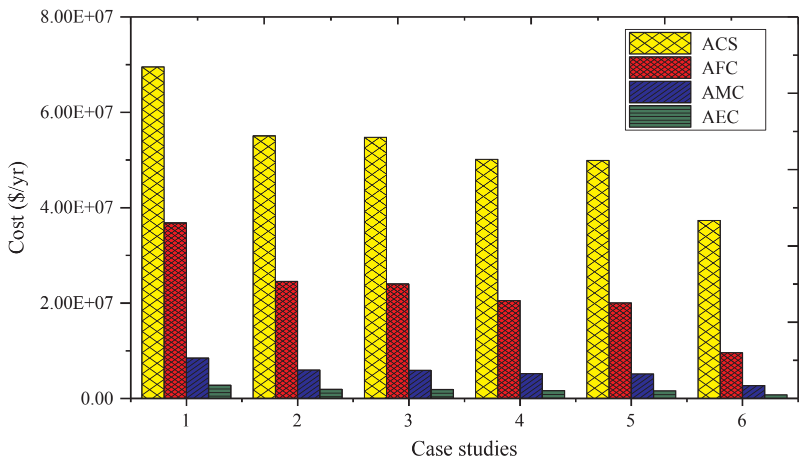

Fig. 13a. Annualised costs of the proposed power system.

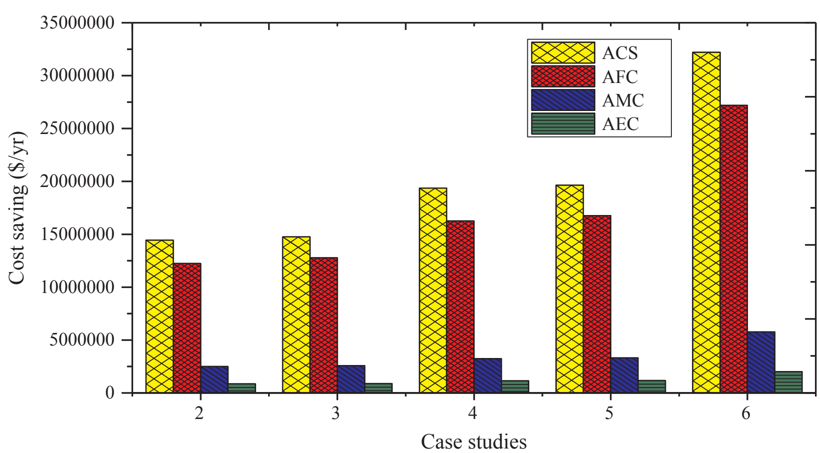

Fig. 13b. Improved cost saving of the proposed power system with the integration of renewable energy resources.

with the application of RERs in a power system. The reliability indices of the system are measured to investigate the effects of integrating the PV system for the enhancement of the reliability performance of the system. The penetration of the PV system into a power system has created a substantial impact on the reliability of the system as presented in Table 7 and Figs. 15a and 15b. The results indicate significant savings in the cost of EENS, ECOST and TOC with the integration of the PV system. The cost savings of EENS, ECOST and TOC have been improved by 21%, 9.87% and 16.05% respectively when compared with the first case study. The system average interruption frequency index (SAIFI) has been reduced from 0.8654 to 0.6384 f/customer.yr with about 26.23% improvement while the system average interruption frequency index (SAIDI) has been reduced from 2.0291 to 1.563 h/customer.yr with an improvement of 22.97% as shown in Figs. 15c and 15d. The comparative analysis of the operating cost and reliability assessment of the proposed power system has established that more cost savings can be achieved with the incorporation of RERs.

Case study 3

In this case study, the diesel generator, PV system and BSS with the installed capacities of 24.32 MW, 12 MW and 2 MW respectively are utilized. The impact of integrating the PV system and BSS into a microgrid system is discussed and analyzed in this section. The penetration of the PV system and BSS into the proposed power system has a substantial influence on the reliability and operating costs of the power system. The values of ACS, AFC, AMC, AEC, COE and NPC for this case study are presented in Table 5 and Fig. 13a respectively. It is clear that the incorporation of the PV system and BSS into the existing system contribute to the cost savings as depicted in Fig. 13b. The results presented in Fig. 13c have justified that the ACS, AFC, AMC and AEC cost savings of the system improved significantly by 21.23%, 34.73%, 30.43% and 32.08% with the application of the PV system and BSS when compared with the first case study. The annual quantity of the CO_2, SO_2 and NOx emissions produced and the fuel consumed by the diesel generator reduced significantly as shown in Table 6. The impacts

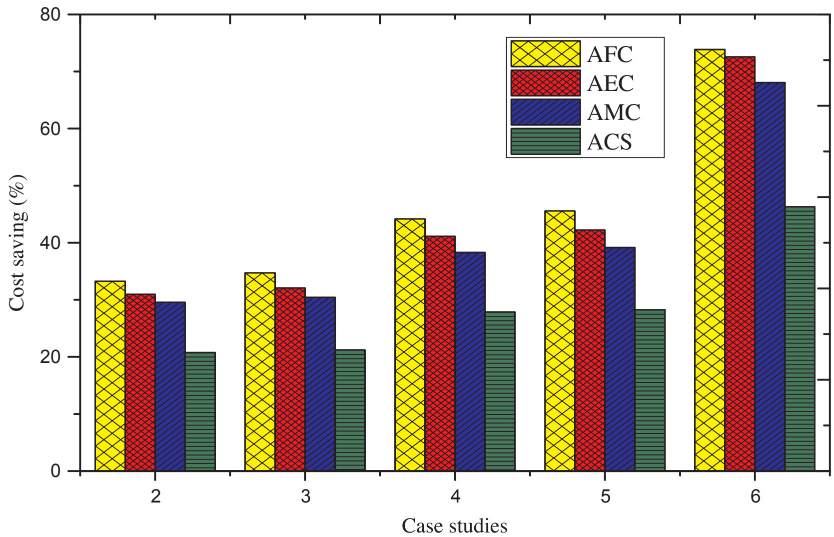

Fig. 13c. Percentage improved cost saving of the proposed power system with the integration of renewable energy resources.

Table 6
Impacts of incorporating numbers of WTG, PV and ESS on the annual emissions and fuel consumption.

Description	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Fuel (L/yr)	40,442,000	26,992,000	26,396,000	22,573,000	22,017,000	10,564,000
CO2 (kg/yr)	96,009,000	66,269,000	65,211,000	56,521,000	55,463,000	26,346,000
NOx (kg/yr)	977,870	674,960	664,180	575,670	564,900	268,340
SO2 (kg/yr)	52,538	36,264	35,685	30,929	30,351	14,417

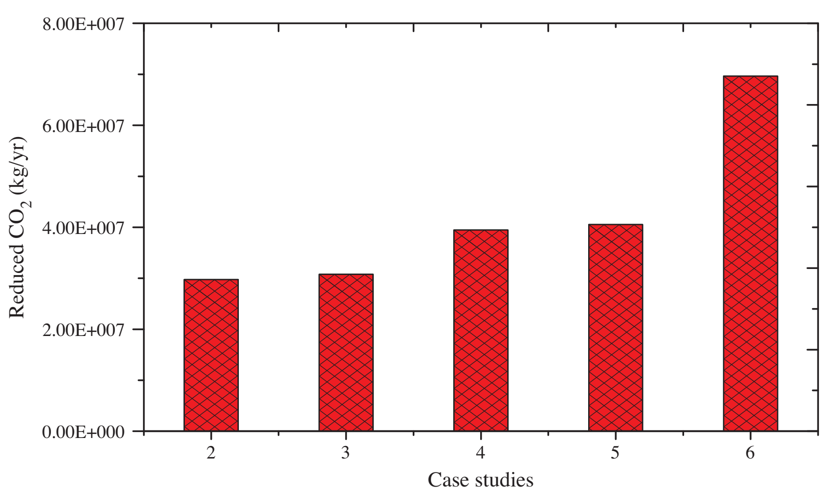

Fig. 14a. Quantity of CO_2 emission reduced per annual with the integration of renewable energy resources.

of the PV system and BSS on a microgrid system are illustrated in Figs. 14a–14d where the annual amount of the CO_2, SO_2 and NOx emissions produced and the fuel consumption are reduced with the incorporation of PV system and BSS. The annual fuel consumption by the diesel generation has been reduced by 34.73% in this case study.

In Table 7 and Fig. 15a, the values EENS, ECOST and TOC are utilized to investigate the effects of incorporating the PV and BSS units in the proposed power system. It is observed that the combined operation of the PV system and BSS at their respective load points increases the reliability of the system. This will increase the performance of the power system and revenue of the power utilities. The improved cost savings of the EENS, ECOST and TOC of the system also increased as reflected in Fig. 15b when compared with the first case study. It can also be seen from Table 7 that the cost savings of the EENS, ECOST and TOC also improved by 37.43%, 41.40% and 39.20% based on the PV system and BSS that are incorporated into a microgrid system. The SAIFI of the system also reduced from 0.8654 to 0.5687 f/customer.yr with a substantial improvement of 34.28%, while the SAIDI of the system has been reduced from 2.0291 to 1.4050 h/customer.yr with an improvement of 30.76% as shown in Figs. 15c and 15d. The results obtained from this study show that the incorporation of the PV system and BSS will not only improve the reliability, but also has significant impacts on the economy and environment by reducing the values of ACS, AFC, AMC, AEC, COE and NPC respectively.

Case study 4

In this case study, the installed capacities of the diesel generator and WTG system are 24.32 MW and 12 MW respectively. This section demonstrates the influence of incorporating the WTG system in a microgrid power system having considered each component of the power system. The results that are presented in Table 5 and Fig. 13a have further justified that increase in the penetration of the WTG system in a microgrid system reduced the values of ACS, AFC, AMC, AEC, COE and

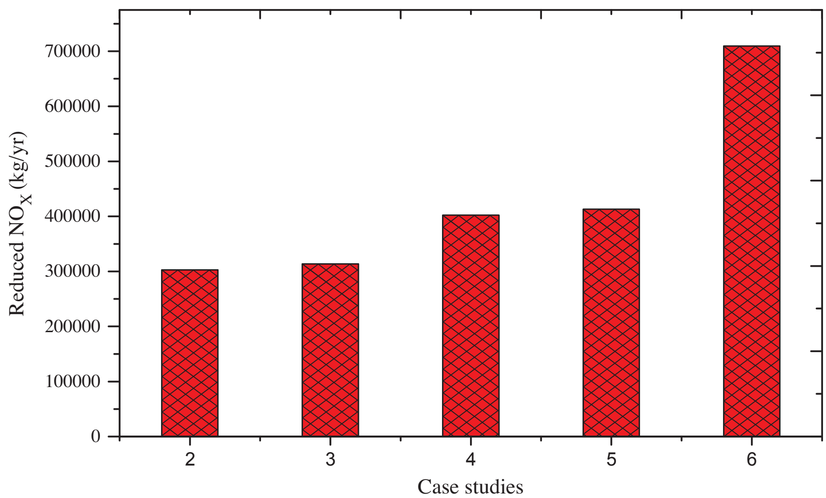

Fig. 14b. Quantity of NOx emission reduced per annual with the integration of renewable energy resources.

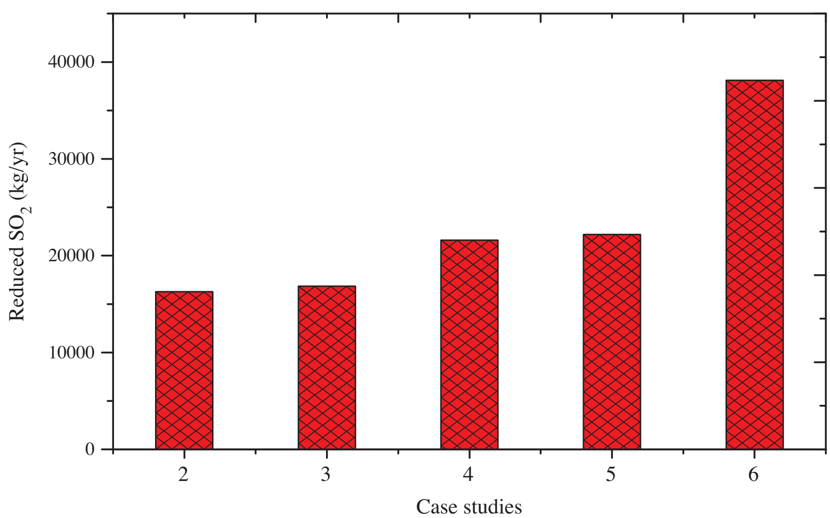

Fig. 14c. Quantity of SO_2 emission reduced per annual with the integration of renewable energy resources.

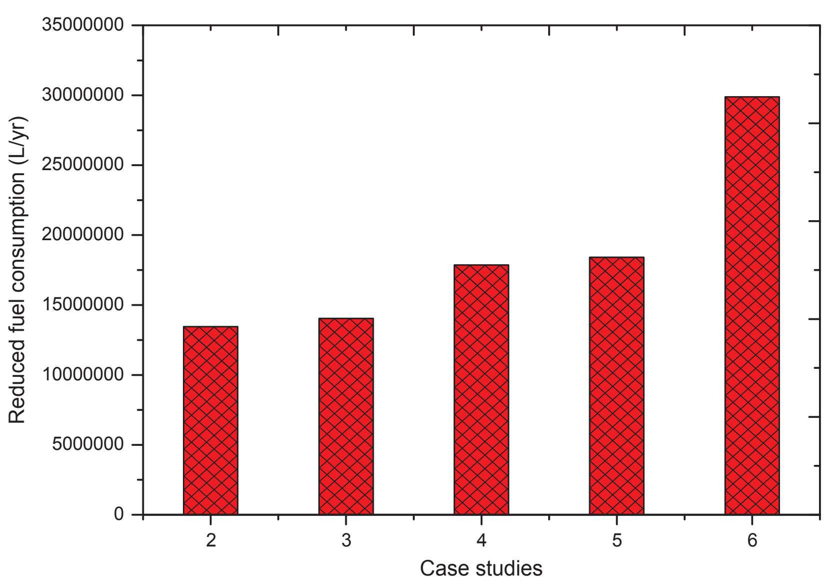

Fig. 14d. Amount of fuel reduced per annual with the integration of renewable energy resources.

NPC. The economic and environmental impacts of utilizing the WTG system in the proposed power system are presented in Fig. 13b. It can be seen that the cost savings of ACS, AFC, AMC and AEC have been improved substantially by 27.87%, 44.18%, 38.30% and 41.13% based on the results presented in Fig. 13c. There is a significant improvement in the cost savings of the system when compared with a situation when the power demand is only met from a single power source. The annual quantity of the CO_2, SO_2 and NOx emissions produced and the fuel

Table 7
The impacts of WTG, PV and ESS on the reliability of a power system.

Description	DG Case study 1	PV Case study 2	PV + BSS Case study 3	WTG Case study 4	WTG + BSS Case study 5	PV + WTG + BSS Case study 6
EENS (MW h/yr)	22.818	18.027	14.277	18.435	15.082	10.291
ECOST ($/yr)	100487	90573.3	58885.86	86162.42	56541.23	46627.55
Total cost of EENS ($/yr) KeEENS	125499	99148.5	78523.5	101392.5	82951	56600.5
Total outage ($/yr)	225986	189721.8	137409.36	187554.92	139492.23	103228.05
Total improved cost saving of EENS ($/yr)	–	26350.5	46975.5	24106.5	42548	68898.5
Total improved cost saving of EENS (%)	–	20.99658165	37.43097555	19.20851959	33.90305899	54.89964063
Total improved cost saving of ECOST ($/yr)	–	9913.7	41601.14	14324.58	43945.77	53859.45
Total improved cost saving of ECOST (%)	–	9.865654264	41.39952432	14.25515738	43.73279131	53.59842567
Total improved outage cost saving ($/yr)	–	36264.2	88576.64	38431.08	86493.77	122757.95
Total improved outage cost saving (%)	–	16.04710026	39.19563159	17.00595612	38.2739506	54.32104201

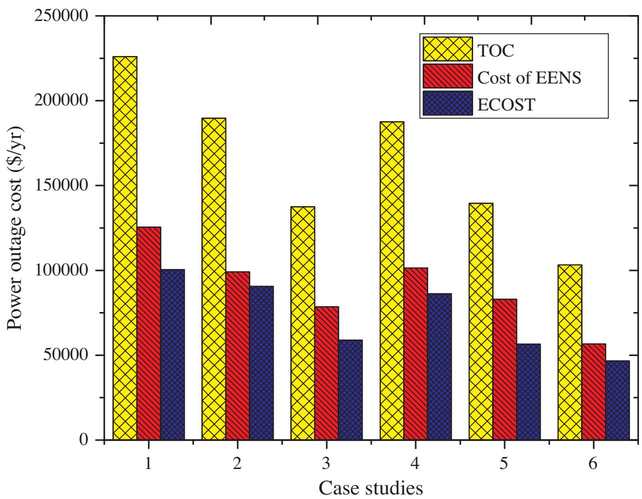

Fig. 15a. Total outage cost, ECOST and EEENS costs with the integration of renewable energy resources.

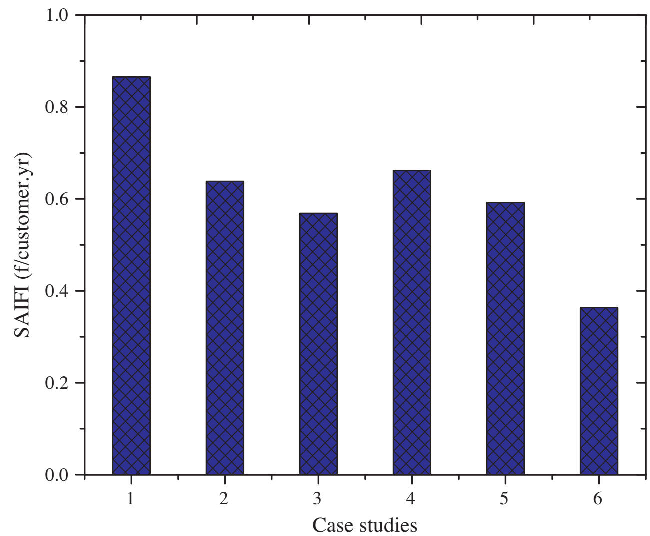

Fig. 15c. SAIFI of a microgrid system.

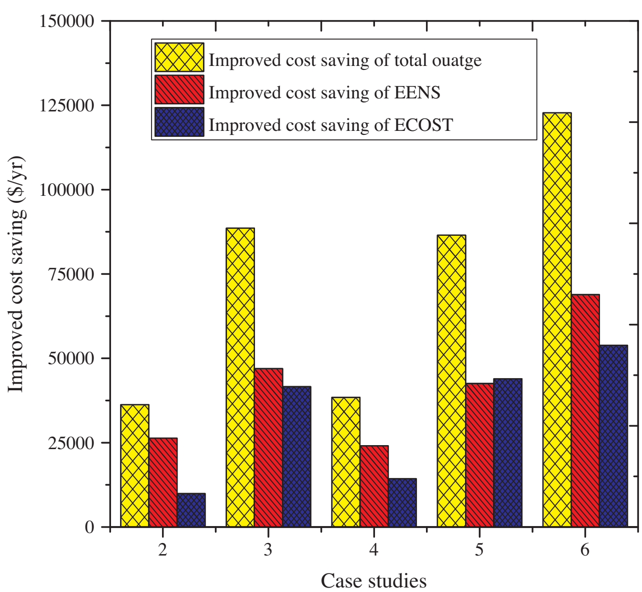

Fig. 15b. Improved cost saving of total outage cost, EENS and ECOST with the integration of distributed energy resources.

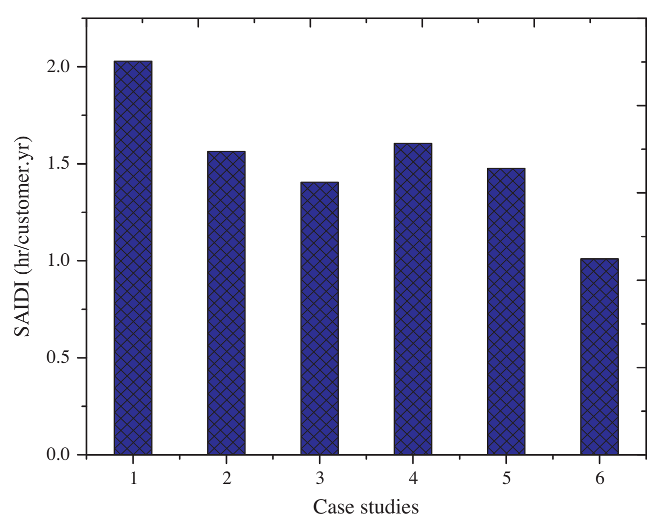

Fig. 15d. SAIDI of a microgrid system.

consumption of the diesel generator are reduced respectively, with the integration of the WTG system as shown in Table 6. The annual amount of CO_2, SO_2 and NOx emissions and the fuel consumption of the diesel generator also witnessed a significant reduction with the application of the WTG system as presented in Figs. 14a–14d respectively. It is established that an increase in the penetration of WTG system reduced the annual fuel consumption by 44.18%.

The penetration of the WTG system into a microgrid system also has an important influence on the reliability of the distribution power system just as it reflected in Table 7 and Fig. 15a. The costs of power outages experienced by the consumers at the load points have been reduced significantly, which translates to the cost savings of EENS, ECOST and TOC with improvements of 19.21%, 14. 26% and 17.01%

respectively. The results obtained from this case study show that the improved cost savings of EENS, ECOST and TOC increase rapidly with the incorporation of the WTG system as presented in Fig. 15b. This has ultimately reduced the frequency and duration of the power outages at the consumer load points. The value of the system SAIFI has reduced from 0.8654 to 0.662 f/customer.yr with an improvement of 23.5% while SAIDI has also been reduced from 2.0291 to 1.6048 h/customer.yr with a significant improvement of 20.91% as shown in Figs. 15c and 15d. The reduction in the values of the SAIDI and SAIFI has indicated the positive impacts of RERs on a power system. The increase in the integration of the WTG system in a microgrid system has also reduced the COE that is a source of challenge for many power utilities. This has further reduced the ACS and the power outages at the load points as well as increased the efficiency of the power system and substantially improved the system performance.

Case study 5

In this case study, the capacities of the diesel generator, WTG system and BSS are 24.32 MW, 12 MW and 2 MW respectively. The impact of the WTG system and BSS on a microgrid power system is investigated in this section with the results of ACS, AFC, AMC, AEC, COE and NPC presented in Table 5 and Figs. 13a and 13b. The penetration of the WTG system and BSS units into the existing power system has improved the cost savings of the ACS, AFC, AMC and AEC by 28.26%, 45.56%, 39.16% and 42.23% based on the results presented in Fig. 13c. The aforementioned key operating indicators are more fiscal achievable when operating with the first case study when the diesel generator is used alone to meet the load requirements. The increase in penetration of the WTG system and BSS into the proposed power system has a vital influence on the amount of CO_2, SO_2 and NOx emitted into the atmosphere and the fuel consumed by the generator as shown in Table 6. The quantity of CO_2, SO_2 and NOx emissions and the fuel consumption reduced per annum with the incorporation of the WTG system and BSS are presented in Figs. 14a–14d. The application of the WTG system and BSS on a microgrid system also reduces the fuel consumption of the diesel generator by 45.56%.

The integration of the WTG system and BSS at the load points where the customer sectors can be residential, commercial, industrial, office building and government and institution has improved the cost savings of EENS, ECOST and TOC when compared with the first case study as shown in Table 7 and Fig. 15a. The results obtained from the integration of the WTG system and BSS into the power system show that the improved cost savings of the above reliability indices have been increased as follows: EENS = 33.90%, ECOST = 43.73% and TOC = 38.27%. The cost savings gained from the application of RERs as shown in Fig. 15b can increase the revenue of the power utilities. The value of the system SAIFI has reduced substantially from 0.8654 to 0.5923 f/customer.yr with an improvement of 23.5% while SAIDI has also reduced from 2.0291 to 1.4759 h/customer.yr with a considerable improvement of 20.91% as presented in Figs. 15c and 15d. The values presented in Tables 4–6 have validated the fact that the integration of the WTG system and BSS into a power system has improved the reliability and optimized the operating costs of the proposed power system.

Case study 6

In this case study, the installed capacities of the diesel generator, PV system, WTG system and BSS are 24.32 MW, 12 MW, 12 MW and 2 MW respectively. The values of ACS, AFC, AMC, AEC, COE and NPC for this case study are reduced significantly when compared with the first case study as is reflected in Table 5 and Fig. 13a. This case study established the fact that some benefits can be derived from the application of RERs and BSS units based on the results presented in Fig. 13b. The results obtained from utilizing the WTG and PV systems and BSS as presented in Fig. 13c show that the cost savings of ACS, AFC, AMC and AEC have been improved considerably by 46.32%, 73.88%, 68.07% and 72.56% respectively. The quantity of CO_2, SO_2 and NOx emissions produced and the fuel consumed by the diesel generator are presented in Table 6, these values have been reduced substantially with the application of RERs. The amount of CO_2, SO_2 and NOx emissions and the fuel consumption reduced per annum with the integration of the WTG and PV systems and BSS are presented in Figs. 14a–14d. The annual fuel consumption of the diesel generator has been reduced significantly by 73.88% with the application of the WTG system, PV system and BSS.

The values of EENS, ECOST and TOC in this case study are shown in Table 7 and Fig. 15a. The results obtained from the simulations have indicated that the cost savings of the EENS, ECOST and TOC have been improved by 54.90%, 53.60% and 54.32% with the integration of renewable energy sources. The improved cost savings of the reliability indices of the system also increased significantly as shown in Fig. 15b. The value of the system SAIFI has reduced from 0.8654 to 0.3635 f/customer.yr with an improvement of 58% while SAIDI has also reduced from 2.0291 to 1.0099 h/customer.yr with an important improvement of 50.22% as presented in Figs. 15c and 15d. The maximum reduction in the cost that is associated with the power outages that occur at the load points is achieved if all the RERs, a diesel generator and a BSS are utilized. This has validated the fact that the integration of RERs and BSS into a power system has improved the reliability of the proposed system.

Table 5 and Figs. 13a–13c also illustrate that the COE and ACS of the power system improve with the integration of the WTG system, PV system and BSS. It can be clearly seen from Table 7 and Figs. 15a–15d that an additional number of BSS and RERs significantly improve the reliability of the system. It can be suggested from this study that significant savings in fuel, maintenance and emission costs as well as a considerable improvement in the reliability of the proposed power system have been achieved with the incorporation of RERs. The results obtained from this research work has demonstrated that case study 6 is

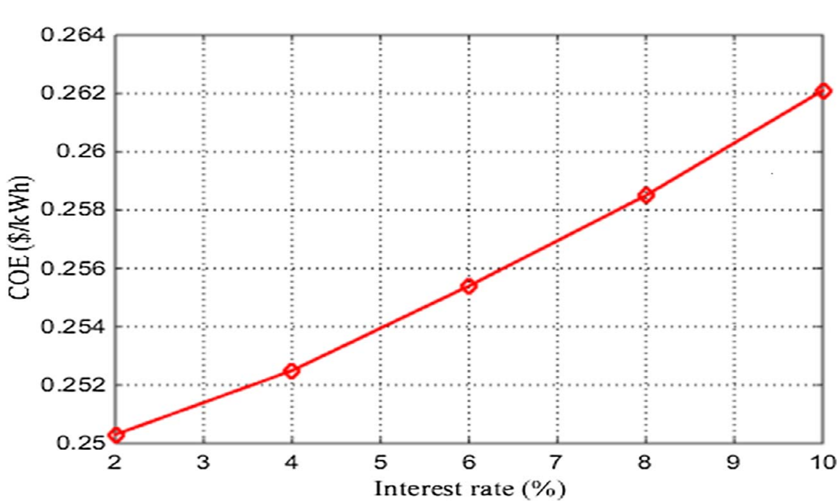

Fig. 16a. Impacts of variation of interest rates on the COE.

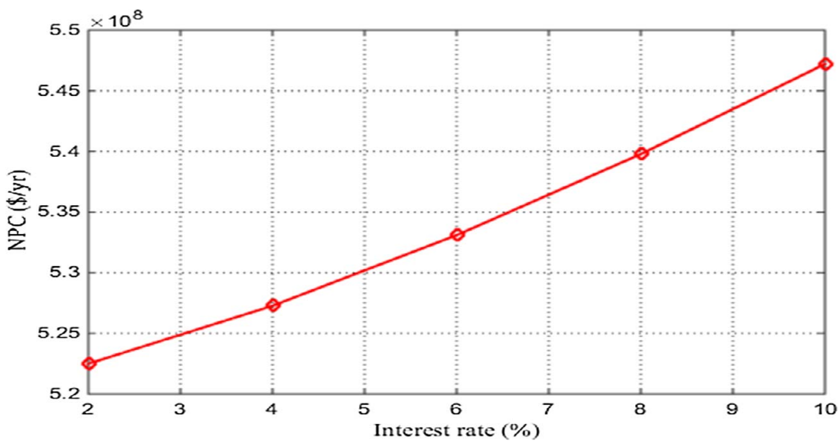

Fig. 16b. Impacts of variation of interest rates on the NPC.

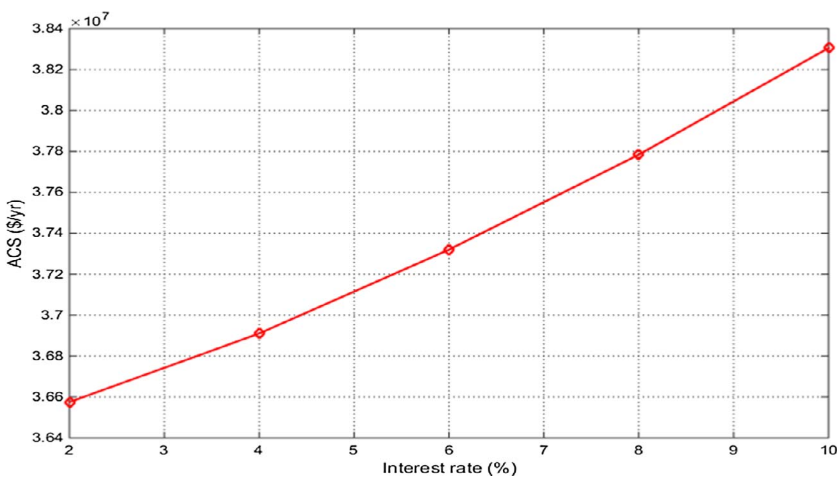

Fig. 16c. Impacts of variation of interest rates on the ACS.

the best option when compared with other operation strategies in terms of emissions, reliability and economic benefits. Thus, case study 6 has the lowest COE (0.2554 $/kW h), ACS (37,320,000 $/yr), NPC (533,140,000 $/yr), TOC (103228.05 $/yr) and AEC (765,240 $/yr) as depicted in Tables 5 and 7 respectively. In addition to this, the strength of one RER can be used by the power utilities to overcome the weakness of other RERs based on the available meteorological data.

5.1. Impacts of variation of interest rates

This section analyses the effects of variation of interest rates on the operating parameters of the proposed microgrid power system. In this regard, the impacts of variation in the interest rates of the major components of the RERs, BSS and diesel generator are investigated on the COE, NPC and ACS. From the results presented in Figs. 16a–16c, it has established that the fact that the values of COE, NPC and ACS change with proportion to changes in the value of the interest rates. This indicates that the variation in the interest rates will have a considerable effect on the aforementioned operating parameters.

6. Conclusions

In this paper, the reliability, environmental and economic benefits of utilizing the diesel generator, WTG system, PV system and BSS in a microgrid system have been investigated by using the meteorological data of De Aar, a town in South Africa. The integration of RERs in the proposed power system has demonstrated its effect on the operating costs of the system. The results obtained from this study have established the significant effects of RERs and BSS on the reliability indices and COE and ACS of the power system. The AFC, AMC and AEC that carry the largest percentage of the ACS of the system have been reduced considerably based on the results obtained in this study. The method adopted in this study can be used in real time to improve the level of reliability and reduce the COE and ACS of the power system, which have been sources of challenge for power utilities. The integration of RERs into a power system reduces the fuel consumption and the quantity of CO_2, SO_2 and NOx emitted into the atmosphere by the conventional power generating units. With the policies that government have put in place to encourage embedded power generation, it has become necessary that RERs should be employed by the utilities to meet the power requirements of consumers. This will reduce the power shortages and load shedding that have characterized some countries. The results obtained from this study have substantiated the fact that the optimal solution to reduce power interruptions and costs that related to the improper management of power outages in the distribution system can be achieved with the integration of PV, WTG and BSS units. It is expected that improvement in the reliability of the distribution system will enhance the performance and efficiency of a power system. In the near future, renewable energy is projected to supply the majority of the global power demand at minimal energy cost due to current decline in the prices of renewable energy components.

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