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Reliability and economic evaluation of a microgrid power system

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Abstract

The renewable energy resources (RERs) have been globally accepted for power generation due to the high prices of fossil fuels, environmentally friendly, low operation and maintenance (O&M) costs, no carbon emission and escalation in power demand due to rapid growth in population and industrialization. A microgrid (MG) power system that consists of the diesel generator, wind turbine generator (WTG), photovoltaic (PV) and electric storage system (ESS) is utilized in this study with the aim of improving the reliability and minimizing the cost of energy (COE) and annualized cost of the system (ACS). This objective is achieved by using the expected energy not served (EENS), loss of load expectation (LOLE), cost of load loss, loss of load probability (LOLP), net present cost (NPC), annualised fuel cost (AFC), annualised emission cost (AEC), annualised maintenance cost (AMC), annualised capital cost (ACC) and annualized replacement cost (ARC) of the system. These operating parameters are used in this work to investigate the effects of RERs in a power system. To achieve the main objective of this paper, the basic probability concept is utilized to find the reliability indices of the proposed power system as well as the development of a software in the MATLAB programming environment by using fmincon optimization tool to investigate the economic impact of RERs in a micro grid power system. The results obtained from the research work show that RERs can be used to improve the reliability and reduce the COE and ACS of a power system.

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Keywords: Renewable energy resources, reliability, anaulized cost of the system, cost of energy, net present cost, cost of loss load.

1. Introduction

The incorporation of the RERs into a power system has received considerable global attentions because of their significant impacts such as improved reliability of a power system and reduction of fuel cost, O&M costs and emission

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cost [1]. These unique characteristics have facilitated many power utilities in the world to encourage utilization of RERs as measures to increase the capacity of electric power generation. The micro grid energy systems are considered to be the most cost effective power solutions to meet the load requirements of the people that live in the rural areas. Due to the intensive cost of extending the transmission and distribution lines to the remote communities, the power demands in such areas can be met by using a micro grid power system that consists of the diesel generator, PV, WTG and ESS. Solar and wind resources are potential renewable energy technologies which have recently received global attention because of their economic and technical benefits [2]. These resources can be efficiently and economically harnessed by the power utilities for climate change mitigation as well as for reduction of the side effects of greenhouse gas emission to the public.

In the past, RERs have been the subject of many researchers with an emphasis on the optimization technique that involves a combination of operating cost, reliability and emission of a power system. In view of this, Caballero [3] et al. [3] have presented a technique for the optimal operation of a hybrid system that consists of PV and wind system. The objective of the study is to limit life cycle of the system and to improve the reliability of the system by using loss of power supply probability. Ramli et al. [4] have performed a technical and economic analysis of wind and solar hybrid system by using energy production and cost of energy as the benchmarks to assess the impacts of RERs in a hybrid system. Meanwhile, Bilil et al. [5] have presented a multi-objective genetic algorithm for optimization of the annualized renewable energy cost and the reliability indices of a power system. The main challenge faced in the aforementioned body of literature is the complexity to design an optimal energy management system that will satisfy the load demand by considering the non-linearity of renewable energy resources, diesel generator fuel consumption and load demand. The body of literatures described above has not established the relationship between the reliability, operating cost, emission and cost of energy of a power system. In the perspective of this weakness, this work exhibits a streamlining technique that incorporates reliability, AFC, AMC, COE, AEC and ACS of a power system.

Nomenclature

ACS	Annualized cost of system ($/yr)	RI	Reliability index
AEP	Annual energy production (kWh/yr)	EENS	Expected energy not supplied (kWh/yr)
COE	Cost of energy ($/kWh)	C_{loss}	Value of lost load ($/kWh)
AMC	Annualized O&M cost ($/yr)	AFC	Annualized fuel cost ($/yr)
AEC	Annualized emission cost ($/yr)	ACC	Annualized capital cost ($/yr)
$P(C_i)$	Probability of the state i	ARC	Annualized replacement cost ($/yr)
AEC	Annualized emission cost ($/yr)	C_i	Generation capacity
L_i	Expected load demand	C_k	Amount of load curtailment
P_1	power generated by the diesel generator	P_2	Power generated by the PV system
P_3	Power accepted by the battery for charging application	P_4	Power discharged by the battery
P_5	Power generated by the wind system	P_L	Power demand at load points
P_i	Probability of specific capacity outage	$P(C_i)$	Probability of loss of capacity
p_k	Individual probability of capacity in outage	t_k	Duration of loss of power supply in days
$P(L_i > C_i)$	Duration of loss of capacity in percent	FOR	Forced outage rate

2. Micro grid power system

The proposed MG power system consists of diesel generator, WTG, PV and ESS for the purpose of meeting the consumers' load requirements. It is designed to supply the consumers' load points based on the availability of the local RERs. The MG system is the most economical viable solution for supplying electricity to the remote areas or standalone systems that are not connected to the national grid owing to technical, economic and complexity of the terrain [6]. It can be used by the utilities to enhance the reliability and minimize the COE and ACS of a power system [7]. The capability of the proposed methodology is validated with a number of case studies by using the meteorological data of De Aar, a town situated in the Northern Cape Province of South Africa. A typical diagram of the microgrid system with some major components is presented in Fig. 1.

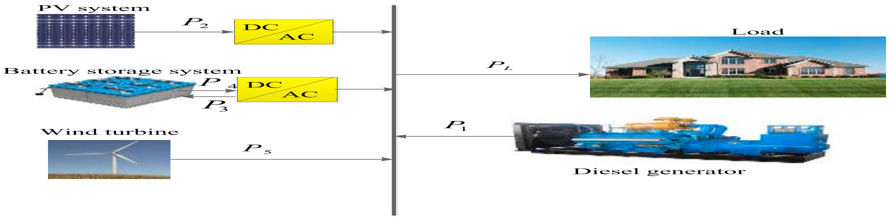

Fig. 1. Micro grid power system.

3. Objective function

The main objective function of this study is to improve the reliability of the proposed power system as well as minimizing the annualized cost of the system and cost of energy while satisfying the consumers' power requirements and the system constraints. This objective can be achieved with the integration of the RERs and ESS units in a MG power system. The objective function of the proposed power system is expressed as:

$$F = \min \sum_{i=1}^{n} (RI + ACS + COE) \quad (1)$$

The first component of the objective function of the proposed power system contains the reliability index as presented in equation 2.

$$RI = EENS \times C_{loss} \text{ (\$/yr)} \quad (2)$$

The second element of the objective function is the ACS, which is the sum of the annualized capital cost (ACC), AMC, AFC, AEC and ARC of the generating unit i [8].

$$\text{ACS} = (\text{AMC+AFC+AEC+ACC+ARC}) \text{ (\$/yr)} \quad (3)$$

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

$$\text{COE} = \frac{ACS}{AEP} \text{ (\$/kWh)} \quad (4)$$

3.1. Power system limits

The power requirements of the system are subject to power generated from the diesel generator, WTG, PV and ESS within the operating limits of the system.

$$\sum_{i=1}^{n} P_{1,i} + \sum_{i=1}^{n} P_{2,i} - \sum_{i=1}^{n} P_{3,i} + \sum_{i=1}^{n} P_{4,i} + \sum_{i=1}^{n} P_{5,i} = \sum_{i=1}^{n} P_{Li} \quad (5)$$

3.2. Power constraints for each unit

The power output of each generating unit is restricted to the minimum and maximum limits specified by the manufacturers of each component of the proposed MG system. These constraints are represented in equation 6.

$$0 \le P_{1,i} \le P_1^{\max}, P^{\min}{}_2 \le P_{2,i} \le P_2^{\max}, P_3^{\min} \le P_{3,i} \le P_3^{\max}, P_4^{\min} \le P_{4,i} \le P_4^{\max} \text{ and } 0 \le P_{5,i} \le P_5^{\max} \quad (6)$$

4. Power system reliability assessment

Reliability is the probability that a power system will meet the load requirements at any time [9]. To meet this objective, RERs are incorporated into a power system in such a way to have a sufficient power to meet the load demand. The performance metrics used for the reliability assessment in this study are briefly explained as follows [9-10]:

4.1. Loss of load probability

Loss of load probability (LOLP) is the probability that the generating capacity of the power systems is less than daily peak load at a giving time usually one year [9-10].

$$\text{LOLE} = \sum_{i=1}^{n} P(C_i)P(L_i > C_i) \tag{7}$$

4.2. Loss of load expectation

Loss of load expectation (LOLE) represents the number of hours per annum in which the expected power generation will not meet power demand at the consumers' load points. It depicts the loss of load duration when the daily peak demand surpasses the available power generation capacity [9-10].

$$\text{LOLE} = \sum_{k=1}^{n} p_k t_k \text{ (hr/yr)} \tag{8}$$

4.3. Expectation energy not supplied

Expected energy not supplied (EENS) is the total energy that is not delivered at the system load points. It is an energy shortage in a period of time when the load demanded is greater than the available generating capacity [9-10].

$$EENS = \sum_{i=1}^{n} \left(L_i - C_i\right) \times P_i \times 8760 \text{ (kWh/yr)} \tag{9}$$

The load curtailment can be expressed as:

$$C_k = \left(L_i - C_i\right) \tag{10}$$

4.4. Cost of loss load

The cost of load loss (AC_{loss}) is used by the power utility to monetize the effect of power outage in a power system where the value of lost load (C_{loss}) is estimated. To obtain the value of the cost of load loss in a power system, the value of EENS is multiplied by C_{loss} [9-10]. In this study, the monetary value of the loss of load caused by the power outage is assumed to be \$ 5.5 kWh.

$$AC_{loss} = EENS \times C_{loss} \tag{11}$$

5. Economic analysis of renewable energy resources in a power system

The technical specifications and cost for each component of a MG system are presented in Table 1 [11]. These technical and financial details can be used to determine the economic feasibility of RERs in a power system.

Table 1: Technical and cost parameters of the proposed MG system [11]

Description	Replacement cost	Capital cost	Maintenance cost	FOR	Lifetime
Diesel generator	1521 $/kW	1521 $/kW	0.01258 $/kWh	0.06	25000 hr
Wind turbine	651 $/kW	651 $/kW	20 $/kW/year	0.04	25 yr
PV	550 $/kW	550 $/kW	10 $/kW/year	0.03	25 yr
Battery	300 $/battery	300 $/battery	10 $/battery/year	0.04	5 yr
Converter	300 $/kW	300 $/kW	3 $/kW	0.03	15 yr

6. Results and discussions

The RERs have been integrated in a power system to reduce the economic impacts of power interruption as well as to minimize the COE and ACS of the system. The results obtained in this section are analyzed to determine the effects of RERs on the economic operation and reliability of a power system. The optimization technique described in section 3 is implemented on a MG system by using the case studies presented in Table 2.

Table 2: Configuration of the case studies

Case studies	Diesel Generator (kW)	PV (kW)	WTG (kW)	ESS (kW)
1	48	0	0	0
2	48	3	1	1
3	48	6	2	1
4	48	9	9	3
5	48	12	12	4
6	48	15	15	5

The operating parameters of the proposed MG system have witnessed a rapid reduction in costs with the increase in incorporation of RERs and ESS in the existing power system. It can be established from Table 3 that the values of AMC, AFC, AEC, ACC, ARC, ACS, NPC and COE have been reduced significantly with the integration of RERs. The COE, ACS and NPC are compared with a situation where the diesel generator is only used to meet the power requirements of a MG system. The values of the aforementioned parameters from the second to sixth case studies are more economic viable when compare with using the diesel generator to supply the entire power system. The results obtained from each case study as presented in Table 3 have validated that the proposed technique can be used to reduce the ACS of the system and the COE of a MG power system. The integrating WTG, PV and ESS into the MG system has also improved the reliability of the system based on the results presented in Fig. 2. The values of LOLP, LOLE, EENS and AC_{loss} obtained from each case study have established the fact that RERs can be used to improve the reliability of a power system. The simulated results show that these values are decreasing with the penetration of RERs into a MG system. This indicates that the reliability of the system has been improved with the incorporation of RERs.

Table 3: Comparison with different configurations.

Description	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
AMC ($/yr)	17801	16820	15923	13413	11985	10557
AFC ($/yr)	156300	142660	131090	101170	86139	72546
AEC ($/yr)	28242	26592	25089	20821	18397	15972
ACC ($/yr)	28085	28430	28677	29296	29732	31069
ARC ($/yr)	24434	24590	24677	24911	25092	25274
ACS ($/yr)	254860	239090	225460	189610	171350	155420
NPC ($/yr)	3640900	3415600	3220800	2708700	2447800	2207400
COE $/kWh	0.8012	0.7516	0.7088	0.5961	0.5387	0.4858

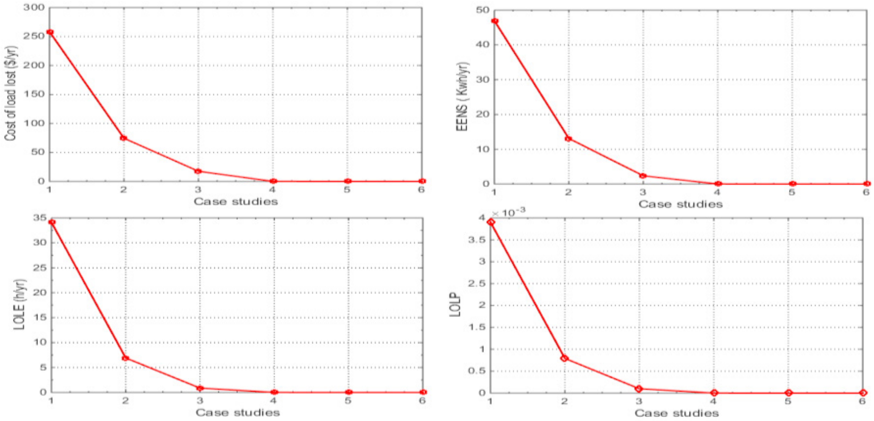

Fig.2: Impacts of renewable energy resources on the reliability of a power system

7. *Conclusions*

The results obtained from this study have established the substantial influence of PV, WTG and ESS units on the reduction of annualized, and energy costs and reliability improvement of a MG power system. The power interruption and the cost that is associated with power outage can be reduced with the application of RERs. The technique applied in this paper can be used in a real time power system to reduce the operating cost and energy cost and improve the reliability of a power system. The results obtained from this work can be utilized by the power utilities as a benchmark to enhance the performance and efficiency of a power system.

References

[1] Adefarati T, Bansal RC. Integration of renewable distributed generators into the distribution system: a review, IET-*Renewable Power Generation, 2016*; 10 (7): 873-884.

[2] Adefarati T, Bansal RC. Reliability assessment of distribution system with the integration of renewable distributed generation, Applied Energy, 2017; 185: 158-171.

[3] Caballero F, Sauma E, Yanine F. Business optimal design of a grid-connected hybrid PV (photovoltaic)- windenergy system without energy storage for an Easter Island's block, *Energy,2013;* 61 :248-261.

[4] Ramli MA, Hiendro A, Al-Turki YA. Techno-economic energy analysis of wind/solar hybrid system: Case study for western coastal area of Saudi Arabia, *Renewable Energy, 2016;* 91: 374-385.

[5] Bilil H, Aniba G, Maaroufi M. Multiobjective optimization of renewable energy penetration rate in power systems, *Energy Procedia, 2014;* 50: 368-375.

[6] Bansal RC, Bhatti TS. Small signal analysis of isolated hybrid power systems: reactive power and frequency control analysis. *Oxford UK: Alpha Science International* 2008.

[7] Liu X, Bansal RC. Thermal power plants: modelling, control and efficiency improvement. *New York, USA: CRC Press* 2016.

[8] Khare R, Kumar Y. A novel hybrid MOL–TLBO optimized techno-economic-socio analysis of renewable energy mix in island mode. *Applied Soft Computing* 2016; 43: 187-198.

[9] Allan RN, Billinton R, Sjarief L, Goel L, So KS. A reliability test system for educational purposes—basic distribution system data and results, *IEEE Trans. Power Systems, 1991;* 6 (2): 813–820.

[10] Bansal RC, Handbook of distributed generation: Electrical power technologies, economic and environmental impacts, Springer, 2017.

[11] Das BK, Al-Abdeli YM, Kothapalli G. Optimisation of stand-alone hybrid energy systems supplemented by combustion-based prime movers, *Applied energy, 2017;* 196: 18–33.

Biography

Prof. Ramesh Bansal has over 25 years of experience and currently he is a Professor and group head (Power) in the Department of EEC Engineering at University of Pretoria. He has published over 250 papers. Prof. Bansal is an Editor of IET-RPG & Electric Power Components and Systems. He is a Fellow and CEngg IET-UK, Fellow Engineers Australia and Institution of Engineers (India) and Senior Member-IEEE.