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Thermal energy storage has been becoming increasingly popular for peak-shifting to reduce energy consumption. It is also expected that sharing heat among several buildings in a district uses energy efficiently. However, optimization of energy systems at the district level poses a difficult problem due to the large number of decision variables compared to a single building with complex characteristics of heat sources. Therefore, an epsilon constrained differential evolution with random jumping algorithm (DE-RJ) has been proposed in this study to solve the problem directly without linearization. This method can rapidly resolve the issue while maintaining accuracy and obtain more efficient results than an empirical operation.

1. Introduction

In recent years, thermal energy storage (TES) has become increasingly popular for peak-cutting or peak-shifting. Internet of things (IoT) also attracted attention and it is expected to make optimal operation useful by gathering real-time data from numerous measurement points. Although nonlinear optimization of energy systems has been increasingly carried out, most research aims to deal with large scale optimization using a linear programming method. Therefore, we proposed metaheuristic optimization methods, which can optimize a problem consisting of nonlinear and iterative calculations to represent unsteady phenomena [1]. In this study, we expanded the method for a large scale optimization, representing a district heating and cooling system (DHC) and a heat-sharing network, which implies that all the buildings are able to share the cooling heat through TES.

2. Materials

2.1 Demand and electricity price profiles

The district chosen for this study consists of seven buildings, including: office 1; office 2; office 3; a commercial building 1; a commercial building 2; a hospital; and a hotel, as shown in Fig. 1. Calculations were based on a 24 h period in August and demand curves of each building were referred to [2]. We assumed a dynamic pricing system based on a merit order when electricity price was determined. Power plant data consisted of nuclear (market share: 20.4%, unit price: 10.3 yen/kWh), coal fired (26, 12.9), LNG fired (27, 13.4), oil fired (3, 41.7), hydroelectric (9.2, 11), solar (7, 15.6), wind (1.7, 21.5), biomass (4.6, 29.7), and geothermal (1.1, 16.8) [3].

2.2 Energy system

Two energy systems were modeled in order to assess district energy systems. Fig. 1 (a) indicates DHC system and (b) indicates the heat-sharing network. Both systems contain...
thermal energy storage to share cooling heat. For heat source machines, rated coefficient of performance (COP) of centrifugal refrigerator (CR) and air-source heat pump (AHP) were set to 6.0 and 4.0, respectively. Although these values were determined when outdoor temperature was 30°C and cooling water inlet temperature of CR was fixed to 32°C, COP varies in accordance with outdoor condition and water temperature. Rated cooling capacity is described in Fig 1 (b). The characteristics of heat source machines were referred to [4]. For TES, the storage capacity in DHC was set to 40,000 m³. In the heat-sharing network, we assumed two cases regarding rated capacity: no limited capacity and with rated capacity set to 100,000 m³. The maximum amount of charging and discharging heat was set to 30% of rated capacity.

2.3 Case study

In Case 1-1, an operation schedule represents an empirical model of the DHC system. TES conducted full-charge when price was low and full-discharge when price was high. For operating heat source machines, CR has high rated COP compared to AHP and was the priority mode of operation and allowed optimal operation as COP of TR demonstrated to be more efficient than AHP. Thus, this operation is suitable to evaluate the efficiency of the proposed method. In Case 1-2, operating schedules of all equipment were optimized using an epsilon constraint differential evolution with random jumping (εDE-RJ) detailed in Section 3-2. Case 1-3 aimed to minimize the maximum electricity consumption for peak-cutting. For optimization of heat-sharing networks, there are two case studies to minimize operating costs: Case 2-1 and Case 2-2. The capacity of TES did not be limited in Case 2-1, whereas the limit was set at 100,000 m³ in Case 2-2.

3. Optimization method

3.1 Mathematical formulation

In this study, the objective functions of Case 1-1, 1-2, 2-1, and 2-2 are formulated as follows:

\[
\min f = \sum_{t=1}^{TH} \left( \sum_{k}^{NCR} E_{CR,k} + \sum_{l}^{NAHP} E_{AHPl} \right)
\]

(1)

where, \( t \) indicates time interval (h), \( TH \) denotes time horizon (24h), \( N_{CR} \) is number of CR, \( N_{AHP} \) is number of AHP, \( E_{CR,k} \) indicates electricity consumption of \( k \)-th XX machine at time step \( t \), \( E_{AHPl} \) is formulated as follows:

\[
E_{CR,k} = E_{CR,k} + E_{FP,k} + E_{CTP,k} + E_{CT}
\]

(2)

\[
E_{AHPl} = E_{M,k} + E_{FP,k}
\]

(3)

where, \( E_{CR,k} \) denotes electricity consumption of \( k \)-th machine, \( E_{FP,k} \) is electricity consumption of the first pump (proportional to 10% of heat generation), \( E_{CT} \) indicates electricity consumption of the cooling tower pump, and \( E_{CT} \) denotes electricity consumption of the cooling tower. The objective function of Case 1-3 is as follows:

\[
\min f = \max \left( \sum_{k}^{NCR} E_{CR,k} + \sum_{l}^{NAHP} E_{AHPl} \right)
\]

(4)

The decision variables, \( R_i^l \in [0-Capacity] \), represent heat generation by each machine continuously. In Case 1, the number of decision variables was 144 (6 equipment \( \times \) 24 hours). In Case 2, this number was 576 (24 equipment \( \times \) 24 hours).

3.2 Epsilon constraint mutation differential evolution

εDE-RJ is combined with original εDE [5] and a random jumping method such as a mutation method of genetic algorithm to improve εDE. εDE and original DE use following equations to generate a donor vector \((\mathbf{v}_i^{\theta+1})\) and a new individual \((\mathbf{Newx}_i^{\theta+1})\) as follows:

\[
\mathbf{v}_i^{\theta+1} = x_p^g + M(x_q^g - x_r^g)
\]

(5)

\[
\mathbf{Newx}_i^{\theta+1} = \begin{cases} 
\mathbf{v}_i^{\theta+1} & \text{if } rand \leq C_r \\
\mathbf{x}_{ij}^g & \text{otherwise}
\end{cases}
\]

(6)

where, \( g \) is the current generation, \( i \), \( p \), \( q \), and \( r \) are individual numbers, \( M \) denotes mutation rate (=0.5), \( x_{ij}^g \) is \( j \)-th dimension of \( i \)-th individual at \( g \)-th generation. \( rand \) represents uniformly distributed random number \([0-1]\), and \( C_r \) is the crossover rate, which decreases exponentially from 0.5. Although this formulation can expand or shrink depending on the distance between individuals, there are possibility that an individual cannot move from a certain position. In order to solve this problem, when \( \mathbf{v}_i^{\theta+1} \) is zeros, we used \( rand \in [0-1] \) instead of \( \mathbf{v}_i^{\theta+1} \) in equation (6).
4. Results and discussion
4.1 DHC system
4.1.1 Case 1-1 (empirical operation)

Fig. 3 indicates an empirical operation of Case 1-1, where CR was operated on priority. The amount of charging heat was constant from 1 a.m. to 4 a.m. when electricity price was lowest. During daytime, particularly between 3 p.m. and 4 p.m. when the price was highest, full discharging operation, providing 12,000 kW, was carried out to reduce heat generation of the heat machine. Between 1 p.m. and 2 p.m. when the price was second highest, TES provided constantly 8,000 kW heat. When demand was low, between 1 a.m. and 8 a.m. and 8 p.m. to 12 p.m., CR1 and CR2 held enough energy to generate heat. There is one house when all AHP machines involved should generate heat simultaneously.

4.1.2 Case 1-2 (minimization of operating costs)

Fig. 4 indicates the result of an optimization using εDE-RJ. We set minimum load rate to 40% when operating the machine. In Fig. 4(a), between 1 a.m. and 8 a.m., CR worked at 60%–80%. Although COP of CR depends on cooling water temperature, the value was between 6.7–7.5 at that load rate range, as shown in Fig. 4(b). CR generated heat at efficient load rates despite COP variation. On the other hand, AHP generated heat during daytime at 40%-80% load rate, as shown in Fig. 4, demonstrating efficient load rates relative to itself. In terms of nonlinearity of machine characteristics, CR has a highly nonlinear configuration at range between 40%-100%. In addition, CR requires iterative calculation to represent cooling water temperature and this factor affects COP variation. Computation time is 80 secs using MATLAB R2016a with parallel computing toolbox on Windows 10 (64bit), CPU i7-3770 (eight thread used), RAM 8GB.

4.1.3 Case 1-3 (minimization of peak consumption)

Table 1 indicates results of Cases 1-1, 1-2, and 1-3. Although operating costs of Case 1-3 was highest, the peak electricity consumption of Case 1-3 was lower by 17.7% when compared to the other cases. Fig. 5 shows electricity consumption and operating costs of all cases at each time step. In Case 1-1 and Case 1-2, grey and blue bar sections depict a decrease from 1 p.m. to 4 p.m. when the electricity price was high as these cases aimed to minimize operating costs. For Case 1-3, electricity consumption during the daytime was constant at around 5,500 kW.

4.1.4 Summary of Case 1

εDE-RJ can derive a result lower than Case 1-1 in short computation time and suitable for both of minimizing operating costs and peak electricity consumption.
4.2 Heat sharing network

4.2.1 Case 2-1 (No limited capacity of TES)

To evaluate an ability of the proposed method with 576 decision variables, rated capacity of TES was primarily discounted. In Fig. 6(a), maximum stored heat rose to 16,000 kWh. Between 1 a.m. and 8 a.m., all buildings provided heat to TES, while all buildings except for the hotel required heat from TES during daytime. As seen in Fig. 7, between 9 a.m. to 4 p.m., all heat source machines generated heat and provided excessive heat to TES. Notably, not all machines were functioning while electricity price was highest, between 3 p.m. and 4 p.m.

4.2.2 Case 2-2 (Limited capacity of TES)

The same operation pattern as Case 2-1 can be found in Fig. 6(b). The hotel and hospital that had some demand during night obtained heat from the other buildings. Office 3 provided a great deal of heat to the hotel and hospital because it had three CRs with large capacity.

4.2.3 Summary of Case 2

Fig. 8 indicates total amount of input and output heat of each building. The output heat from Office 3 and Commercial 2, which had several CRs, was greater than the input heat. On the other hand, the total input heat of the hotel and hospital were greater than output heat because these buildings received heat from TES at night.

5. Conclusion

In this study, we proposed a new method (DE-RJ) to rapidly solve problems relating to nonlinear and iterative calculations. The proposed method could resolve large scale problems for current models of DHC systems and heat-sharing networks that require complex calculation. Future work should also consider piping flow connection and heat loss that occurs during transport of heat in order to represent a more realistic district model.

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References