Environmental/Economic Power Dispatch of MicroGrid Using Multiobjective Optimization

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Abstract. This paper proposes a generalized formulation to determine the optimal operating strategy and cost optimization scheme as well as the reduction of the emissions for a MicroGrid (MG). Multiobjective (MO) optimization is applied to the environmental/economic problem of the MG. The proposed problem is formulated as a nonlinear constrained MO optimization problem. Prior to the optimization, models for system components from real data are constructed. The problem formulation takes into consideration the operation and maintenance costs as well as the emissions NOx, SO_2, and CO_2 reduction. The MG considered in this paper consists of a wind turbine, a micro turbine, a diesel generator, a photovoltaic array, a fuel cell, and a battery storage. The optimization is aimed at minimizing the cost function of the system while constraining it to meet the costumer demand and safety of the system. We also add a daily income and outgo from sale or purchased power. The results demonstrate the efficiency of the proposed approach to satisfy the load and to reduce the cost and the emissions. The comparison with other techniques demonstrates the superiority of the proposed approach and confirms its potential to solve the problem.

Key words

Microgrid, Multiobjective optimization, Load management, Environmental/economic power dispatch.

1. Introduction

MultiObjective (MO) optimization has a very wide range of successful applications in engineering and economics. Such applications can be found in optimal control systems [1], and communication [2]. The MO optimization can be applied to find the optimal solution which is a compromise between multiple and contradicting objectives.

In MO optimization we are more interested in the Pareto optimal set which contains all non-inferior solutions. The decision maker can then select the most preferred solution out of the Pareto optimal set. The weighted sum method to handle MO optimization applied in this paper. Furthermore, the weighted sum is simple and straightforward method to handle MO optimization problems. The need for more flexible electric systems to cope with changing regulatory and economic scenarios, energy savings and environmental impact is providing impetus to the development of MicroGrids (MG), which are predicted to play an increasing role of the future power systems [3]. One of the important applications of the MG units is the utilization of small-modular residential or commercial units for onsite service. The MG units can be chosen so that they satisfy the customer load demand at compromise cost and emissions all the time. Solving the environmental economic problem in the power generation has received considerable attention. An excellent overview on commonly used environmental economic algorithms can be found in [4]. The environmental economic problems have been effectively solved by multiobjective evolutionary in [5] and fuzzy satisfaction-maximizing approach [6].

Several strategies have been reported in the literature related to the operation costs as well as minimizing emissions of MG. In [3] the optimization is aimed at reducing the fuel consumption rate of the system while constraining it to fulfil the local energy demand (both electrical and thermal) and provide a certain minimum reserve power. In [3] and [7], the problem is treated as a single objective problem by neither considering the emission nor the operation and maintenance costs as well as no sold or purchased power to or from the uppergrid. This formulation, however, has a severe difficulty in finding the best trade-off relations between cost and

emission. In [8] the problem is handled as a multiobjective optimization problem without considering the sold and purchased power.

The algorithm in [8] is modified in this paper, the modification is to optimizes the MG choices to minimize the total operating cost. Based on sold power produced by Wind turbine and Photovoltaic Cell, then the algorithm determines the optimal selection of power required to meet the electrical load demand in the most economical and environmental fashion. Furthermore, the algorithm consists of determining at each iteration the optimal use of the natural resources available, such as wind speed, temperature, and irradiation as they are the inputs to windturbine, and photovoltaic cell, respectively. If the produced power from the wind turbine and the photovoltaic cell is less than the load demand then the algorithm goes to the next stage which is the use of the other alternative sources according to the load and the objective function of each one.

This paper assumes the MG could operate independently of the uppergrid, but they are usually assumed to be connected, through power electronics, to the uppergrid. The MG can purchase some power from utility providers when the production of the MG is insufficient to meet the load demand. There is a daily income to the MG when the generated power exceeds the load demand.

The second objective of this paper deals with solving an optimization problem using several scenarios to explore the benefits of having optimal management of the MG. The exploration is based on the minimization of running costs and is extended to cover a load demand scenario in the MG. Furthermore, income also considered from sold power of WT and PV. Switching off one load is also considered in this paper.

2. A Illustrative Microgrid Model

The MG study architecture is shown in Fig.1. It consists of a group of radial feeders, which could be part of a distribution system. There is a single point of connection to the utility called point of common coupling (PCC). The feeders 1 and 2 have sensitive and normal loads which should be supplied during the events. There are three load would be divided to sensitive loads and normal load. The normal load will be switched off in certain step in the algorithm. The feeders also have the microsources consisting of a photovoltaic cell (PV), a wind turbine (WT), a fuel cell (FC), a microturbine (MT), a diesel generator (DG), and a battery storage. The third feeder has only traditional loads. The static switch (SD) is used to island the feeders 1 and 2 from the utility when events happened. The fuel input is needed only for the DG, FC, and MT as the fuel for the WT and PV comes from nature. To serve the load demand and charge the battery, electrical power can be produced either directly by PV, WT, DG, MT, or FC. Each component of the MG system is modelled separately based on its characteristics and constraints. The battery storage is required to meet the load demand for a period of time. A charger controller is required to limit the depth of discharge of the battery, to

limit the charging current supplied to the battery, and to prevent overcharging, while making use of the power from the other microsources when it is available.
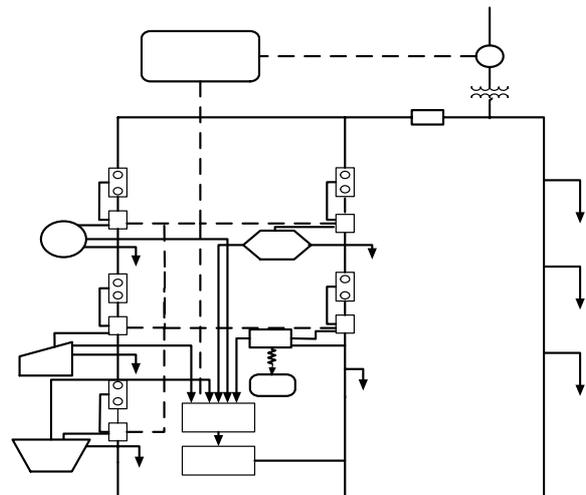

Fig. 1. MicroGrid Architecture

3. Optimization Model

The output is the optimal configuration of a MG that takes into account technical performance of supply options, locally available energy resources, demand characteristics, and system reliability.

To use the model, the following have to be defined:

1) *The power demand by the load.*
2) *Locally available energy information: This includes solar irradiation data (W/m^2), temperature (^oC), wind speed (m/s), as well as cost of fuels ($/liter) for the DG and natural gas price for supplying the FC and MT ($/kWh).*
3) *Daily purchased and sold power tariffs in ($/kWh).*
4) *Start-up costs in ($/h).*
5) *Technical and economic performance of supply options: These characteristics include, for example, rated power for PV, power curve for WT, fuel consumption characteristics DG and FC.*
6) *Operating and maintenance costs and the total emission: Operating and maintenance costs must be given ($/h) for DG, FC, and MT.*
7) *Emission level must be given in kg/h for DG, FC, and MT.*

4. Proposed Objective Function

The major concern in the design of an electrical system that utilizes MG sources is the accurate selection of output power that can economically satisfy the load demand, while minimizing the emission. Hence the system components are found subject to:

1) *Minimizing the operation cost ($/h).*
2) *Minimizing the emissions (kg/h).*

3) Ensuring that the load is served according to constraints.

A. Operating Cost

As in Figure (1), the main utility balances the difference between the load demand and the generated output power from the microsources. Therefore a cost has to be paid for the purchased power whenever the generated power is insufficient to cover the load demand. On the other hand there is an income because of sold power when the power generated is higher than the load demand but the price of the sold power is lower than the purchased power tariff. It is possible that there will be no sold power at all. Then the cost function in \$/h takes the form:

$$CF(\mathbf{P}) = \sum_{i=1}^{N} (C_i F_i(P_i) + OM_i(P_i) + STC_i + DCPE_i - IPSE_i) \qquad (1)$$

$CF(\mathbf{P})$ represents the operating costs in \$/h, C_i fuel costs of the generating unit i in \$/l for the DG, natural gas price for supplying the FC and MT (\$/kWh), $F_i(P_i)$ fuel consumption rate of a generator unit i, $OM_i(P_i)$ Operation and maintenance cost of the generating unit i in \$/h, P_i decision variables, representing the real power output from generating unit i in kW and defined as: $P_i = P_{FC}$ or P_{MT} or P_{DG}, $\mathbf{P}$ is the vector of the generators active power and is defined as: $\mathbf{P} = [P_1, P_2, ..., P_N]'$, N is the total number of generating units.

STC_i is the start-up costs of the unit generator i \$/h. The start-up cost in any given time interval can be represented by an exponential cost curve:

$$STC_i = \sigma_i + \delta_i \left[1 - \exp\left(\frac{-T_{off,i}}{\tau_i} \right) \right] \qquad (2)$$

The start-up cost depends on the time the unit has been off prior to a start up.

where, σ_i is the hot start-up cost, δ_i the cold start-up cost, τ_i the unit cooling time constant and $T_{off,i}$ is the time a unit has been off.

$DCPE_i$ is the daily purchased electricity of unit i if the load demand exceeds the generated power in \$/h. $IPSE_i$ is the daily income for sold electricity of unit i if the output generated power exceeds the load demand in \$/h. the expression for $DCPE_i$ and $IPSE_i$ can be written as [9]:

$$DCPE_i = C_p \times \max(P_L - P_i, 0)$$
$$IPSE_i = C_s \times \max(P_i - P_L, 0) \qquad (3)$$

where $DCPE_i$ is the daily purchased electricity of unit i if the load demand exceeds the generated power in \$/h. $IPSE_i$ is the daily income for sold electricity of unit i if the output generated power exceeds the load demand in \$/h. C_p and C_s are the tariffs of the purchased and sold power respectively in (\$/kWh).

System Constraints:

Power balance constraints: To meet the active power balance, an equality constraint is imposed

$$\sum_{i=1}^{N} P_i = P_L - P_{PV} - P_{WT} - P_{batt} \qquad (4)$$

Where $P_L = P_{L1} + P_{L2} + P_{L3}$.

Generation capacity constraints: For stable operation, real power output of each generator is restricted by lower and upper limits as follows:

$$P_i^{\min} \le P_i \le P_i^{\max} \quad \forall_i = 1, ..., N$$

where, $P_i^{\min}$ is the minimum operating power of unit i and $P_i^{\max}$ the maximum operating power of unit i.

Each generating unit has a minimum up/down time limit (MUT/MDT). Once the generating unit is switched on, it has to operate continuously for a certain minimum time before switching it off again. On the other hand, a certain stop time has to be terminated before starting the unit. The violation of such constraints can cause shortness in the life time of the unit. These constraints are formulated as continuous run/stop time constraints as follows [10].

$$(T_{t-1,i}^{on} - MUT_i)(u_{t-1,i} - u_{t,i}) \ge 0$$
$$(T_{t-1,i}^{off} - MDT_i)(u_{t,i} - u_{t-1,i}) \ge 0 \qquad (5)$$

$T_{t-1,i}^{off} / T_{t-1,i}^{on}$ represent the unit i off/on time, at time $t-1$, while $u_{t-1,i}$ denotes the unit off/on [0,1] status.

Finally the number of starts and stops ($\varepsilon_{start-stop}$) should not exceed a certain number ($N_{\max}$).

$$\varepsilon_{start-stop} \le N_{\max}$$

The operating and maintenance costs OM are assumed to be proportional with the produced energy, where the proportionally constant is K_{OM_i} for unit i.

$$OM = \sum_{i=1}^{N} K_{OM_i} P_i \qquad (6)$$

Emission Level

The atmospheric pollutants such as sulphur oxides SO_2, carbon oxides CO_2, and nitrogen oxides NOx caused by fossil-fueled thermal units can be modeled separately. The total kg/h emission of these pollutants can be expressed as [11]:

$$E(\mathbf{P}) = \sum_{i=1}^{N} 10^{-2}(\alpha_i + \beta_i P_i + \gamma_i P_i) + \zeta_i \exp(\lambda_i P_i) \qquad (7)$$

where α_i, β_i, γ_i, ζ_i, and λ_i are nonnegative coefficients of the ith generator emission characteristics.

For the emission model introduced in [4] and [11], the parameters α_i, β_i, γ_i, ζ_i, and λ_i are evaluated using the data available in [12]. Thus, the emission per day for the DG, FC, and MT is estimated, and the characteristics

of each generator will be detached accordingly.

5. Implementation of the Algorithm

The following items summarize the key characteristics of the proposed algorithm:
- Power output of WT is calculated according to power the relation between the wind speed and the output power.
- Power output of PV is calculated according to the effect of the temperature and the solar radiation that are different from the standard test condition.
- There will be income whenever the power from the wind and PV are greater than the load.
- WT and PV are assumed that they deliver free cost power in terms of running as well being emission free. Furthermore, their output power is treated as a negative load, determine the different between the actual load and WT and PV output power. If the output from PV and WT is greater than the load, the excess power is directed to charge the battery.
- The power from the battery is needed whenever the PV and WT are insufficient to serve the load. Meanwhile the charge and discharge of the battery is monitored.
- The net load is calculated if the output from PV and WT is smaller than the total load demand.
- Choose serving the load by other sources (FC or MT or DG) according to the objective functions.
- If the output power is not sufficient then purchase power from the main grid, and if the output power is more than the load demand, sell the exceed power to the main grid.

6. Multiobjective Optimization

Multiobjective optimization is a method to find the best solution between different, usually conflicting objectives. In the MO optimization problem we have a vector of objective functions. Each objective function is a function in the decision (variable) vector [13]. Mathematically the environmental/economic problem is formulated as follows:

Find the output generator power vector $P = [P_1, P_2, ..., P_N]^T$ that minimizes the function:

$$F(\mathbf{P}) = \{CF(P_i), E(P_i)\} \qquad (8)$$

Subject to
$$h_k(P_i) = 0 \qquad k = 1, ..., q$$
$$g_j(P_i) \le 0 \qquad j = 1, ..., p$$
$$P_i^{\min} \le P_i \le P_i^{\max}, \qquad \forall_i = 1, ..., N$$

where the number of the objective functions ≥ 2, and $F(\mathbf{P}): R^n \to R$. The vector of objective functions is denoted by $F(\mathbf{P}) = (F(P_1), F(P_2), ..., F(P_k))^T$. The decision variable vector $\mathbf{P} = (P_1, P_2, ..., P_N)^T$ consists of all design variables in the problem and may be bounded. The collection of the equality constraints, $H(P) = (h_1(P_1), h_2(P_2), ..., h_q(P_i))^T$, is an equality constraint vector, and similarly the inequality constraint vector, $G(P) = (g_1(P_1), g_2(P_2), ..., g_p(P_i))^T$ is less or equal to zero.

7. Results and Discussion

At first, the optimization model is applied to the load. The load demand varies from 4 kW to 14 kW. The available power from the PV and the WT are used first. The best results of the cost and emission functions, when optimized individually, are given in Table I. Convergence of operation cost and emission objectives for both approaches, when the purchased tariff is 0.12 $/kWh and the sold tariff 0.07 $/kWh, is as shown in Figure (2).
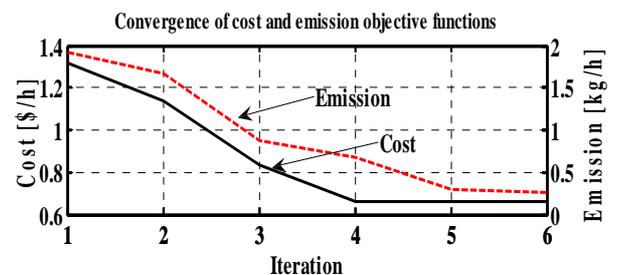

FIG. 2. Convergence of cost and emission objective functions.

TABLE I
THE OBJECTIVE FUNCTION WHEN OPTIMIZED INDIVIDUALLY .

	Total Load (kW/Day)	Total Emissions (kg/Da)y	Total Costs ($/Day)	Optimal Generation (kW/Day)	Sold Power (kW7Day)	Purchased Power (kW/Day)
Case 1	171.4009	149.9198	76.1973	241.9197	70.5188	14.8635
Case 2	171.4009	12.3885	124.6914	36.0860	00.0000	135.3149

Figure (3) illustrates the hourly operating costs and emissions. However, the costs and emissions are high when the generators are on and the load is high.
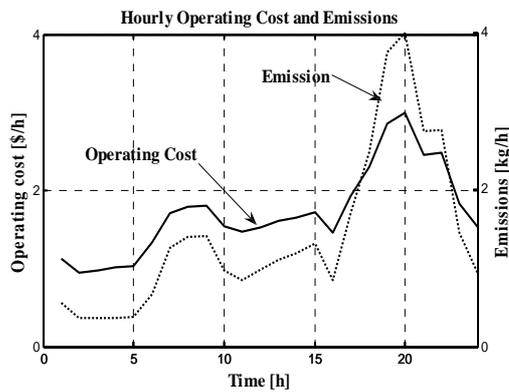
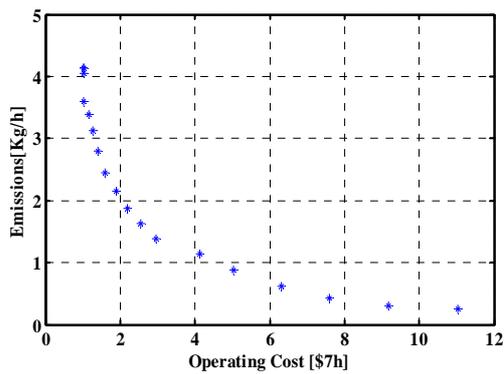**FIG. 3.** Convergence of cost and emission objective functions.

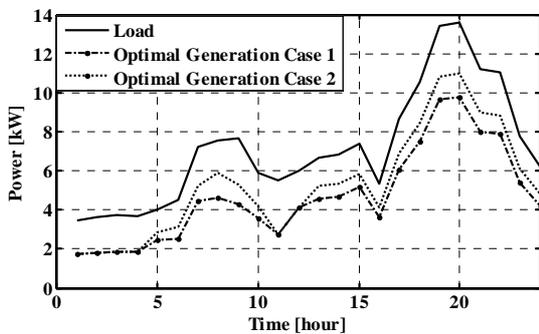**FIG. 4.** Trade- off in cost and emission.

FIG. 5. Effect of purchased power tariffs on the MG optimal operation.

Operational cost and emission objectives are optimized individually in order to explore the extreme points of the trade-off surface. The first case is when the cost objective function is optimized and the second when the emission objective function is optimized. The best results of cost and emission functions, when optimized individually, are given in Table I. Convergence of operation cost and emission objectives is shown in Fig. (3). Where faster. Figure (4) shows the relationship (trade-off curve) of the operating cost and emission objectives of the non-dominated solutions obtained for different purchased and sold tariffs. The operating costs of the non-dominated solutions thus appear to be inversely proportional to their emissions.

Table II and Figure (5) show the effect of changing the purchased and sold tariffs on the optimal setting of the MG. There are all together four cases.

In case 1, the effect of the changing the purchased tariffs is studied, when the sold power was 0.04 $/kWh and the purchased tariffs were 0.1 $/kWh, while in Case 2 the value of the purchased tariffs has increased to 0.16 $/kWh and the sold was the same as in Case 1. During changing the purchased tariffs values, it was noticed that when the tariffs were low, it was preferable to buy as much power from the main grid as possible. However, when the tariffs were higher, it was more economic to generate the required power from the MG.

In Cases 3 and 4, the purchase power tariff is kept constant at 0.12 $/kWh, while the sold tariffs was 0.0 $/kWh in case 3 and 0.04 $/kWh in case 4. It is noticeable that, the changing of the sold tariffs has no effect for such a small change. It only reacts if the change is much larger.

TABLE II
THE EFFECT OF THE PURCHASED AND SOLD TARIFFS ON THE OPTIMAL GENERATION .

	Total Load (kW/Day)	Optimal Generation (kW/Day)	Total Cost ($/Day)	Total Emission (kg/Day)
Case 1	171.4009	112.5081	58.5862	40.3235
Case 2	171.4009	127.1114	61.3490	49.4893
Case 3	171.4009	117.7365	60.4168	44.6083
Case 4	171.4009	117.7365	60.4168	44.6083

Table III illustrates the cost savings and emission reductions of the MG using different cases and compares them with the proposed technique. The results obtained using the proposed technique to minimize the total cost and total emissions is compared with some conventional strategies of settings. The first case is when the DG, FC, and MT operate at their rated power for the whole day (Case A). The second is to optimize the cost individually (Case B). The third scenario is to optimize the emissions objective function individually (Case C).

Case A gives higher operating cost and higher emissions which indicates that it is not relevant. The larger generating power, the larger costs and emissions are attained. In the Case B, the cost is relatively reduced, while the emissions were increased. In the third case, the cost increased while the emissions decreased and the optimal choice was to purchase more power from the main grid.

For achieving the completeness and checking the effectiveness of the proposed cost function and proposed solution, the problem was treated as single objective optimization problem by a linear combination of the cost and emission objectives as follows [11] (case D):

$$\underset{P}{Minimize} \quad \omega CF(P)+(1-\omega)\rho E(P) \qquad (9)$$

where ρ is the scaling factor and ω is the weighting factor.

In this study the weighting factor ω was selected to be varying randomly ω=rand[0,1] and ρ was

chosen equal to 3000.

With the proposed free power sale the total operating cost was reduced to 43.3754 \$/day and 34.0102 kg/day for the emissions after increasing the number of WT and PV, also switching off one of the load comparing to other settings.

TABLE III
COST SAVING AND EMISSIONS REDUCTIONS OF THE MG .

	Average Cost & Emission		Average difference with respect to the optimal case			
	Cost $/Day	Emissions kg/Day	Cost $/Day	Emissions kg/Day)	Cost %	Emissions %
Case A	95.3091	229.4892	51.9337	195.4793	119.7307%	574.7666%
Case B	86.6616	61.3615	25.2862	27.3513	58.2961%	80.42%
Case C	113.7293	13.0826	70.3539	-20.9276	162.1967%	-61.533%
Case D	53.5643	58.9397	4.1663	24.9295	23.49%	73.30%
MOSQP	49.3980	44.0851	6.0230	10.0749	13.88%	29.62%
Optimal setting	**43.3754**	**34.0102**	**00.0000**	**00.0000**	**00.0000%**	**00.0000%**

Table II confirms that the MO optimization technique has made reasonable selections. The selections were not so straightforward, because of the existing the start-stop time limit constraints which have a big effect on

4. Conclusion

A model to determine the optimum operation of a MG with respect to load demand and environmental requirement is presented. The optimization problem includes a variety of energy sources that are likely to be found in a microgrid: a fuel cell, a diesel engine, a microturbine, a PV arrays, a wind generators, and battery storage. Constraint functions are added to the optimization problem to reflect some of the additional considerations often found in a small-scale generation system. From the results obtained, it is clear that from the operating costs and emissions curves for the MG that the optimization works very well and can give the optimal power to the generators after taking into account the sold of the extra power produced by the free generation units and the operating cost and emissions objective functions for Mt, FC, and DG.

the performance of the algorithm. It can be seen that the load was served perfectly.

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