Optimization of Energy Systems in a Distribution Micro grid: An Application of the Particle Swarm Optimization

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ABSTRACT:
This article proposes a method for optimizing the energy systems in a distribution micro-grid using particle swarm optimization. The method considers the optimal production planning of simultaneous production systems and takes into account the loss of electric energy transmission resulting from the concurrent production systems to the grid bus. The article establishes the correlation between the development of optimal load distribution methodology systems and the supply of electrical or thermal load. The advantages of the proposed algorithm have been demonstrated through numerical studies and comparisons, which showed a reduction in operational expenses, carbon dioxide emissions, and fuel consumption during both summer and winter seasons. The proposed method is an effective way of providing the required electrical energy of the sub-grid with minimal compliance requirements. The implementation of the proposed method during a single day and night in the summer season results in significant reductions of 17.5%, 13%, and 1% in operational expenses, carbon dioxide emissions, and fuel consumption, respectively. In the winter season, the pre-charge method also results in reductions of 10%, 7%, and 2% in operating cost, carbon dioxide emissions, and fuel consumption, respectively.

KEYWORDS: Micro-grid; Optimization; Following the Electric Load; Following the Thermal Load.

1. INTRODUCTION

Persian Gulf energy supply and demand have been greatly affected by energy sanctions [1]–[3]. To ensure a sustainable and stable energy supply, these countries are studying new energy management and optimization approaches [4],[5]. Renewable energy, energy storage, and smart grid technologies are growing in popularity [6]. These technologies reduce dependence on existing energy sources and optimize energy usage and efficiency [7]. Demand response, energy audits, and energy efficiency can also reduce energy waste and improve energy system efficiency [8]. Persian Gulf countries can reduce energy sanctions and maintain a sustainable and stable energy supply by using these new and creative energy management and optimization approaches [9].

Micro-grids are small-scale electrical grids that can operate independently or in conjunction with the main grid [10]–[12]. The optimization of energy systems in micro-grids is a crucial factor in achieving efficient and cost-effective operation [11]. Particle Swarm Optimization (PSO) is a powerful optimization

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technique that has been successfully used in various optimization problems [13],[14]. Several studies have been carried out in the area of micro-grid optimization using different optimization techniques. In [15], a hybrid optimization technique was proposed for the optimal sizing and operation of a micro-grid. The study in [16] focused on the economic dispatch problem of a micro-grid using a hybrid PSO and genetic algorithm. Another study in [17] used a modified PSO algorithm for the optimal allocation of distributed generation units in a micro-grid. However, to the best of our knowledge, no previous study has used PSO to optimize the energy systems of a distribution micro-grid with no thermal connection between bus-bars.

In this article, PSO is applied to optimize the energy systems of a distribution micro-grid. The objective is to minimize the total cost of energy production while meeting the demand of the micro-grid. The proposed methodology consists of two stages. In the first stage, the optimal production planning of the micro-grid is determined using PSO. The cost function of each energy system is considered as the objective function to be minimized. In the second stage, the strategy for optimal utilization of simultaneous production systems is determined using the proposed algorithm. The algorithm is based on the universal performance criteria (UPC) and provides the electric energy of all the micro-grid buses.

The optimization of energy systems in micro-grids is a challenging task that requires the use of powerful optimization techniques [18]–[20]. In this article, PSO was applied to optimize the energy systems of a distribution micro-grid. The proposed methodology consists of two stages, where the optimal production planning of the micro-grid is determined in the first stage, and the strategy for optimal utilization of simultaneous production systems is determined in the second stage. The proposed algorithm is based on the universal performance criteria and provides a solution for the electric energy demand of all the microgrid buses. The results of the study show that PSO can successfully optimize the energy systems of a distribution microgrid and reduce the total cost of energy production.

2. SYSTEMS MODELLING

In this part, we describe the details of separate production systems and simultaneous production of electricity, heat and cooling.

2.1. Separate Production System

Fig. 1 illustrates the energy flow within a distinct production system that caters to the provision of electrical, heating, and cooling loads. The feasibility of utilizing an electric chiller to meet the cooling demands of the system is being evaluated, while the heat generated by the steam boiler is being harnessed to meet the heating requirements. The electric chiller and the consumer's electricity demands are met through the national electricity grid. Fig. 1 depicts the amount of electricity that is necessary for the network, which is referred to as E_{grid}. The variables E_{req} and E_c denote the electrical power demanded by the equipment and lighting, as well as the electrical power supplied to the electric chiller in the context of a distinct generation approach. Q_c and Q_h represent the cold output generated by the chiller and the heat output produced by the heating coil, respectively. The specialized gas boiler necessitates the utilization of F_{boiler} as its fuel source. The provision of heat is necessary.

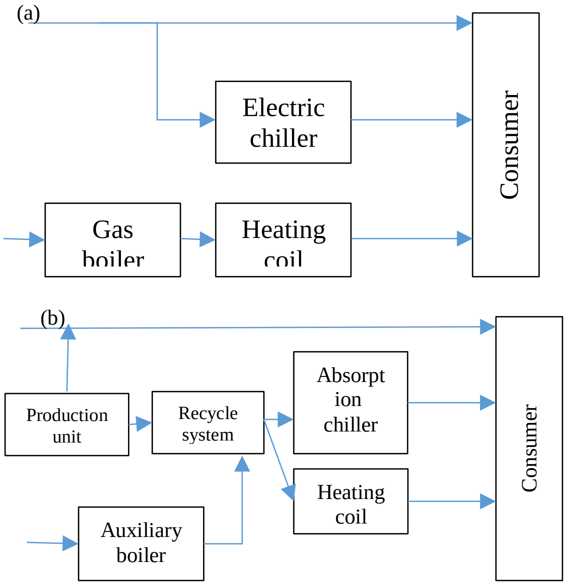

Fig. 1. a) Energy flow diagram in the usual way, b) energy flow diagram in the simultaneous production method.

2.2. Combined Cool, Heat, and Power Production System

The model of the simultaneous production system of electricity, heat and cooling is shown in Fig. 2. This simultaneous production system includes a gas turbine power generation unit, a heat recovery system, an auxiliary boiler, an absorption chiller and a heating coil.

2.3. Micro Grid Distribution

The micro-grid used in this article is a 9-bus distribution system, which is shown in Fig. 3. In the micro-grid, 3 simultaneous production systems of electricity, heat and cooling are set, which aim to optimize, optimal production planning and determine the optimal strategy. The vector of production systems is also time.

3. INVESTIGATION CRITERIA

Simultaneously considering multiple criteria is crucial for the functioning of production systems. The aforementioned criteria may be employed to ascertain the optimal course of action.

The calculation of initial energy consumption is derived from Eqs. 1 to 3 [21].

$$PEC_{SP} = F_{\text{boiler}}^{SP} K_f + E_{\text{grid}}^{SP} K_e \tag{1}$$

$$PEC_E = F_{m-E} K_f \tag{2}$$

$$PEC_T = E_{\text{grid}} K_e + F_{m-T} K_f \tag{3}$$

Where, the primary fuel consumption values for the cogeneration system in distinct production modes, namely separate production mode, FEL mode, and FTL mode, are represented by P_{ECE}, P_{ECSP}, and P_{ECT}, respectively. The provision of heat by a boiler requires the utilization of F_{boiler} as fuel, while the conversion of fuel into primary energy is determined by the conversion factor K_f. The variable E denotes the amount of electricity procured from the national grid for the purpose of meeting the requisite energy demand. Meanwhile, the variable K represents the conversion coefficient that facilitates the transformation of electricity into primary energy units. The total fuel required for the cogeneration system in FEL mode is F_{m-E}. The cogeneration system's fuel consumption in FTL mode and the electricity demand in the mode are denoted as F_{m-T} and E_{grid}, respectively. FTL can be procured from the network if deemed necessary.

The model for carbon dioxide emissions is derived from Eqs. 4 to 6 [22].

$$CDE_{SP} = F_{\text{boiler}}^{SP} \mu_f + E_{\text{grid}}^{SP} \mu_e \tag{4}$$

$$CDE_{FEL} = \left(F_{pgu} + F_{\text{boiler}}\right)\mu_f \tag{5}$$

$$CDE_{FTL} = E_{\text{grid}} \mu_e + F_{m-T}\mu_f \tag{6}$$

Where, the variables C_{DEE}, C_{DESP}, and C_{DET} represent the carbon dioxide emissions during the utilization of the production system in the separate production mode, the FEL mode, and the FTL mode, respectively. The production unit of the system requires F_{pgu} as its fuel source.

The operating cost model is defined by Eqs. 7 to 9.

$$\text{COST}_{SP} = F_{\text{boiler}}^{SP} C_f + F_{\text{boiler}}^{SP} \mu_f C_c + E_{grid}^{SP} C_e \tag{7}$$

$$\text{COST}\, T_E = F_{m-E} C_f + F_{m-E} \mu_f C_c \tag{8}$$

$$\begin{aligned}\text{COST}_T = E_{\text{grid}} C_e + F_{m-T} C_f + F_{m-T} \mu_f C_c \\ - E_{\text{excess}} C_s\end{aligned} \tag{9}$$

Where, the variables C_c, C_f, and C_e represent the costs of fuel, carbon dioxide emissions, and electricity within the relevant network. Additionally, COST_E, COST_{SP}, and COST_T correspond to the operating costs associated with distinct production modes, namely separate production, FEL mode, and FTL mode. The term E_{excess} refers to the surplus electricity generated by a cogeneration system that is utilized when the electricity is sold to the grid. The variable "Cs" represents the price at which the electricity is sold from the system to the grid. If the sale of electricity for the generation system is unfeasible within the examined network, the value of Cs is rendered as 0.

4. PLANNING AND STRATEGY

Following the development of a production plan that considers the contribution and participation of each system in total electricity production, while also accounting for losses, it has been determined that the most effective approach involves utilizing the cost function of systems (Eq. 10). The multi-criteria PSO algorithm is utilized to determine the strategy for utilizing each simultaneous production system, following the determination of the optimal contribution of production for each system. The Krone approach, which accounts for micro-grid losses, has been employed in order to achieve optimal production planning utilizing Landa's method. The coefficients denoted by B are commonly referred to as loss coefficients within academic discourse.

$$E_L = \sum_{i=1}^{n_g} \sum_{j=1}^{n_g} E_i B_{ij} E_j + \sum_{i=1}^{n_g} B_{.i} E_i + B \tag{10}$$

The optimization of production planning and power distribution in the micro-grid under consideration necessitates the establishment of a cost function that is contingent upon production, given the absence of heat transmission and sole reliance on electric transmission. It is important to take note of the production unit consumption that exceeds the E_{pgu}, can the FEL mode be deemed a viable utilization strategy. In other words, the FEL mode is only feasible when the grid generation systems solely cater to the electricity demand that surpasses the E_{pgu}, thereby enabling the replacement of E_{pgu} with E_{req}. In the event that the conditions of $E_{req}<K_{Qreq}$ are present within the simultaneous generation system during a particular hour, the FEL mode is employed. The optimal time for generation planning in a micro-grid is determined by the hour in which it occurs (Eq. 11). The replacement of E_{pgu} with E in the cost function and the determination of each system's contribution to the micro-grid's overall electricity provision can be achieved under these specified conditions, as expressed by Q_{req} (Eq. 12). The lack of heat transfer within this micro-grid is the likely cause. The E_{pgu} will be ascertained as the aggregate of each co-generation system, subsequent to the optimal load allocation of the entire electricity consumption within the micro-grid.

$$E_{req} < \frac{\eta_{pgu} Q_{req}}{\eta_{rec}(1-\eta_{pgu})} \tag{11}$$

$$\mathrm{COST}_{CCHP} = E_{pgu} \times \left(\frac{1}{\eta_{pgu}} - \frac{(1-\eta_{pgu})\eta_{\mathrm{rec}}}{\eta_{pgu}\eta_{\mathrm{boiler}}}\right) \times \left[C_f + \mu_f C_c\right] + \frac{Q_{\mathrm{req}}}{r\eta_{\mathrm{boiler}}} \times \left[C_f + \mu_f C_c\right] \tag{12}$$

The determination of the optimal exploitation strategy is based on the comprehensive performance criteria of each simultaneous production system, which is derived from the optimal production planning in the preceding stage. This determination is made in consideration of the new production of each system.

The comprehensive performance criterion, which incorporates the aforementioned criteria with assigned weighting coefficients, aims to minimize operational costs, carbon dioxide emissions, and primary energy consumption. The weight coefficients are distributed uniformly among the three criteria mentioned, utilizing the same weighting techniques commonly employed in various decision-making contexts (Eq. 13) [23].

$$UPC = W_{,} \frac{PEC_{CCHP}}{PEC_{SP}} + W_r \frac{CDE_{CCHP}}{CDE_{SP}} + W_r \frac{COST_{CCHP}}{COST_{SP}} \tag{13}$$

$$W_r + W_r + W_r = 1$$

The methodology employed to ascertain the most effective approach for concurrent production systems centers on evaluating the comprehensive performance criterion, as expressed in Eq. 14, across two FEL and FTL modes.

$$UPC_E - UPC_T = \frac{1}{r}\left(\frac{PEC_E - PEC_T}{PEC_{SP}} + \frac{CDE_E - CDE_T}{CDE_{SP}} + \frac{COST_E - \mathrm{COST_T}}{\mathrm{COST}_{SP}}\right) \tag{14}$$

By considering the relationship between the electricity generated by the simultaneous generation system and the heat recovery in the heat recovery unit in the form of Eq. 15, a K coefficient can be obtained, representing the ratio of electricity to heat in both FEL and FTL modes.

$$E_{pgu} = \frac{\eta_{pgu}}{\eta_{rec}(1-\eta_{pgu})} Q_R = KQ_R \tag{15}$$

Consequently, based on the aforementioned equation, the electrical output generated by the cogeneration system may exhibit a linear relationship with respect to the heat recovery process. If we consider the simultaneous production system that exhibits the highest efficiency ratio, the correlation between the electricity and heat consumed by the consumer can be expressed as Eq. 16.

$$E_{req} = \frac{\eta_{pgu}}{\eta_{rec}(1-\eta_{pgu})} Q_{req} = KQ_{rvq} \tag{16}$$

In this case, if the balance of electricity and heat demands collides, the mentioned conditions should be checked in two cases $E_{req}<KQ_{req}$ and $E_{req} \geq KQ_{req}$.

5. RESULTS AND DISCUSSION

This section has explored the parameters for achieving optimal utilization. To ensure efficient production planning, the load ratio condition specified in Eq. 11 is carefully evaluated for both systems. The outcomes of this analysis are presented in Fig. 2 for each respective system.

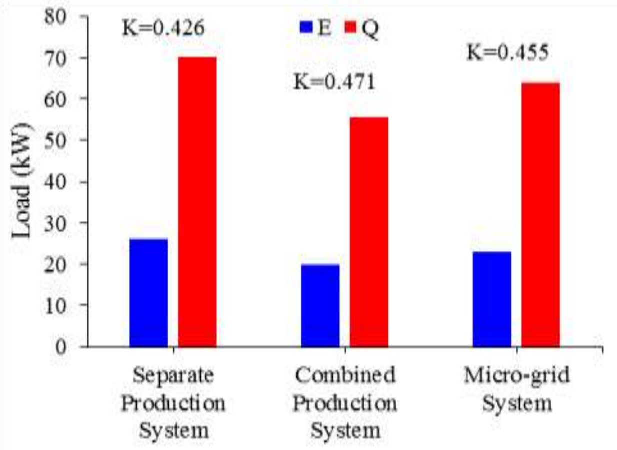

Fig. 2. Optimal planning parameters for simultaneous production.

The findings pertaining to optimal production planning, as depicted in Fig. 3, indicate that the quantity of electricity that the micro-grid system ought to generate is represented by the value of E_{pgu}. Through the identification of production values for each system and the establishment of a relationship between new production capacity and strategy determination algorithms, as outlined in Fig. 3, both the production value of each system component and the optimal strategy can be determined. According to the results, the optimal strategy for all three systems will be the FEL mode (Fig. 3-a). Fig. 23-b illustrates that micro-grid and combined system generate surplus heat despite the optimal implementation of the FEL strategy. This excess heat is ultimately wasted due to inadequate storage capacity. Incorporating storage into the modeling process results in a subsequent reduction in the criteria's value.

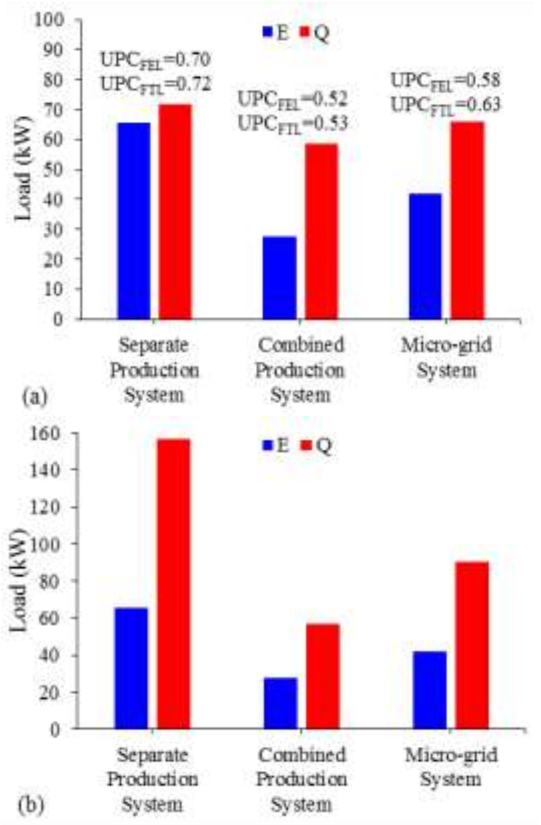

Fig. 3. The amount of a) new and b) optimal production of each of the components of the production system at the same time in one hour.

The study has conducted optimal production planning for a single day and night during both summer and winter seasons. The production rate of each system during these periods is presented in Fig. 3, and the simulation results are outlined in Table 1. Table 2 provides a comparison of the criteria levels between two modes of electricity generation: separate generation for each bus and simultaneous co-generation with optimal energy production planning for the entire grid system. The results indicate a significant reduction in inspection criteria when using the proposed method in the second case.

Table 1. The optimal production and losses of the systems in a day.

System	Load (kW)	
	Summer	Winter
Separate Production System	125.0	26.6
Combined Production System	251.3	207.1
Micro-grid System	226.3	130.3
Loss	21.0	10.9

The evaluated parameters exhibit a notable decrease in comparison to the parameters observed when energy is supplied individually and without the transmission of electric energy. Moreover, the computations of the aforementioned issue indicate that during the time intervals in which the magnitude of E_{req} approximates that of KQ_{req}, the diminution of the criteria's value is more pronounced. The proposed method offers an advantage in reducing the cost of operation, energy consumption, and emission of pollution for providing the load when the electrical and thermal load patterns are more similar to the mentioned ratio.

Table 2. The optimal production and losses of the systems in a day.

System	Summer		Winter	
	Ordinary	Optimal	Ordinary	Optimal
Operation cost ($)	105.8	87.2	95.5	85.7
CO_2 emission (kg)	996	867	1052	977
Fuel consumption (kWh)	3875	3827	4692	4583

6. CONCLUSION

This article presents a proposed method for optimal production planning of simultaneous production systems in a micro-grid, highlighting their importance. Additionally, the contribution of these systems towards providing the required electrical energy of the sub-grid is determined. Furthermore, the present planning takes into account the loss of electric energy transmission resulting from the concurrent production systems to the grid bus. The correlation between the development of optimal load distribution methodology systems and the supply of electrical or thermal load has been established. The interconnection facilitates the micro-grid in dispensing electrical power to all buses with minimal compliance requirements through the employment of concurrent generation systems. This article takes into account various criteria, including primary energy consumption, carbon dioxide emissions, and operating costs. The advantages of the presented algorithm have been demonstrated through numerical studies and comparisons. While, during a single day and night in the summer season, implementation of the pre-charge method results in a reduction of 17.5%, 13%, and 1% in operational expenses, carbon dioxide emissions, and fuel consumption, respectively. During the winter season, the percentages for operating cost, carbon dioxide emission, and fuel consumption are 10%, 7%, and 2%, respectively.

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