Optimal Configuration of Microgrid for Green Data Centres: A Radial Movement Optimization Approach

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Abstract

With the dramatic worldwide growth of information technology sectors, the traffic of data centres is projected to experience an increase of about 80% by 2020. Green data centres are proposed as a solution towards sustainable platform providing IT services. This paper presents an optimal microgrid configuration for a green data centre. The mathematical models for the costs and the green gas emissions associated with all components of the microgrid system as well as their interactions are taken into consideration in the optimisation model. The capital, operational, and degradation costs during a life-time of 20 years of the system are also considered. The optimum microgrid configuration is composed of 38% renewable energy generation that reduces the total cost by 37% and greenhouse gas emissions by 16%.

Keywords: optimal microgrid design, green data center, renewable energy resources, microgrid configuration, metaheuristic optimization

1. Introduction

The growth of demand for information and communication technology (ICT) services and their associated concerns such as data security and privacy has increased the need for designing and constructing sophisticated data centres. In 2014, data centres consumed 2% of the total energy consumption of USA which means 70 billion kWh. This was equal to the energy demand for 6.4 million average American households. It is even more interesting to know that, this energy demand has doubled during the last five years [1, 2].

These data centres facilities provide business holders with servers, virtual machines, data storage and other services for rent. If a data centre actively participates in demand response (DR) programs for electricity conservation, it qualifies as a green data centre [3, 4, 5].

Green data centres are usually energy efficient and sometimes fed with renewable energy [6].

Microgrid provides several benefits as an alternative to conventional electricity infrastructure specially when the load is concentrated like a data centre. These include, reduction of transmission losses, increased power generation efficiency, increased reliability, and pollution reduction.

In general, the literature on microgrid design is divided into two main streams which have to be considered for a successful microgrid architecture: microgrid components and operation planning [7,8]. The system design deals with the sizing and selection of the components with the objective of minimising capital and operational costs considering some environmental aspects [9]. The selection of the distributed energy resources (DERs), energy storage system and other components has to involve several constraints such as power loads, information technology, capital, operational and maintenance costs, climate information and, utility tariff. Besides the variable nature of renewable energy sources, the load demand fluctuations due to unpredictable human behaviours has to be applied to the microgrid design methodology [10].

On the other hand, microgrid operation planning deals with the optimal operation over a short/medium term for a given system. This aims at coping with the existing uncertainty, fluctuations and disturbances by incurring the minimum cost which is performed by optimising the supply and demand side management at the same time [11, 12]. The existing demand response programs are reviewed by Deng et al. [13].

Generally, the optimisation problems associated with microgrid and power system are complex; therefore, the quality of results obtained are highly dependent on the optimisation algorithm and the problem formulation. In light of this fact, many researchers have focused on developing efficient methodologies with less computational burden [14, 15].

In this paper, we generate an optimisation model for configuring an optimal microgrid system for a green data centre using a novel metaheuristic technique. The
selection criteria of the renewable energy sources and the parameters affecting their generation as well as the storage system are explained and proper generation and storage units are selected. The Radial Movement Optimisation (RMO) technique is used to optimise the size of generation and storage components by considering the capital and operational costs, battery degradation costs, and emissions produced by electricity purchased from the main grid. The costs are considered for the whole project life time of 20 years and represented into annual costs.

2. Microgrid system components

The microgrid components with the parameters to be considered for their selection are investigated as follows:

2.1 Green data centre load demand

The data, air and power flow, as well as the interconnection of all components in a typical green data centre, are shown in Fig. 1. The cooling system is assumed to be based on chilled water which is very popular. The data load determines server utilisation and the total power demand is highly dependent on the data load. The subcomponents composing a green data centre with their mathematical models developed in a separate publication [16].

![Figure 1](image-url)  
**Figure 1** The interconnection of components in a typical green data centre

2.2 Generation units and storage system

The selection of distributed energy resources for a microgrid requires the consideration of diverse criteria among which load type and priority, average load and available distributed energy resource technologies, and operational mode are very important [17]. The parameters that affect the optimal size of the selected DERs are capital cost, installation cost, operation and maintenance cost, power rating, reliability of the system, green gas emission, and life-time of the microgrid.

The cost benefit of the renewable energy based microgrid system is often calculated by comparing the cost of energy extracted from the DER units with the same amount purchased from the main grid. However, the cheap energy is not the sole aim of designing a DER based microgrid system; environmental friendliness and energy security are the other factors to be taken into consideration while planning power distribution systems [18].

The power generation system considered in this research includes photovoltaic generation and wind turbines while battery system is used as the energy storage system. The power generation of photovoltaic (PV) panels mainly depends on the solar irradiation which can be obtained from Eq. (1).

$$P_{PV} = \frac{H}{1000}[P_{\max} + y_{P_{\max}}(T_{\text{amb}} + \frac{NOCT - 20}{80} - 25)] \quad (1)$$

Where $H$ is the solar irradiation in W/m², $P_{\max}$ is the peak power being generated by the PV panel, $y_{P_{\max}}$ denotes the temperature coefficient of the maximum power point, $T_{\text{amb}}$ is the ambient temperature of the PV panel, and $NOCT$ denotes the normal operating cell temperature of the PV panel.

The power generation model used for the wind turbines is shown in Eq. (2). Each wind turbine’s rated power is 100 kW; therefore, the optimal size of the wind energy system is to find the optimum number of wind turbines. It is worth mentioning that the wake effect in a wind farm is neglected in this study [19].

$$R_{WT} = 1.43v^2 - 4.29v \quad (2)$$

where $3 \leq v \leq 25$ is the wind speed in m/s, and $P_{WT}$ is equal to zero for other values of the wind speed due to cut in and cut off constraints of the wind turbine.

Regarding the state of charge (SOC) of the battery system, some constraints have been taken into account. As suggested by Prajapati et al. [20], a SOC of greater than 20% can help to bridge the gap between the renewable energy shortage and the load demand. On the other hand, overcharging of the battery to more than 80% of SOC is not recommended due to possible physical damages to the storage system.

3. Microgrid Optimisation Model

This section provides mathematical models for the various costs and the green gas emission associated
with all components of the microgrid system as well as their interactions. Also, the search space and fitness function for the optimisation process are presented.

### 3.1 Generation and storage costs

Photovoltaic generation generally does not incur much operational cost to the system, instead its capital cost is quite considerable. For the wind turbines, although the maintenance and operational costs are considerable, their capital investment costs are rather expensive. In general, the life time cost of a renewable energy generation unit including its operational, maintenance and capital investment is divided by the life time of the system to obtain the annual cost. In this study, the fixed annual cost \(C_{\text{fix}}\) of PV and wind energy are set to 350 and 120 $/kWyear, as used by Mizani and Yazdani [21]. Since some utility companies agree to buy the excess renewable energy generation using a feed in tariff, this has to be considered in the model as a feed in rate \(R\) which is normally varies based on the utility companies and also the type of renewable energy system. The feed in rate is chosen as 0.14 $/kWh for both PV and wind energy based on local feed in tariff rates in Australia. Eq. (3) shows the annual cost \(C_{\text{an}}\) for \(g^{\text{th}}\) renewable energy generation units.

\[
C_{\text{an}}[g] = C_{\text{fix}}[g] - \sum_{h=1}^{8760} P_{g} [h] \times R \tag{3}
\]

where \(P_{g}[h]\) is the power sold to the utility company at \(h\) hour from \(g^{\text{th}}\) renewable energy generation unit.

For the battery system, in addition to a fix installation and investment cost, degradation cost \((D)\) has to be considered as well. Although, the exact degradation cost of a battery system can be dependent on the depth of charge (DOC) and SOC, it is accurate enough to assume it as a fix cost per kW; therefore, the annual cost of the battery system consists of 24 $/kWyear as the investment and 0.04 $/kW as the charge/discharge degradation cost [22]. Therefore, the annual cost of the battery system is obtained using Eq. (4).

\[
C_{\text{bat}}[g] = C_{\text{fix}}[g] - \sum_{h=1}^{8760} P_{\text{bat}}[h] \times D \tag{4}
\]

where \(P_{\text{bat}}[h]\) denotes the hourly charging/discharging power in kW.

The total annual cost for generation and storage is then calculated as in Eq. (5) wherein \(N_{\text{RE}}\) denotes the number of renewable energy generation units. Equations (6) and (7) show the net present value (NPV) of the system calculated using annual cost \(C_{\text{an}}\) and present value function (PVF).

\[
C_{\text{tot}}[g] = \sum_{n=1}^{N_{\text{RE}}} C_{\text{an}}[n] + C_{\text{bat}}[g] \tag{5}
\]

\[
NPV = C_{\text{tot}} \times PVF(r, l) \tag{6}
\]

\[
PVF(r, l) = \frac{(1 + r)^{l} - 1}{r(1 + r)^{l}} \tag{7}
\]

where \(r\) is annual interest rate as a percentage and \(l\) is the project life time in years which are considered as 6% and 20 years in this study.

### 3.2 Grid electricity costs

The electricity purchased from the utility companies is considered as purchased from the grid which can be represented by various cost functions relative to the tariff \(f_{\text{grid}}(P_{\text{grid}})\). Therefore, the annual cost of the electricity purchased from the grid can be obtained from Eq. (8).

\[
C_{\text{grid}} = \sum_{h=1}^{8760} f_{\text{grid}}(P_{\text{grid}}[h]) \tag{8}
\]

where \(P_{\text{grid}}\) is the hourly power purchased from the grid in kW. In this study, the price function of the grid electricity is considered to be flat rate at 0.34 $/kWh.

### 3.3 Emissions costs

The green gas emission is another important factor in microgrid design and planning which is modelled as a cost in this study. No pollutant is taken into account for PV, wind generation and battery system, but the annual emission of the electricity purchased from the grid is obtained using Eq. (9).

\[
E_{\text{an}}[g] = \sum_{h=1}^{8760} P_{\text{grid}}[h] \times \sum_{p=1}^{M} \mu_{p} \tag{9}
\]

where \(M\) is the number of pollutants and \(\mu_{p}\) is the emission factor of \(p^{\text{th}}\) pollutant in $/kWh. The major pollutants considered in this study are Carbon Monoxide (CO), Carbon Dioxide (CO2), Sulfur Dioxide (SO2), Unburnt Hydrocarbons (UHC), Particulate Matter (PM), and Nitrogen Oxides (NOx) which are represented with their emission factors in Table 1 [21].

<table>
<thead>
<tr>
<th>pollutant</th>
<th>CO</th>
<th>CO2</th>
<th>SO2</th>
<th>UHC</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_{p})</td>
<td>6.5e-3</td>
<td>0.632</td>
<td>7.2e-4</td>
<td>7.2e-4</td>
<td>1.34e-3</td>
<td>4.9e-4</td>
</tr>
</tbody>
</table>

### 3.4 Microgrid reliability

There are two factors for consideration in microgrid reliability which are loss of power supply (LPS) and loss of load (LOL) [9]. In this study, all shortages are determined to be covered by the electricity purchased from the grid. In order to ensure that the reliability, the power balance shown in Eq. (10) must always hold.

\[
P_{\text{grid}} + P_{\text{tot}}^{PV} + P_{\text{tot}}^{WT} = P_{DC} + P_{\text{bat}} \tag{10}
\]

where \(P_{\text{grid}}\), \(P_{\text{tot}}^{PV}\) and \(P_{\text{tot}}^{WT}\) are the total power generation by PV panels and wind turbines utilised.

### 3.5 Radial movement optimisation

Radial Movement Optimization (RMO) is a metaheuristic optimisation technique developed by Rahmani and Yusof [23, 24] that uses a vectorised search space to model the problem environment where each particle at each step proposes a solution to the problem. RMO consists of two different main steps which are initialisation and movement. The initialisation is the first part of the algorithm, in which the particles are spread in the search space, and any of them proposes a solution to the problem. \(X_{i,j}\) is the matrix which stores the
locations of the particles and has a dimension of $nop \times nod$ where $nop$ and $nod$ represent the number of particle and dimension respectively. The $nod$ depends on the parameters which affect the optimisation process, while the $nop$ can be chosen wisely by the user. The $nop$ and $nod$ must be kept constant throughout the optimisation process. To spread the particles, we have to make sure that our assignment covers all the area of the solution search space uniformly.

The $V_{ij}$ matrix determines how far each particle goes. Eq. (11) shows the Velocity matrix which has a dimension of $nop \times nod$, just the same as the Location matrix.

$$V_{ij} = W_k \times \text{rand}(-1,1) \times \frac{X_{\text{max}}[j] - X_{\text{min}}[j]}{d}$$

where $i \in \{1, 2, ..., nop\}$ and $j \in \{1, 2, ..., nod\}$ , $d$ determines the maximum allowed distance which particles can be sprinkled and must be chosen an integer, $\text{rand}(-1,1)$ returns a random value between -1 and 1, and $W_k$ is the inertia weight which is reduced from 1 to 0.2 throughout the generations.

After the particles are sprinkled, their locations are evaluated using the objective function. The location of the best fitness value is stored as the radial best ($R_{best}$). The best $R_{best}$ found through all the generations past is known as the global best ($G_{best}$). The location of the $R_{best}$ and $G_{best}$ are used to create the update vector ($up$) vector which is obtained from Eq. (11). Later on, as in (12), the $up$ vector is used to update the location of the $cp$ for the next generation. The vector diagram of the particle movement is shown in Figure 2.

$$cp^{k+1} = cp^{k} + up$$

$$up = C1 \times (G_{best} - cp^{k}) + C2 \times (R_{best} - cp^{k})$$

In Eq. (12), $C1$ and $C2$ are the movement coefficients and must be adjusted prior to running the algorithm. The process will be repeated for the new generation, where the sprinkling of the particles will be done from the new $cp$, until the stoppage criteria is met.

### 3.6 Search space and fitness function

Since RMO algorithm uses a vectorised search space for the particles exploration, there is a necessity to define a multidimensional solution space which contains all the possible solutions. In this study, the search space consists of $N_{PV}$, $N_{WT}$, and $N_{bat}$ which are the numbers for PV panels, wind turbines and battery banks respectively. The constrains for the three variables are shown in Eq. (13). It is notable that each 4 PV modules of 250 W are considered to be the minimum scale for installation.

$$N_{PV} = 4 \times x_1 : x_1 \in Z^*$$

$$N_{WT} = x_2 : x_2 \in Z^*$$

$$N_{bat} = x_3 : x_3 \in Z^*$$

Each solution returned from the search space has to be evaluated using a fitness function. The fitness value can be obtained from the fitness function shown in Eq. (14). The smaller the fitness value, the better the solution proposed.

$$\varphi = \theta \times NPV + (1 - \theta) \times E_{an}$$

where $\varphi$ is the fitness value for each proposed solution, and $0 \leq \theta \leq 1$ is the weighting coefficient which determine the importance of cost and emission which is set to 0.9.

### 4. Simulation Results and Discussion

In this section, the simulated power load demand of a data centre by considering real climate data is presented. Also, the simulation results for optimal design of a microgrid consisting of PV, wind battery system using RMO algorithm is demonstrated.

#### 4.1 Environmental parameters

The hourly environment temperature, irradiation, and wind speed are obtained from the National Renewable Energy Laboratory (NREL) website [25] and used in the simulation. Fig. 3 demonstrates the hourly temperature profile for the first week of June 2016 (summer week) and December 2016 (winter week). In addition, the hourly solar irradiation and wind speed of the summerweek is shown in Fig. 4.
4.2 Data Centre Load Demand Simulation

As a case study for modelling, we assume a data centre with a structure shown in Fig. 1 and a server farm consisting of 40,000 computer servers. The cooling system of the data centre consists of a chiller plant and a computer room air handler (CRAH) unit which was chosen due to its popularity. The calculations of the physical size of the computer room and server racks are out of the scope of this research. Each server's power consumption can vary between 120 W (at idle mode) and 250 W which is within the range of Dell PowerEdge servers. The key parameter in the power load model of the server farm is the utilisation of servers. The hourly utilisation profile of the data centre workload for one week is assumed to be presented in [26]. It is also assumed that the server clusters are homogeneous and load balancing is perfect. Fig. 5 shows the area plot for the power consumption profile of the components of the data centre during the summer week.

To analyse the annual energy consumption profile of the data centre, an hourly utilisation profile is generated using the pattern of the weekly utilisation profile. The breakdown of the annual energy consumption is shown as a pie chart in Fig. 6. It can be observed that 55% of the annual energy is consumed by the server farm itself. The chiller plant consumes the second highest portion of energy by 15% followed by 12% for the CRAH unit. The cooling system consumes 31% of the total annual energy of the data centre which is $1.0937 \times 10^{11}$ kWh.

4.3 Optimal Microgrid Design Simulation

Using the annual hourly data and the models for renewable energy generation units and battery system, the optimal design of the microgrid is obtained by utilising the RMO algorithm. The experiment included 10 simulation runs from which the best results are presented. Table 2 shows the capacity of PV, wind and battery systems and some details about the cost and emission for the optimal configuration and the grid only. Fig. 7 shows the annual contribution of different energy sources in supplying the electricity of the green data centre for the optimal configuration. It can be observed that the renewable sources supply 38% of the load demand for a year while wind energy provides 6% more than that of PV systems with 16%. The main grid still provides 62% of the electricity required for the data centre.

Table 2 Cost and emission of the optimal configuration

<table>
<thead>
<tr>
<th>Config.</th>
<th>PV (kWh)</th>
<th>Wind (kWh)</th>
<th>Battery capacity (kWh)</th>
<th>$C_{\text{total}}$ ($)</th>
<th>$E_{\text{em}}$ (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>optimal</td>
<td>3.605e7</td>
<td>2.3109e7</td>
<td>9.2436e6</td>
<td>2.257e10</td>
<td>4.760e5</td>
</tr>
<tr>
<td>Grid only</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.587e10</td>
<td>5.664e5</td>
</tr>
</tbody>
</table>

Figure 7 The contribution of PV, wind and grid in supplying the load demand

The energy control and management strategy is based on supplying the load demand with the renewable energy generation and storing the excess green energy generation in the batteries. In case that the batteries are charged enough, the power can be fed in to the grid. If the renewable energy is insufficient, first, the batteries will be discharged to supply the load demand, and purchasing from the grid will be the second option.

Fig. 8 demonstrates the power dispatch for the optimal configuration of the microgrid, over a 24-hour period. It can be observed that the control and management strategy of the microgrid let the excess renewable power generation be stored in the batteries first, and if exceeds will feed in to the main grid.
5. Conclusions

In this paper, we presented an optimal microgrid configuration design for a green data centre. The proposed optimisation model consists of mathematical models for the costs and the green gas emissions associated with all components of the microgrid system. The capital, operational, and degradation costs during a life-time of 20 years of the system are also considered. Hourly environmental data such as ambient temperature, solar irradiation and wind speed is used to calculate the renewable energy generation of the microgrid and the load demand. As a case study, a green data centre composed of 40,000 servers is modelled and its power load demand is analysed. The optimal microgrid configuration is composed of 38% of renewable energy generation that reduces the total cost by 37% and greenhouse gas emissions by 16%.

Reference


