ANALYSIS AND APPLICATION OF BUILDING HEATING AND THERMAL ENERGY MANAGEMENT SYSTEM

by

Zhinong LIAO *

School of Economics and Management, Jiangxi University of Science and Technology, Jiangxi, Ganzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI191212125L

Objective: Through the analysis and application of building heating and thermal energy management system, this paper proposes a new thermal energy control strategy to improve the automation level of building heating optimization. Method: This study analyzes the principle of indoor heat balance in buildings. Aiming at the different heating needs of different buildings, a new control strategy is proposed by combining neural network models and fuzzy control theory. Finally, this strategy is applied to the actual building heating, and the practical application value of the strategy proposed by this study is verified through experiments. Result: In the heating stage, after applying the control strategy, the maximum relative error of the temperature is 0.047, and the average error is 0.013. In the antifreeze stage, the maximum error is 0.143 and the average error is 0.09. After the implementation of the control strategy, the temperature fluctuations in the room change little and remain almost between 19 °C and 21 °C. Buildings consume less heat with the highest energy saving rate of 14.37% and the average energy saving rate of 9.23%. Conclusion: The control strategy proposed in this study can adjust the indoor temperature according to the actual situation and achieve the purpose of reasonable heat use. Moreover, it has certain energy-saving effects and can be applied to building heating.

Key words: *heating, thermal energy, building, neural network, fuzzy control*

Introduction

Energy is the basis for the development of productivity and the improvement of human living standards. The sustainable use of energy is significant to the survival and development of human society. The energy issue has become an important subject of worldwide attention [1, 2]. The 12th Five-Year Plan states that the main goal of resource conservation and environmental protection in the next five years is to reduce energy consumption per unit of GDP by 16% and reduce carbon dioxide emissions by 17% per unit of GDP [3]. Therefore, the shortage of energy makes people realize the importance of energy saving. Energy saving is the key to achieving sustainable development of the energy economy, but it is not easy to answer what energy saving is. The First law of thermodynamics, which only considers the energy balance of the system, cannot answer this question. If it is considered from the whole life cycle, the energy consumption of buildings accounts for more than one-third of the total energy consumption of the whole society. The building energy saving has become an important influencing factor for achieving the national *energy saving and emission reducing* goals.

* Author's e-mail: 29228395@qq.com

The energy consumption of building heating accounts for about 60% of the energy consumption of the entire building system [4, 5]. The current heat consumption per unit area in China is still high. It is three times higher than some developed countries in similar climatic conditions. The energy consumption of building heating accounts for more than half of the energy consumption of buildings. Therefore, the waste of energy consumption for building heating is the most serious, and the potential for saving is also relatively large. There are two main reasons for this. The first is the poor insulation performance of the building envelope. The second is the lack of reasonable means of indoor regulation. At present, most users have not installed a device for regulating the room temperature. When the room temperature is too high, windows are opened for heat dissipation with seriously wasting heat [6-8].

This paper proposes a new thermal energy management control strategy based on the disadvantages of traditional building heating and the principle of indoor thermal balance in buildings. The neural network and fuzzy control are combined and applied to actual building heating. It has a good adjustment and improvement effect for indoor temperature. It cannot only provide users with a comfortable heating experience but also effectively prevent excessive heat loss. And it has a superior energy-saving optimization effect, which brings certain benefits to the actual building heating.

Methodology

Indoor thermal balance in buildings

In general, the indoor air temperature is mainly used to measure the main indicators of the indoor thermal environment [9, 10]. The equation used is the heat balance equation for indoor air. In this equation, many factors affecting the heat balance are designed, such as radiation, convection, and conduction. In the process of heating, it will be affected by various disturbance factors, such as indoor heating equipment, refrigeration equipment, other lighting equipment, and furniture. In addition, there are also some outdoor factors, such as solar radiation, temperature and wind speed. In the end, all the heat that enters the room under the interference of various disturbance factors is called heat gain, and the heat loss is the total heat emitted from the room to the outside [11, 12]. Due to factors such as artificial window opening and ventilation, a small part of the heat will be consumed. Therefore, the heat obtained by solar radiation will no longer be calculated separately. The equilibrium equation for the temperature stability of a continuous heating room at any time:

$$\begin{gathered}[(1+x_g)\sum a_i K_i F(1+x_{ch}+x_f)+0.278 G_n C_p \rho_n \\ [tin(\tau)-tout(\tau)]\mathrm{d}\tau + I\mathrm{d}\tau = HGn(\tau)\mathrm{d}\tau + Q(\tau)\mathrm{d}\tau\end{gathered} \tag{1}$$

where x_g [%] is the additional factor for room height. The value range of this study is set from 0-15% and a_i represents the correction coefficient of temperature difference, F_i – the building envelope area, K_i – the heat transfer coefficient, $tout(\tau)$ – the outdoor temperature at the time τ, $tin(\tau)$ – the indoor temperature at the time τ, x_f – the additional factor for wind force, x_{ch} – the orientation correction percent, G_n – the specific heat at constant pressure, C_p – the total cold air volume penetrated by the room, ρ_n – the air density, $HG_n(\tau)$ – the internal disturbance heat dissipation, and $Q(\tau)$ – the heat from heating facilities. I represents the indoor unit heat capacity.

Indoor temperature cooling design

When the heating state is intermittent heating, once the valve is closed, the heating system stops heating the building. However, the high temperature medium in the room will continue to dissipate heat, and the thermal energy will enter the outdoor. At this time, the balance equation will change:

$$[(1+x_g)\sum a_i K_i F(1+x_{ch}+x_f)+0.278 G_n C_p \rho_n \\ [tin(\tau)-tout(\tau)]\mathrm{d}\tau = HGn(\tau)\mathrm{d}\tau - I\mathrm{d}\tau - I_s\mathrm{d}\tau \tag{2}$$

Assuming:

$$A=[(1+x_g)\sum a_i K_i F(1+x_{ch}+x_f)+0.278 G_n C_p \rho_n \tag{3}$$

Equation (3) represents the heat transfer per unit temperature difference. Thus, it can-be further simplified:

$$\mathrm{A}[tin(\tau)-tout(\tau)]\mathrm{d}\tau + I\mathrm{d}\tau = HGn(\tau)\mathrm{d}\tau + Q(\tau)\mathrm{d}\tau \tag{4}$$

where I_s is the heat capacity of heating facilities. When the valve is closed for a period of time, the hot water from the radiator heating package will begin to radiate heat into the room.

Outdoor temperature cooling design

When the heating system stops working, the building heating balance equation is shown:

$$[\theta(\tau)-HGn/A]\mathrm{d}\tau = -[I+I_s)/A]\mathrm{d}\theta \tag{5}$$

where the calculation of $\theta(\tau)$ is shown:

$$\theta(\tau) = tin(\tau)-tout(\tau) \tag{6}$$

The closing time of the valve is assumed to be τ_0, then the indoor temperature at this time is *tin*0. The aforementioned equation can be further simplified:

$$\int_{\theta_0}^{\theta} \frac{1}{\theta(\tau)-\dfrac{HGn}{A}}\mathrm{d}\theta = \int_{\tau_0}^{\tau} -\frac{A}{I+I_s}\mathrm{d}\tau \tag{7}$$

$$\int_{\theta_k}^{\theta} \frac{1}{\dfrac{HGn+Q}{I}-\dfrac{\theta}{T}}\mathrm{d}\theta = \int_{\tau_k}^{\tau} \mathrm{d}\tau \tag{8}$$

The equation for calculating its integral:

$$\theta(\tau) = \left(\theta_0 - \frac{HGn}{A}\right)\exp\left[-\frac{A}{I+I_s}(\tau-\tau_0)\right]+\frac{HGn}{A} \tag{9}$$

where $(HGn)/A$ is the reduction of indoor temperature against the heat obtained by indoor disturbance. Assuming temperature $T = (I + I_s)$ /A [S] is the ratio of total indoor heat to heat transfer per unit temperature difference. In this study, this ratio is called the indoor heat reserve coefficient. From the previous equation, when the valve is closed, the indoor air temperature will begin to decline with a negative exponential state. The rate of decline will also be different, and it will be affected by the indoor heat reserve coefficient and indoor factors. The indoor heat capacity will affect the T value. If the performance of the building envelope is worse, the smaller the internal heat capacity, the faster the room temperature decreases.

If the valve is opened, the heat balance equation in the room:

$$A\theta(\tau)\mathrm{d}\tau + I\mathrm{d}\theta = HGn(\tau)\mathrm{d}\tau + Q(\tau)\mathrm{d}\tau \tag{10}$$

After considering the indoor interference factors as fixed constants in this study, the balance equation can be further simplified:

$$\frac{\mathrm{d}\theta}{\mathrm{d}\tau}+\frac{A\theta}{I}=\frac{HGn+Q}{I} \tag{11}$$

Assuming the moment when the valve opens and the room temperature are τ_k and tink, the balance equation can be further transformed:

$$\int_{\theta_k}^{\theta}\frac{1}{\dfrac{HGn+Q}{I}-\dfrac{\theta}{T}}\mathrm{d}\theta=\int_{\tau_k}^{\tau}\mathrm{d}\tau \tag{12}$$

The equation for calculating its integral:

$$\theta=\left(\theta_k-\frac{HGn+Q}{A}\right)\exp\left[\frac{\tau_\mathrm{k}-\tau}{T}\right]+\frac{HGn+Q}{A} \tag{13}$$

The value of θ_k – $[(HGn + Q)/A]$ is less than 0. Thus, after opening the valve, the indoor temperature will gradually increase in an exponential pattern, which is contrary to the law of the cooling process. The cooling process is mainly to transfer heat to the outside, and it will go through convection, heat conduction and radiation in the process. But the way the indoor temperature rises is mainly convection. When the temperature rises to a certain degree, the temperature and heat will be gradually stored in some indoor furniture. As shown below, it is a diagram of the change process of the indoor temperature of the building.

Neural network model design

In this study, a model is established to accurately predict the indoor temperature. Control measures can be implemented in a timely and accurate manner, and room temperature needs to be predicted and controlled. The phenomenon of indoor overcooling and overheating should be avoided as far as possible to improve the heating quality. Therefore, the design of neural networks is launched in this study. In general, a back propagation (BP) neural network model includes at least an *S*-type hidden layer and a linear output layer. Because of these two functional layers, the rational function can be further approximated. To achieve a balance between the number of hidden layers and the training time, this study uses a three-layer neural network structure. At present, the specific number of hidden layer neurons has not been determined. This study uses eq. (14) to calculate the number:

$$n_1=\sqrt{(n+m)}+a \tag{14}$$

where m represents the number of output neurons, n – the number of input neurons, and a – the constant with the value ranges from 1-10. After a series of reasoning calculations, this study finally determines that the number of hidden layer neurons is 7, with the learning rate of 0.03, and the expectation error of 0.0004.

Neural networks usually use gradient descent method to train the algorithm. The main meaning of the gradient descent method is to calculate the gradient of the performance function, and adjust the connected thresholds and weights. The adjustment direction of the path is opposite to the gradient of the error function. By adjusting it, the value is converged to the minimum point. The calculation equation:

$$x(k+1)=x(k)-ag(k) \tag{15}$$

where x is the number of iterations, $x(k)$ – the current weight and error, $x(k + 1)$ – the next weight and error generated by the iteration, and a – the learning rate, which is a constant.

The radial basis function (RBF) neural network model can be divided into two learning stages, namely the unsupervised learning stage and the supervised learning stage. In the unsupervised learning stage, the node base width σ_i and the node's center c_i will have a great influence on the parameters of the Gaussian function. In the supervised learning stage, the weights between the output layer and the hidden layer can be calculated by applying a linear optimization algorithm. These parameters mainly include expansion constants, data centers, and output weights. The equation of the objective function:

$$E = \frac{1}{2}\sum_{j=1}^{N} e_j^2 = \frac{1}{2}\sum_{j=1}^{N}\left[y_j - \sum_{i=1}^{k} w_i \varphi_i(x_i) \right]^2 \tag{16}$$

where w is the weight of connected neurons.

The calculation of the center vector:

$$\nabla c_i = \frac{2w_i}{\sigma_i^2}\varphi(x_i)(x - c_i) \tag{17}$$

The correction equations can be further obtained:

$$c_i(n+1) = c_i(n) - \eta_1 \frac{2w}{\sigma_i^2}\sum_{j=1}^{N} e_j \varphi_i(x_j)(x_j - c_i) \tag{18}$$

$$\sigma_i(n+1) = \sigma_i(n) - \eta_2 \frac{w_i}{\sigma_i^3}\sum_{j=1}^{N} e_j \varphi_i(x_i)\left\| x_j - c_i \right\| \tag{19}$$

$$w_i(n+1) = w_i(n) - \frac{1}{2}\eta_3 \sum_{j=1}^{N} e_j \varphi_j(x_j) \tag{20}$$

where η_1, η_2, and η_3, respectively, represent the learning rate, and these rates are different. The $\varphi_i(x_j)$represents the input of hidden node i to x_j. The neural network improves the performance of the algorithm by applying the gradient descent method, which can automatically update the center position of the hidden layer processing unit. However, it also makes the network complicated and the training time will be extended. The neural network model is shown in fig. 1.

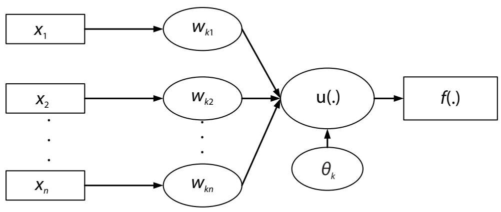

Figure 1. Neural network model

Thermal energy control based on fuzzy control theory

First, the input and output variables need to be determined. Then, the universe, quantification parameters, and membership functions are determined. After that, the fuzzification and the establishment of fuzzy control rules are carried out. Finally, the most important step is to perform defuzzification.

Fuzzification is the process of mapping the change range to the corresponding domain and converting the input data in the domain into corresponding linguistic variables to form a fuzzy set. It is to convert the related quantity of the control object into electricity through the sensor. If the output is a continuous analog, it is necessary to use the A/D converter to convert it into a digital quantity as the input measurement value of the computer, and this measurement value is standardized. In this way, the precise input quantity is converted into the value of a fuzzy variable represented by a membership function. Then, it is assumed that A and B are fuzzy sets on the universe:

$$A = \{a_1, a_2, ..., a_m\} \tag{21}$$

$$B = \{b_1, b_2, ..., b_m\} \tag{22}$$

If the union of A and B is $A \cup B$ and the intersection is $A \cap B$, the complement of A is $\overline{A}$:

$$\mu_{(A \cup B)}(x) = \max[\mu_{\mathrm{A}}(x), \mu_B(x)], \forall x \in U \tag{23}$$

$$\mu_{(A \cup B)}(x) = \min[\mu_{\mathrm{A}}(x), \mu_B(x)], \forall x \in U \tag{24}$$

$$\mu_{(\overline{A})}(x) = 1 - \mu_{(A)}(x), \ \ \forall x \in U \tag{25}$$

After this, the steps of inferring the fuzzy control rule by using the detected input quantity as a condition in the fuzzy control rule can be completed. Among them, the module that can accomplish the purpose is called a state interface or a fuzzed interface. The most important thing in the operation is to convert the accurate quantity of the input into the fuzzy quantity. The input quantity mainly includes the input of the external system and the output of the system.

The design process of the fuzzy controller is shown in fig. 2.

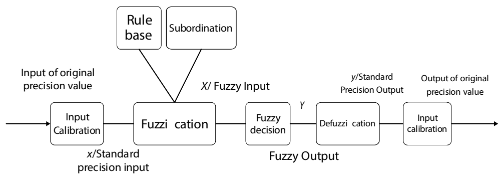

Figure 2. The general structure of a fuzzy controller

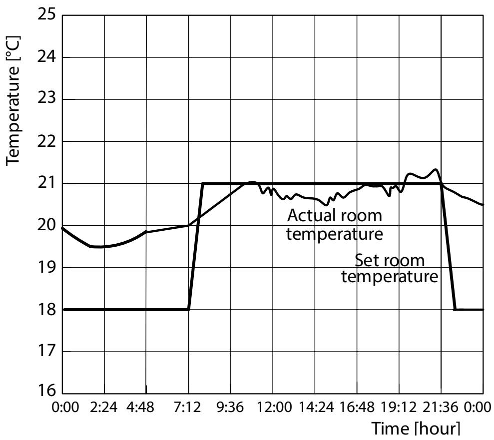

Figure 3. The indoor temperature on January 3

Result

This study uses an office building as an example. It is setting the heating time of the office building to 8 o'clock and the antifreeze time to 22 o'clock. Heating starts 4 hours ago and stops 2 hours in advance. During the heating period, the temperature is 21 °C, and during the antifreeze time, the temperature is 18 °C. According to the fig. 3, the minimum outdoor temperature is –3.6 °C and the highest is 5.7 °C on January 3. After calculation, it is found that the average temperature is –1.2 °C. By controlling the valve, it is found that the indoor temperature also starts to change, but it is a relatively comfortable temperature. During the period from 3 a. m. to 8 a. m., the building is still in the preheating stage with the large difference between the indoor temperature and the set value. When the valve is always in the open stage, the indoor temperature continues to rise. But when the valve is closed to keep it unchanged, the indoor temperature changes from heating to antifreeze. Because the building has a certain heat storage capacity, its temperature decreases relatively slowly.

According to the fig. 4, on December 21, the outdoor temperature changes are in a similar situation. The minimum outdoor temperature is –3.4 °C and the highest is 4.5 °C. After calculation, the average temperature is –1.6 °C, and no valve control operation is performed this time. Therefore, the indoor temperature is high. Even in the absence of people at night, the indoor temperature still exceeds 20 °C. At noon, the indoor temperature is also high, which can even reach 23 °C. It will cause the loss and waste of heat resources.

The heating temperature control on January 3 and December 21 is shown in fig. 5. From the figure, in the heating stage, after applying the control strategy, the maximum relative error of the temperature is 0.047, and the average error is 0.013. In the antifreeze stage, comparing actual measured value and set value of room temperature, the maximum error is 0.143 and the average error is 0.09. By comparing the error values before and after the control, the control strategy proposed in this study can reduce the set value and the actual value with the relatively superior follow degree.

To further verify the superiority of the control strategy proposed in this study, this paper further analyzes and compares the change curve of the building temperature before and after the control. From the fig. 6, before the implementation of the control strategy, the temperature is relatively high regardless of whether the room is in the heating period or the antifreeze stage. Even at the antifreeze stage, the temperature still exceeds 20 °C. However, after the implementation of the control strategy, the temperature fluctuations in the room change little and remain almost between 19 °C and 21 °C. According to user feedback, the temperature after the control is very suitable and has good comfort. Even at the antifreeze stage at night, the temperature drop is small, and it can drop to 19 °C.

To verify the superiority of the control strategy in terms of energy saving, this study chooses a similar office building with similar heat consumption as a reference. This office building does not implement a control strategy, and the heat consumption of this office building is regarded as the original heat consumption. The time is from January 1 to January 10, and the heat consumption of the building before and after the control is compared. According to the

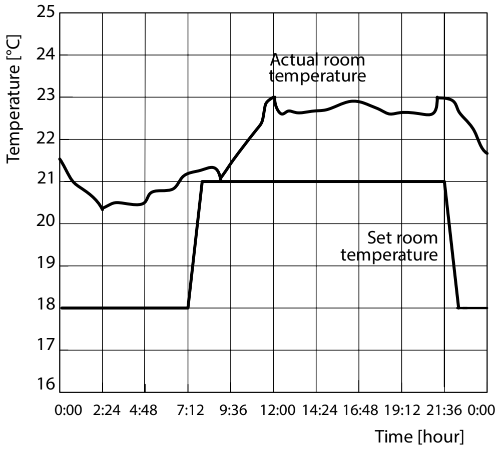

Figure 4. The indoor temperature on December 21

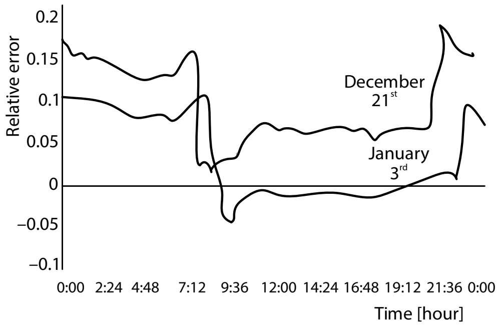

Figure 5. Error curve of indoor temperature measurement value and set value on January 3 and December 21

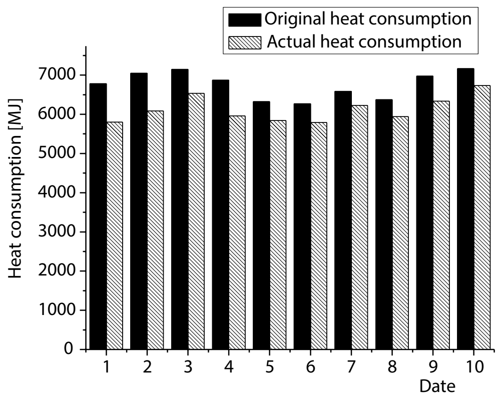

Figure 6. Comparison of original and actual heat consumption

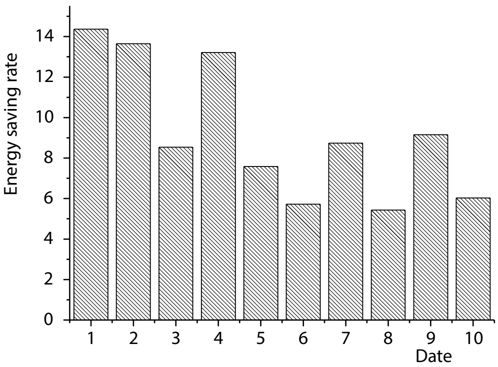

Figure 7. Energy saving rate of building heating

fig. 7, after control, the heating consumption of the building is less. Among them, the highest energy saving rate is 14.37% and the average energy saving rate is 9.23%. It proves that the control strategy proposed in this study has a good energy-saving effect.

Discussion

This paper analyzes the thermal balance theory of building heating, applies the neural network to the prediction of indoor temperature, and establishes a neural network model. It mainly includes BP and RBF neural networks. Then, the fuzzy control algorithm is applied to the predictive model, and a new thermal energy control strategy is proposed by combining the fuzzy control network and neural network. In this study, the experiment is performed to apply the control strategy to actual building heating. It is found that this control strategy has good stability and can provide different heating adjustments according to the characteristics of different heating stages. The thermal energy management system of the building is controlled to meet the heating needs of people and provide them with a comfortable heating experience. Also, it has a good effect on energy saving. In the experimental results, the heat consumption of the building after applying the control strategy is significantly reduced. Its maximum energy saving rate can reach 14.37%, and the average energy saving rate can reach 9.23%. It has a very good effect on the optimization of building heating and the value of social resources.

Conclusion

This study proves the effectiveness and superiority of the strategy proposed in this paper. Applying it to building heating cannot only meet the heating needs of users, provide them with high-quality heating services, but also reduce heat loss and promote the realization of energy saving. However, when designing the neural network model in this study, it does not apply a large number of samples to train it. In future research, representative samples should be selected for training, and the thermal energy management control strategy should be applied to different types of building heating.

References

[1] Aniruddha, Uniyal, P. N., *et al*., Image Processing and GIS Techniques Applied to High Resolution Satellite Data for Lineament Mapping of Thermal Power Plant Site in Allahabad District, U. P. India, *Geocarto International*, *31* (2016), 9, pp. 956-965
[2] Fang, G., *et al*., Analysis on the Optimum Matching of Collector and Storage Size of Solar Water Heating Systems in Building Space Heating Applications, *Building Simulation*, *11* (2018), 3, pp. 1-12
[3] Shaofei, W., Construction of Visual 3-D Fabric Reinforced Composite Thermal Performance Prediction System, *Thermal Science*, *23* (2019), 5, pp. 2857-2865
[4] Wang, Y., Li, B., Analysis and Experiment on Thermal Insulation Performance of Outer Building Envelope for Closed Layer House in Winter, *Non-Gye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, *33* (2017), 33, pp. 190-196
[5] Jun, W., *et al*., Cell-Like Fuzzy P System and Its Application in Energy Management of Micro-Grid, *Journal of Computational and Theoretical Nanoscience*, *13* (2016), 3, pp. 3643-3651
[6] Li, Y., *et al*., Energy Consumption Analysis of Building with Typical External Thermal Insulation System, *Materials Science Forum*, *898* (2017), June, pp. 1970-1977

[7] Yanlei, X., *et al*., A New Method of Computer Image Processing and Detection Based on AHP Analysis, *Journal of Computational and Theoretical Nanoscience*, *13* (2016), 7, pp. 4368-4372
[8] Morteza, D. J., *et al*., Effective Scheduling of Reconfigurable Microgrids With Dynamic Thermal Line Rating, *IEEE Transactions on Industrial Electronics, 66* (2018), 2, pp. 1552-1564
[9] Yang, H., *et al.*, Thermal and Energy Performance Assessment of Extensive Green Roof in Summer: A Case Study of a Lightweight Building in Shanghai, *Energy and Buildings*, *127* (2016), Sept., pp. 762-773
[10] Allouhi, A., *et al.*, Design Optimization of a Multi-Temperature Solar Thermal Heating System for an Industrial Process, *Applied Energy, 206* (2017), Nov., pp. 382-392
[11] Shaofei, W., A Traffic Motion Object Extraction Algorithm, *International Journal of Bifurcation and Chaos*, *25* (2015), 14, 1540039
[12] Lei, Z., Xie, H., Active Regulation of Battery Charge-Sustaining in ECMS: Application in Energy Management for Engine Waste Heat Recovery System, *International Journal of Automotive Technology*, *17* (2016), 6, pp. 1055-1065

Paper submitted: December 12, 2019
Paper revised: January 18, 2020
Paper accepted: February 4, 2020

© 2020 Society of Thermal Engineers of Serbia
Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.
This is an open access article distributed under the CC BY-NC-ND 4.0 terms and conditions