MICROGRID ECONOMIC DISPATCH WITH STORAGE SYSTEMS BY PARTICLE SWARM OPTIMIZATION

SIDNEY CERCUEIRA*, OSVALDO SAAVEDRA*, SHIGEAKI LIMA*

*Universidade Federal do Maranhão-UFMA
Av. dos Portugueses s/n
São Luís, Maranhão, Brasil

Emails: cercqueirasidney@gmail.com, o.saavedra@ieee.org, shigeaki@dee.ufma.br

Abstract—This paper presents the economic dispatch in a microgrid operating connected to main grid. This problem has nonlinear functions with equality and inequality constraints as well be dynamic and time dependent. The objective function takes into account the operation and maintenance costs for diesel generators, state of charge (SOC) constraints for batteries, and includes wind and photovoltaic generation. The PSO algorithm is used to solve the problem to minimize the total system cost. Computer simulations are performed to show the effectiveness of proposed methodology and impacts of price and storage system on economic dispatch.

Keywords—Microgrids, Energy Storage, Economic Dispatch, PSO

1 Introduction

The Electric Power Systems (EPS) has undergone significant changes over the last few years, in the operational and organizational structure. These changes combined with the tendency for efficient production and less environmental impact, directs us to search new alternative sources for the electricity generation. Some of these alternatives are wind and solar energy.

One effect of the deregulated environment of EPS, is the gradual introduction of Distributed Generation (DG). This creates new concepts that associated with the increased use of renewable energy sources, introduces the idea of microgrids (Hatziargyriou, 2013).

The microgrids are defined as part of distribution system and its basic structure has distributed energy resources, storage devices and flexible loads. These systems can operate connected to the main grid or isolated mode (Islanding mode) (de Souza Ribeiro et al., 2011). This microgrids concept can be extended as a platform for integration of microgeneration, demand and storage units, that has some megawatts in a low-voltage system, to meeting a local load, and it can be seen as a part of a SmartGrid when added smart meters, data acquisition and communication system between its basic components (Hatziargyriou, 2013).

There are policies to encourage the implementation of microgrids, due to the benefits derived from these, such as low CO2 emission, increase reliability, low implementation cost, diversification of power generation sources and losses reduction. Other microgrids benefits can be found at (Hatziargyriou, 2013).

The economic dispatch (ED) is an essential problem of short-term operation, and aims to determine the microgrid best optimal operation point at lowest cost. In a microgrid, we need to add renewable energy resources, that due to their intermittent nature, are considered nondispatchable, and thus, its production has priority to serve the demand.

In the literature, some proposals can be found to solve Economic Dispatch problem. In (Logenthiran and Srinivasan, 2009), the authors proposed an efficient method based on three steps for microgrids optimal economic dispatch, considering unit commitment constraints into the objective function. In (Modiri-Delshad et al., 2013), the authors introduced a iterated-based algorithm to solve a microgrid economic dispatch without considering the losses, and compared with the CPLX solver. However they do not considered renewable energy sources and energy storage system in this study. A multiobjective optimal generators allocation was proposed in (Meiqin et al., 2010), where the customer outage cost, emission pollution and production cost was considered into objective function. The solution technique is a hybrid algorithm using fuzzy system and particle swarm optimization. In the microgrid formulation proposed by (Mohamed and Koivo, 2010) its take in a count the operation, start-up and emissions costs into the objective function, and for the solution technique, it was used the Mesh Adaptive
Direct Search algorithm. Applications of multiagent systems in microgrids operation and control can be found in (Dimeas and Hatziargyriou, 2005).

In this paper is proposed the solution to the Economic Dispatch in a microgrid with renewable energy sources, diesel generators and energy storage systems (batteries). The Particle Swarm Optimization algorithm is used to find optimal scheduling, meeting the constraint imposed and battery power and energy limits that makes the problem dynamic.

2 Problem formulation

Figure 1 shows a typical microgrid that contains renewable sources, loads, diesel generator and energy storage system (ESS). There are a variety of loads, and can be classified into three types: controllable, shiftable and critical. For storage systems, the main technologies are ultracapacitors, SMES, flywheels, hydro pumping and batteries. In this paper, batteries are used for ESS and demand side management is not considered.

![Figure 1: Typical microgrid system.](image)

The microgrid optimal operation aims to minimize the total production cost of diesel generators, given all the technical constraints and meet their local demand. Mathematically, its a nonlinear problem and can be formulated as follows:

\[
\min \quad CT = \sum_{t=1}^{T} \left[ \left( \sum_{i=1}^{N_G} (CF_i(P_{i,t}) + OM_i(P_{i,t})) \right) + P_{grid,t} \cdot \pi_{R,t} + C_B(P_{B,t}) \right]
\]

where \(CF_i(P_{i,t})\) is the production cost of diesel generator \(i\) at hour \(t\), \(OM_i(P_{i,t})\) is the operation and maintenance cost of generator \(i\); \(P_{i,t}\) is the output power generator \(i\) at hour \(t\). \(P_{grid,t}\) and \(\pi_{R,t}\) is grid power output and the grid energy price, respectively. The battery power at hour \(t\) is represented by \(P_{B,t}\).

Positive values for grid power, indicate purchasing power at time \(t\), while negative values indicate sale to the grid, that resulting in profit for microgrid.

The operation and maintenance cost, will be given in terms of output power as follows:

\[
OM(P_i) = \lambda_{OP} \cdot P_i
\]

onde \(\lambda_{OP}\) is a proportionality constant in terms of output generator power \(i\).

2.1 Constraints

The objective function (1), is subjected to several constraints, like a power generators limits, power balance, SOC constraint, among others. The instantaneous demand must be met and therefore the power supplied by renewable sources enter as negative charges, given as follows:

\[
\sum_{t=1}^{N_G} P_{i,t} + P_{B,t} + P_{V,t} + P_{W,t} + P_{grid,t} = P_D + P_{loss,t}
\]

where \(P_D\) is the demand power. \(P_{loss}\) are the systems losses. In this paper, losses will be considered equal to zero.

2.2 Generators Modelling

2.2.1 Wind power

The output power of wind turbines are modeled as a function of wind speed. In this paper, the output power of wind turbines is calculated as follow (Mohamed and Koivo, 2012):

\[
P_W = \begin{cases} 
0, & V_w < V_{c1} \\
aw V_w^2 + bw V_w + cw, & V_{c1} \leq V_w \leq V_N \\
P_{wN}, & V_N \leq V_w > V_{co} 
\end{cases}
\]

where \(P_W\) is the output power, \(V_{c1}\) is the cut-in wind speed, \(V_{co}\) is the cut-out speed, \(V_N\) is the rated speed and \(V_w\) wind speed. The power curve coefficients are represented by \(aw\), \(bw\) and \(cw\).

2.2.2 Photovoltaic panels

The power supplied by a solar panel is limited by technical issues and climate factor. Among the technical factors are efficiency, nominal installed capacity and the rated temperature of each cell. Considering the climatic factors, has solar radiation and ambient temperature. The advantages of the implementation of a photovoltaic system are in practical assembly shortly to design, no moving parts (no noise during the operation), easy installation in urban environments, long life and low maintenance (Mohamed and Koivo, 2012). Considering all these factors, the output power is calculated by the equation:

\[
P_V = P_{STC} \frac{G_{ING}}{G_{STC}} [1 + k_{PV}(T_c - T_r)]
\]
where $G_{ING}$ is the solar irradiation, $G_{STC}$ is the irradiation in standard test condition, $T_c$ is the cell temperature, $T_r$ is reference temperature and $kP r$ is the coefficient temperature. $P_v$ is the photovoltaic output power and $P_{STC}$ is the maximum output power in standard test condition.

### 2.2.3 Diesel generator

Diesel generators are important components of a microgrid and its cost curve as a function of output power is represented by a quadratic function as follows:

$$C(P_v) = aP_v^2 + bP_v + c$$

(6)

where $a$, $b$ and $c$ are the generator coefficients. The diesel generators are subjected to a constraint given below:

$$P_{v_{min}} \leq P_v \leq P_{v_{max}}$$

(7)

### 2.3 Batteries

Batteries are devices that convert chemical energy into electrical energy. Together with distributed generation, are used to store energy for use later, when the microgrid distributed generation is not sufficient to meet local demand. Otherwise, serves as reserve and can store excess energy from wind turbines and solar panels until they are fully charged. It is also used to minimize the production cost, when the grid price and production cost of diesel generators increase.

An important factor to preserve the battery lifetime is to monitor the State of Charge (SOC). There are energy limitation in batteries, where the measuring the SOC, prevents battery from overcharging and deep discharge, or even to be discharged for a long time. Thus, the energy in each time interval $t$ is calculated as follows:

$$SOC_t = SOC_{t-1} - P_{B,t} \cdot \Delta t$$

(8)

where $SOC_t$ is the energy stored at time $t$ and $\Delta t$ is the time interval. For positive values, batteries are in discharge mode and negative for charge. The batteries must be used into energy limits. Thus:

$$SOC_{min} \leq SOC_t \leq SOC_{max}$$

(9)

To calculate the battery output power, the storage system conversion efficiency must be considered (Hoke et al., 2013). In this case, defining $P_{in}$ and $P_{out}$, as the input and output power for energy storage respectively, we get:

$$P_{out} = \begin{cases} \frac{P_B}{\eta_i}, & if ~ P_B \geq 0, \\ 0, & if ~ P_B < 0 \end{cases}$$

(10)

where $\eta_i$ and $\eta_o$ are the efficiency conversion for $P_{in}$ and $P_{out}$. Thus, the new battery power is calculated as follow:

$$P_B = \eta_o \cdot P_{out} - \frac{P_{in}}{\eta_i}$$

(12)

### 3 Particle Swarm Optimization - PSO

Particle Swarm Optimization (PSO) was introduced by (Kennedy and Eberhart, 1995) through studies on the social behavior of populations of birds and fish (Cerqueira et al., 2011). It is a natured-inspired algorithm for global optimization. Each particle $j$, has a position $X_j$ and velocity $v_j$, and flying through on the search space, and optimized at each iteration their positions and velocities (Shi and Eberhart, 1998). In the iterative process, the best individual position ($P_{Best}$) of each particle and global position ($G_{Best}$) are stored, and will later be used in the process of update their speeds and positions. The following equations, described the update process, for velocity and position, respectively:

$$v_{j}^{k+1} = \omega \cdot v_{j}^{k} + c_1 \cdot \text{rand}(1) \cdot (P_{Best,j}^{k} - X_{j}^{k}) + c_2 \cdot \text{rand}(2) \cdot (G_{Best}^{k} - X_{j}^{k})$$

(13)

$$X_{j}^{k+1} = X_{j}^{k} + v_{j}^{k+1}$$

(14)

where $c_1$ are cognitive factors, that represent the trust for each particle in it and the swarm, $\text{rand}_1$ are $\text{rand}_2$ random numbers in the range [0,1]. For each step, the fitness function of individuals particles will be valued.

The inertial factor $\omega$ control the step size. If the inertia weight is larger, facilitates a global search while a small facilitates a local search. For this reason, a linearly decreasing is used and can be calculated as a function in the iterative process:

$$\omega = \omega_{max} - (\omega_{max} - \omega_{min}) \cdot \frac{\text{iter}}{\text{iter}_{max}}$$

(15)

where $\omega_{max}$ and $\omega_{min}$ the inertia weight maximum and minima ; $\text{iter}$ and $\text{iter}_{max}$ iteration and maximum iteration number, respectively. There are many different strategies for inertia weight to providing balance between PSO exploitation and exploration. A comparative study for inertia weight strategies can be found in (Bansal et al., 2011). The particle velocity is controlled by the following constraint:

$$v_{j}^{k} \in [-v_{max}, v_{max}]$$

(16)

For handling constraints, a most common approach for meta-heuristics algorithm is to apply
penalty functions into the objective function. In this case, for a minimization problem, the objective function is modified and add penalties, as follow equation:

\[ f = CT + \text{penalty} \]  

(17)

where \( f \) é the new cost function. The penalty is a violated constraint multiplied by a coefficient. The penalties coefficients is a value that has the same size of objective function value. The algorithm steps is showed:

1. Initialize the swarm positions with random values as follows:
   \[ X_i = \text{rand}(.) \times (X_i^{\text{max}} - X_i^{\text{min}}) + X_i^{\text{min}} \]  
   (18)

2. The speed must to be initialized with random values:
   \[ v_i = \text{rand}(.) \times (v_i^{\text{max}} - v_i^{\text{min}}) + v_i^{\text{min}} \]  
   (19)

3. Compute the objective function (1) for each particle;
4. Consider the initial population as local best position \( P_{\text{best}} \);
5. From \( P_{\text{best}} \), select the best values for global best position (\( G_{\text{best}} \)) and store;
6. Start PSO loop and iteration counter;
7. Compute the inertia weight, particle speed (13) and position (14);
8. Apply penalty conditions, if necessary;
9. Evaluated equation 1;
10. Update \( P_{\text{best}} \) and \( G_{\text{best}} \);
11. Repeat 7, 8 and 9 for each iteration, until the stop condition;
12. Print \( G_{\text{best}} \) Values;
13. End

4 Simulations and Results

For the simulations, renewable generations have priority because they are non-dispatchable sources, has free delivery cost and zero emissions, contributing to the environmental aspects. In the connected mode, the economic dispatch of microgrid depends on the generation costs of each source, as well as the purchase or sale price of energy from the upstream network and the demand to be meet. In this case, PW, PV and batteries, has priority in the dispatch, meanwhile battery SOC must be monitored. If this sources can’t supply the load, main grid and diesel generators, must to be used to complete. The generations costs and energy price from main grid is compared. If the external grid price is lower than generation, its use to complete the demand, otherwise we use the diesel generators. If battery SOC is above of minimal SOC, the excess can be sale to main grid.

Figure 2 shows the microgrid load profile for a typical day and ranges from 52kW to 90kW. The available power from PW and PV can be seen in figure 3. Its assumed that the data of wind and solar generation as deterministic. Simulations data can be found in (Cai et al., 2012), (Modiri-Delshad et al., 2013).

![Figure 2: Microgrid load profile.](image)

In table 1, the maximum and the minimum power capacity of diesel generator unit and battery limits are shown. Price for the main grid is found on the table 2 (Sobu and Wu, 2012), (Cai et al., 2012). The PSO parameters is considered the same for all simulations. The parameters are \( \text{iter}_{\text{max}} = 2000, n_{\text{par}} = 40, \omega_{\text{max}} = 0.9, \omega_{\text{min}} = 0.4, c_1 = 2.0 \ e \ c_2 = 2.0 \). In all cases, simulations are performed 30 times to insure quality solutions and the non-dependence of initial solution by the PSO algorithm.

![Figure 3: Wind and Photovoltaic forecasted power profile.](image)

<table>
<thead>
<tr>
<th>Table 1: Diesel generator and battery data.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diesel generator</strong></td>
</tr>
<tr>
<td>( P_{\text{min}} )</td>
</tr>
<tr>
<td>0kW</td>
</tr>
<tr>
<td>0kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Battery data</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{SOC}_{\text{min}} )</td>
</tr>
<tr>
<td>60 kWh</td>
</tr>
</tbody>
</table>

2012
The battery efficiency for charging and discharging are the same and equal to 0.95.

Table 2: Price for the main grid ($/kW)

<table>
<thead>
<tr>
<th>Hour</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2400</td>
</tr>
<tr>
<td>2</td>
<td>0.1770</td>
</tr>
<tr>
<td>3</td>
<td>0.1301</td>
</tr>
<tr>
<td>4</td>
<td>0.0969</td>
</tr>
<tr>
<td>5</td>
<td>0.0000</td>
</tr>
<tr>
<td>6</td>
<td>0.1701</td>
</tr>
<tr>
<td>7</td>
<td>0.2710</td>
</tr>
<tr>
<td>8</td>
<td>0.3864</td>
</tr>
<tr>
<td>9</td>
<td>0.5169</td>
</tr>
<tr>
<td>10</td>
<td>0.5260</td>
</tr>
<tr>
<td>11</td>
<td>0.8100</td>
</tr>
<tr>
<td>12</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

4.1 Results

4.1.1 Case 1

For case 1, it's considered that a microgrid can sell to main grid, and the system includes storage system, diesel generator, wind and solar power. Battery bank has operating and maintenance cost fixed and equal to $/kW 0.18. Figure 4 shows the results for case 1. All units operate into their limits and satisfy the load demand during planning period. The renewable sources and battery reduce the total operation cost, because their operation cost are considered zero. The total cost for this case is $283.14. Its observed that, between 1h to 8h and 17h to 23h, the system buy energy from the grid, because these intervals the grid energy price is low reducing the output power from diesel generator.

Its also important to note that the batteries are charging during the first hours, to be used later, when the grid price increases. Batteries are charged when the grid power price is low and energy from renewable is available.

Table 3: PSO best results with storage

<table>
<thead>
<tr>
<th>Total operation cost in ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>289.64</td>
</tr>
</tbody>
</table>

The results obtained from PSO performance can be seen in Table 3. Results show standard deviation of 2.9063, best solution of $283.14 and average value of $289.64. The convergence curve is shown in Figure 5.

4.1.2 Case 2

For the case 2, the battery operation cost is $0.28 and the price for sale energy to the grid is assumed 70% of purchase price. Its also considered a fixed price for grid of $0.7. This case shown the sensibility to the price, when the microgrid is connected to main network.

In this case, the scheduling was changed due to the fixed grid price and battery tariff. For this reason, figure 6 shows that the grid has insignificant participation due to its high cost. Thus, microgrid used more diesel generator and battery energy to meet the demand. Batteries participate to supply the demand during the peak hour and charging in another time.
quantity, because the price is only 70% of the purchase price. This led to increased cost around 59% compared to the case 1. The best value was found to be $ 483.56. The mean value and standard deviation can be seen in Table 4.

<table>
<thead>
<tr>
<th>Table 4: PSO results for case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total operation cost in ($)</strong></td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>487.1327</td>
</tr>
</tbody>
</table>

This case shows the sensitivity to price policy adopted in the realization of the economic dispatch when the microgrid is operating connected to the grid. It is an important issue in decision making in the optimal management of a microgrid.

5 Conclusion

In this paper, the PSO algorithm was applied to solve the economic dispatch of a microgrid with renewable sources, diesel generators and energy storage system. The proposed model taken into account constraint for variety of sources, that make a non-linear and dynamic problem. The results shown satisfactory performance and stability of PSO algorithm. This study shown the relevance of storage system in the economic operation of microgrid allowing the displacement of cheaper energy supply to peak demand period.

Acknowledgment

The authors would like to thank to CAPES and CNPq for the financial support.

References


