Verification Method for Energy Saving of Water Chiller

Yung-Chung Chang[*1], Chai-Chee Kong[†1], Chien-Yi Chen[‡1], Jyun-Ting Lu[§1] and Tien- Shun Chan[¶1]

[1] Department of Air-Conditioning and Refrigeration, National Taipei University of Technology, Taiwan, ROC

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Abstract

This study used linear regression analysis, neural network and genetic neural network to build the coefficient of performance (COP) model of chiller before the condenser was cleaned respectively. The data were collected after the condenser was cleaned. The model was used to simulate the COP before the condenser was cleaned, and analyzed and compared the simulation results and improvement efficiency of the three methods under the same benchmark. The neural network used backpropagation network, whereas the genetic neural network designed appropriate fitness function according to the simulation result of backpropagation network to search for the optimum weighted value and bias value. This study used two cases for simulation comparison. The results showed that the COP of chiller of Case 1 increased by 3.82% in average, and the COP of chiller of Case 2 increased by 3.78% on average. Generally speaking, the accuracy of simulation by neural network was very high. The genetic neural network searched for the optimum weighted value and bias value according to the designed conditions, so as to achieve the optimized simulation result.

keywords : coefficient of performance (COP) , linear regression analysis, backpropagation network, genetic neural network.

[*]ycchang@ntut.edu.tw
[†]chai_qi@hotmail.com
[‡]sug2chen@gmail.com
[§]rasheed0701@hotmaill.com
[¶]james@ntuh.gov.tw

1 Introduction

With rapid development of high-tech industry in Taiwan, numerous commercial buildings have been constructed, resulting in the increased use of air-conditioning systems, whether for industrial or residential use. It is estimated that the air conditioning power consumption in Taiwan during summer is equivalent to Commercial Buildings, in terms of the proportions of annual power consumption of major energy consuming equipments, the air conditioning accounts for 44.5%, the lighting accounts for 24.6%, and other equipments account for 30.9%, as shown in Figure 1 [1]. The chiller is the core of central air conditioning system, its power consumption accounts for about 60% of the power consumption of central air conditioning system. Therefore, increasing the energy utilization efficiency of chiller will be considerably beneficial to improve the energy saving of central air conditioning system and reducing the power consumption [2].

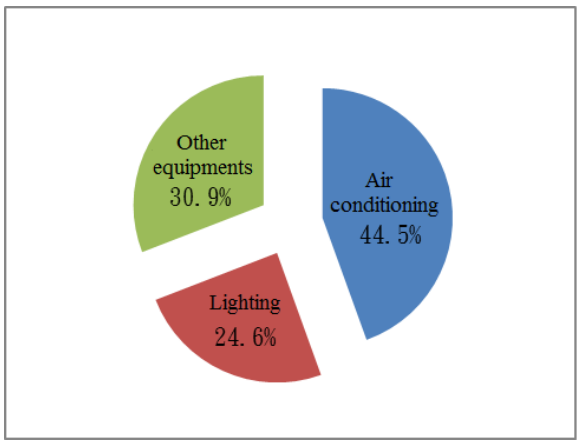

Figure 1 Proportions of annual power consumption of major energy-consuming equipments [1]

There are many methods for energy saving of air conditioning system. This study simulates the COP of chiller of air conditioning system, and uses three methods, linear regression analysis, neural network and genetic neural network to build the model. The model simulates the COP before the condenser of chiller is cleaned to compare and discuss the improved performance and energy conservation potential before and after the chiller is cleaned. It aims to save the energy consumption of chiller.

2. Research Method

2.1 Verification Method [3]

(1.) The data of chiller are collected by instrument before the efficiency improvement (chilled water input/output temperature, cooling water input/output temperature and chiller power

consumption, one data recorded per minute). The chilled water flow rate of chiller is measured and the chiller power consumption model is built, as shown in the distribution diagram of Figure 2.

(2.) The chilled water output temperature, cooling water input temperature and cooling load are collected after efficiency improvement. The data in previous range are shown in the distribution diagram of Figure 3, and the total power consumption is included (total power consumption after improvement).

(3.) The data variables after improvement are substituted in previous power consumption model to obtain the power consumption and sum up (total power consumption before improvement).

(4.) Calculate the percentage of saved power consumption after improvement.

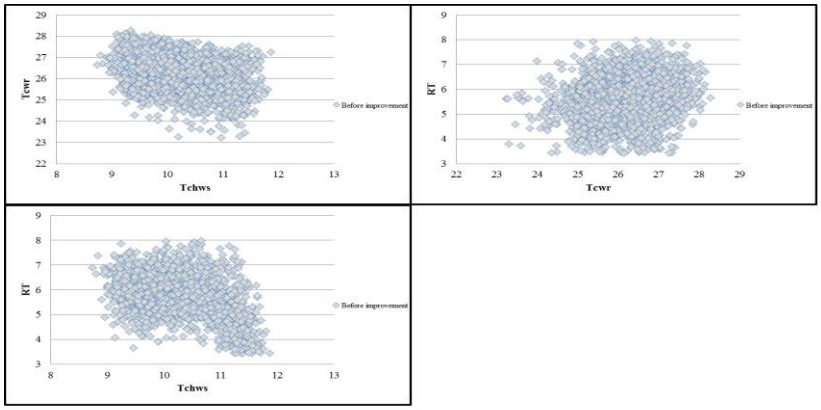

Figure 2 Distribution diagram before improvement

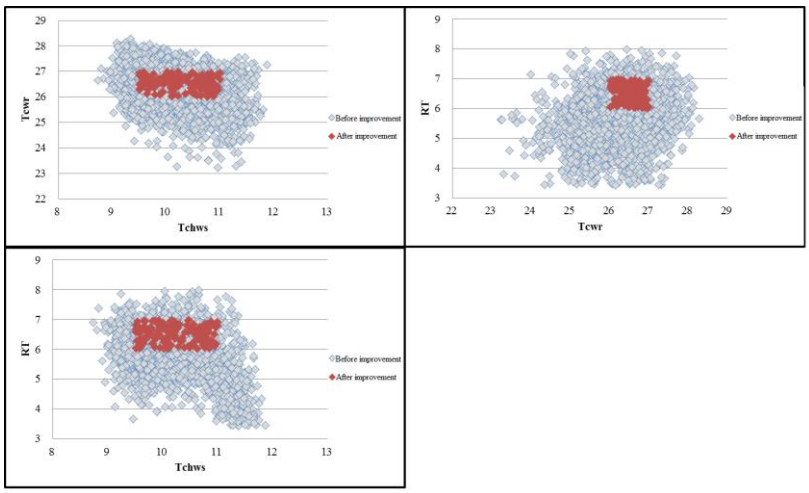

Figure 3 Distribution diagram before and after improvement

2.2 COP model of chiller

2.2.1 Linear regression

The linear regression analysis is a statistical tool for analyzing the relationship between one or more independent variables or dependent variables. Its purpose is to further analyze the simulation relationship between two variables based on the linear relationship between two variables [4]. The major factors influencing the COP of chiller include the chilled water output temperature (Tchws), cooling water input temperature (Tcwr) and cooling load (Qrt). These three parameters are taken as independent variables.

Case 1 takes the operating data of chiller with scale during June 18, 2012 to July 31, 2012 as the data samples for modeling. One data is measured per minute, and the chiller performance model equation is established by linear regression.

Case 1 regression equation is:

$$COP=4.91422-(0.346157*X)-(0.213388*Y)+(0.280182*Z)+(0.00831743*X^2)+(0.00293968*Y^2)+(0.00229123*Z^2)+(0.00525041*X*Y)-(0.00156394*Y*Z)+(0.00330905*X*Z)$$

where X: chilled water output temperature (Tchws)
Y: Cooling water input temperature (Tcwr)
Z: cooling load (Qrt)

Case 2 takes the operating data of chiller before the condenser is cleaned during May 27, 2008 to June 7, 2008 as the data samples for modeling. One data is measured per minute, and the chiller performance model equation is established by linear regression, simulating the COP before the condenser is cleaned during June 11, 2008 to June 19, 2008.

Case 2 regression equation is:

$$COP=12.6349-(1.99677*X)-(0.069085*Y)+(0.0294751*Z)+(0.104349*X^2)+(0.0012196*Y^2)-(0.0000969856*Z^2)+(0.00850531*X*Y)-(0.0000509602*Y*Z)+(0.00117675*X*Z)$$

2.2.2 Neural network

This study used the GUI graphic interface provided by Neural Network Toolbox of Matlab mathematical package to research backpropagation network. The functions of GUI graphic interface include creating network, importing data into interface, initialization, training and artificial network. The parameters are set before training, e.g. number of neurons, transfer function, and learning function. The backpropagation network is then created.

The backpropagation network input parameters selected for the two cases of this study include chilled water output temperature (Tchws), cooling water input temperature (Tcwr) and cooling load (Qrt), the target value is the COP of chiller. Figure 4 shows the experimental structure of backpropagation network of this study. After multiple times of trial and error, using one hidden layer and 3 hidden layer processing elements have better performance. The parameters set by backpropagation network in the two cases are shown in Table 1.

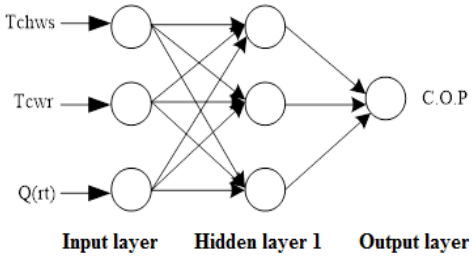

Figure 4 Experimental structure of backpropagation network

Table 1 Parameters set by backpropagation network

Parameter	Set value
Hidden layer 1	logsig(log-sigmoid function)
Output layer	purelin(linear transfer function)
Training function	trainrp(back-propagation algorithm with flexibility)
Adaptive learning function	learngdm(gradient descent weight/bias learning function with momentum)
Performance function	msereg (mean square error with regularization)
Case 1 training cycles	1500
Case 2 training cycles	1500

2.2.3 Genetic neural network

In the past, Trial and Error was used to test many network architectures. When the number of training data increased, the number of neurons of hidden layer of neural network should increase, and the training time should be prolonged. However, this method is time consuming and it cannot guarantee that the network architecture recommended by Trial and Error is the best. Therefore, this study uses genetic algorithm to search for the optimum weighted value and bias value of backpropagation network for effective and accurate calculation. Meanwhile the genetic algorithm is an algorithm with global search capability, and it avoids getting into local optimum. The parameter settings for the two cases are shown in Table 2.

Table 2 Parameters set by genetic neural network of Case 1

Parameter	Set value	Set value
String length	80	80
Population size	30	40
Generation number	600	500
Crossover rate	0.7	0.7
Mutation rate	0.02	0.02

In principle, better fitness function value represents higher fitness of population. However, in order to increase the opportunity for new species to enter population, the fitness function must be able to eliminate the second best species quickly, so as to accelerate the search process [5]. The design of fitness function must be adjusted according to different problems before it is applied. The reciprocal of objective function plus penalty function is the fitness function, and the penalty function is generally set as 1. The fitness function value in the two cases of this study is:

$$\text{fitness function} = \frac{1}{\text{objective function} + \text{penalty function}}$$

3. Results

This study uses two different cases as research background. The experimental site of Case 1 is a senior center in Taipei City, the air conditioning system for experiment is a reciprocating compressor chiller. The scale of cooling tower is adsorbed in the experiment, with chemical dosing, enhancing the anti-scaling and heat exchange effect. This air conditioning system consists of a 25 ton reciprocating compressor chiller, an indoor fan coil, a cooling tower, a primary side chilled water pump, a primary side cooling water pump and a spare pump. Case 2 has two 280 ton centrifugal compressor chillers equipped for the air conditioning of a shopping mall in Taipei City, one chiller is analyzed to compare the system effectiveness before and after the condenser is cleaned, so as to analyze the improvement of chiller performance and energy conservation potential on the same standard.

In the two cases, the instruments are mounted on site to measure the chilled water input/output temperature, cooling water input/output temperature, chilled water flow rate, cooling water flow rate and compressor power consumption. The data are collected in sampling period of one data per minute. The collected data are analyzed by patented technology of patent application number 096111363 [3], the irrational data are deleted, and then the COP model before cleaning of Case 1 and Case 2 is built in three ways, and the COP of chiller before cleaning is simulated on the same standard after cleaning, and the effectively improved performance is analyzed. The three modeling ways are described below:

3.1 Case 1

Case 1 takes the operating data of chiller with scale during June 18, 2012 to July 31, 2012 as data samples for modeling. One data is measured per minute, the chiller performance model equation is established in three ways, simulating the COP before the scale is cleaned off during August (August 9, 2012 to August 31, 2012) and September (September 1, 2012 to September 30, 2012). In order to validate the accuracy of this model, there are 68 data before the scale is cleaned off on August 7, 2012 are taken as test samples.

First, the accuracy of regression modeling is judged, the regression scatter diagram and line chart are shown as Figures 5 and 6.

3.1.1 Method 1: linear regression analysis

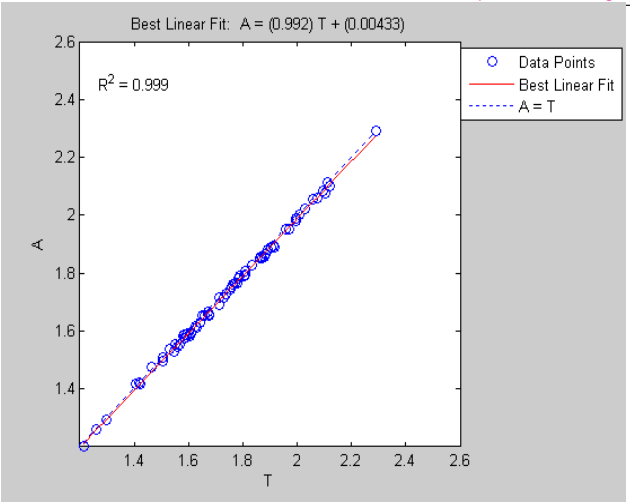

Figure 5 Linear regression scatter diagram of Case 1 test samples

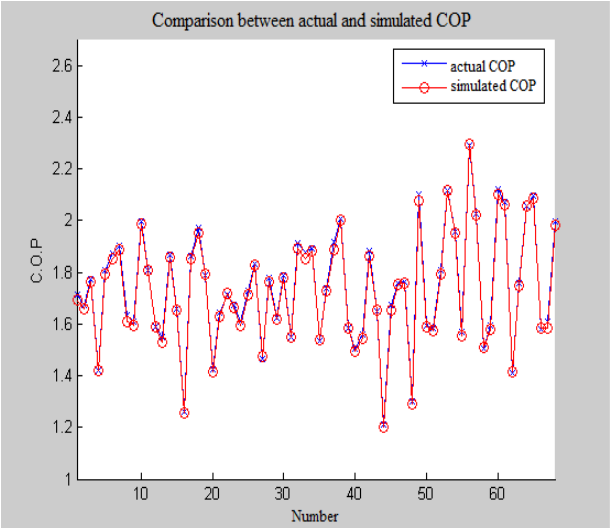

Figure 6 Line chart of actual COP and simulated COP of Case 1 test samples

The above test samples are substituted in the performance model. The analysis result shows R^2 is 0.99, the error between the actual COP and the simulated COP is within 0.1%, the precision is very high.

3.1.2 Method 2: Backpropagation network

The accuracy of the backpropagation network established by training samples is judged. The mean error rate is less than 0.1%, the linear regression analysis is shown in Figure 7, and the line chart is shown as Figure 8. The initial weighted value and bias value of backpropagation network are shown in Table 3. The error analysis of test samples is shown in Table 4.

Table 3 Initial weighted value and bias value of Case 1 backpropagation network

IW{1.1}	-0.0666 -0.0317 0.3870 -0.1355 -0.0502 0.5585 -0.1261 -0.0552 0.5633
b.{1}	-0.0114 -0.0137 -0.0162
LW{2.1}	0.5769 0.7486 0.7571
b.{2}	0.4152

Table 4 Case 1 test sample error analysis

Date of training samples	Date of test samples	RMSE	Cov	EEP	MBE	Mean error (%)
2012/06/18~ 2012/07/31	2012/08/07	0.0487	0.0280	0.0212	0.0013	0.0012

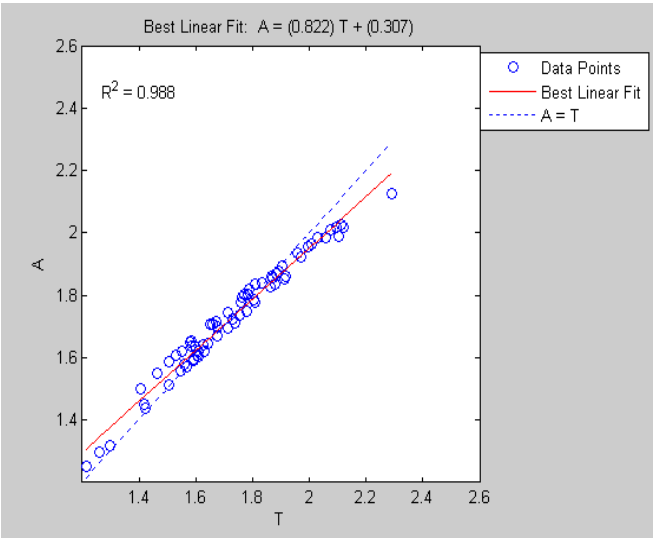

Figure 7 Network regression analysis of Case 1 test samples

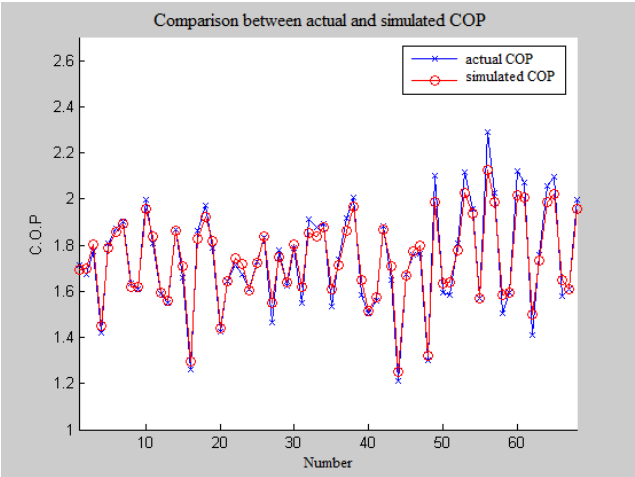

Figure 8 Line chart of actual COP and simulated COP of Case 1 test samples

3.1.3 Method 3: Genetic neural network

The accuracy of the genetic neural network established by training samples is judged. The mean error rate is less than 0.1%, the linear regression analysis is shown in Figure 9. The line chart is shown as Figure 10. The generation number convergence map is shown as Figure 11. The optimum weighted value and bias value searched out by genetic algorithm are shown in Table 5. The error analysis of test samples is shown in Table 6.

Table 5 Optimum weighted value and bias value searched out by genetic algorithm of Case 1

IW{1.1}	0.7292 -0.4192 0.8080 -0.6251 0.0718 0.9539 0.0332 0.1163 0.5765
b.{1}	-0.9682 -0.4959 -0.8675
LW{2.1}	0.5000 0.9570 0.2008
b.{2}	0.6809

Table 6 Error analysis of Case 1 test samples

Date of training samples	Date of test samples	RMSE	Cov	EEP	MBE	Mean error
2012/06/18 ~	2012/08/07	0.0297	0.0171	0.0129	0.0008	0.0008

2012/07/31						

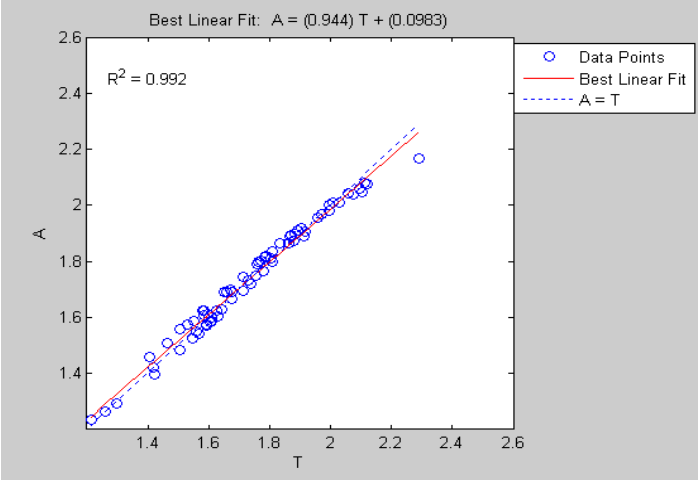

Figure 9 Network regression analysis of Case 1 test samples

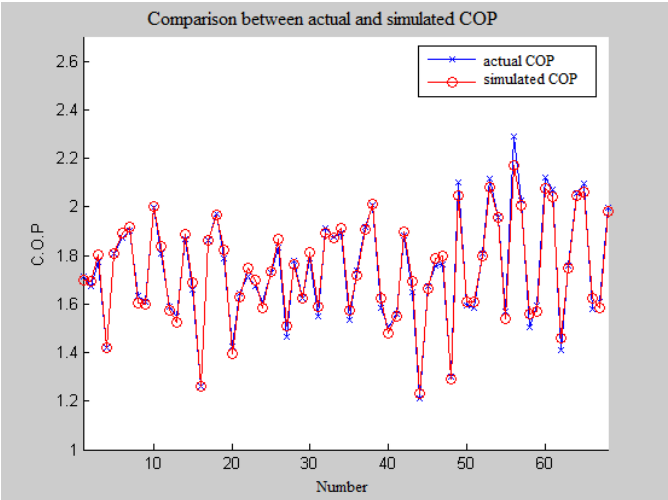

Figure 10 Line chart of actual COP and simulated COP of Case 1 test samples

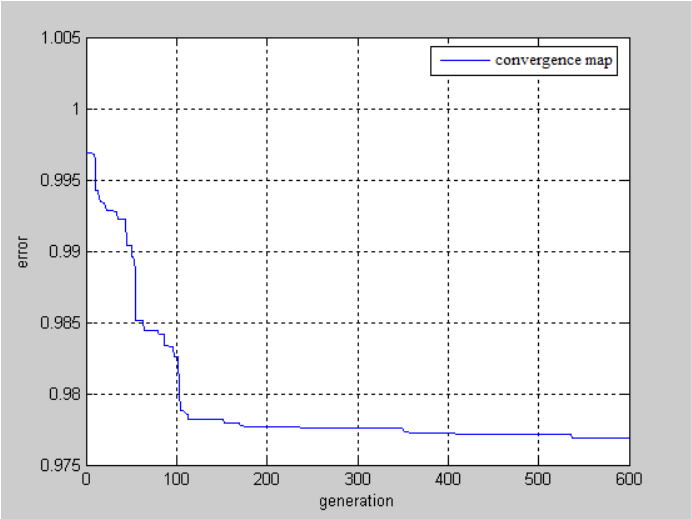

Figure 11 Convergence map of 600 generations of Case 1

The test sample result comparison analysis is shown in Table 7. The result shows that the mean error obtained by using genetic neural network model for modeling is the lowest among three methods, so the accuracy rate of this model is reliable and effective.

Table 7 Test sample result comparison analysis for August 7,2012.

Method	Actual average COP	Simulated average COP	Mean error (%)
Regression model	1.7381	1.7285	0%(0.0055)
Backpropagation network model	1.7381	1.7359	0%(0.0012)
Genetic neural network model	1.7381	1.7395	0%(0.0008)

Afterwards, the genetic neural network model is used to simulate the COP in August and September of that year. The cooling water scale was cleaned on August 8, 2012, so the 156 data collected and analyzed during August 9, 2012 to August 31, 2012 are used as data samples of August, and the 101 data collected and analyzed during September 1, 2012 to September 30, 2012 are used as the data samples of September. The analysis results are shown in Figures 12 and 13.

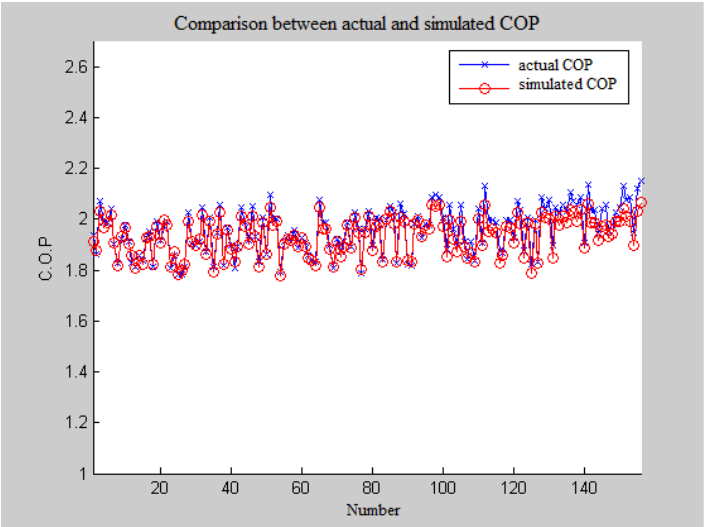

Figure 12 Comparison between actual COP and simulated COP of August of case 1

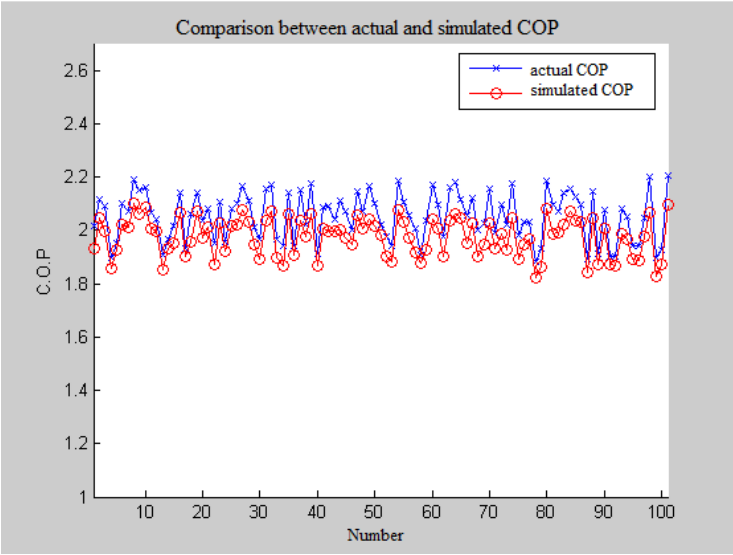

Figure 13 Comparison between actual COP and simulated COP of September of case1

The analysis result shows the COP has not changed significantly at the beginning of cleaning, it changes obviously after a period of time, in one month after the cooling water scale is cleaned out, and the COP is increased by 1.16% in average. In addition, the data during September 1, 2012 to

September 30, 2012 show

the variance in the COP before and after the cooling water scale is cleaned out. The COP is increased by 3.82% in average in two months after cleaning, it is increased to at most 6%. The analysis result of data samples before and after cleaning of Case 1 is shown in Table 8.

Table 8 Result comparison analysis of data samples before and after cleaning of Case 1

Method	Date	Average COP after actual cleaning	Average COP before simulated cleaning	Average increase (%)
Genetic neural network model	August 9, 2012-August 31, 2012	1.9572	1.9346	1.16%
	September 1,2012-September30, 2012	2.0545	1.9761	3.82%

3.2 Case 2

Case 2 takes the operating data of chiller before the condenser is cleaned during May 27, 2008 to June 7, 2008 as the training samples. One data is measured per minute, and the chiller performance model equation is established by three methods, simulating the COP before the condenser is cleaned during June 11, 2008 to June 19, 2008. In order to validate the accuracy of this model, there are 308 data before the scale is cleaned out on June 8, 2008 taken as test samples.

First, the accuracy of modeling by regression model is judged, the regression scatter diagram and line chart are shown as Figures 14 and 15.

3.2.1 Method 1: linear regression analysis

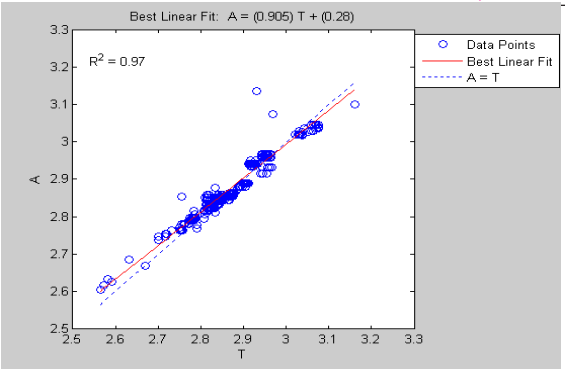

Figure 14 Regression scatter diagram of actual COP and simulated COP of Case 2 test samples

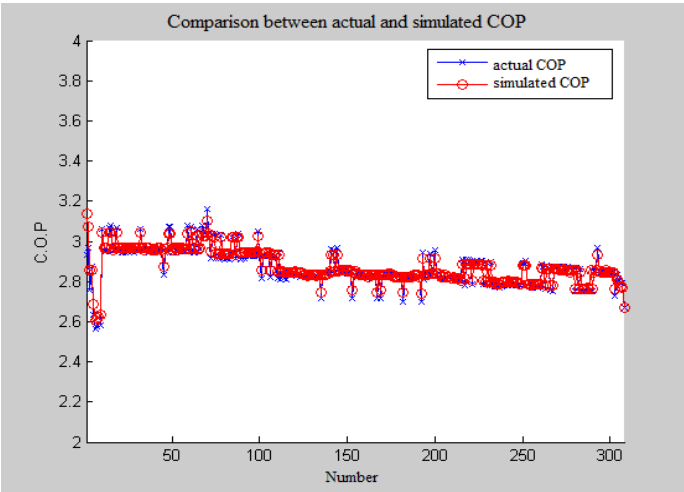

Figure 15 Line chart of actual COP and simulated COP of Case 2 test samples

The aforesaid test samples are substituted in the performance model. The analysis result shows R^2 is 0.97, the error between the actual COP and the simulated COP is less than 0.1%. The precision is very high.

3.2.2 Method 2: Backpropagation network

The accuracy of the backpropagation network established by training samples is judged. The mean error rate is less than 0.1%, the linear regression analysis is shown in Figure 16. The line chart is shown as Figure 17. The initial weighted value and bias value of backpropagation network are shown in Table 9. The error analysis of test samples is shown in Table 10.

Table 9 Initial weighted value and bias value of Case 2 backpropagation network

IW{1.1}	0.0005 -0.0030 0.0521 -0.0180 -0.0849 0.0584

	-0.0117 -0.3504 0.1020
b.{1}	0.0000 -0.0018 -0.0016
LW{2.1}	0.7370 0.7543 0.8413
b.{2}	0.7556

Table 10 Error analysis of Case 2 test samples

Date of training samples	Date of test samples	RMSE	Cov	EEP	MBE	Mean error
2008/05/27~ 2008/06/07	2008/06/08	0.0304	0.0106	0.0096	0.0019	0.0020

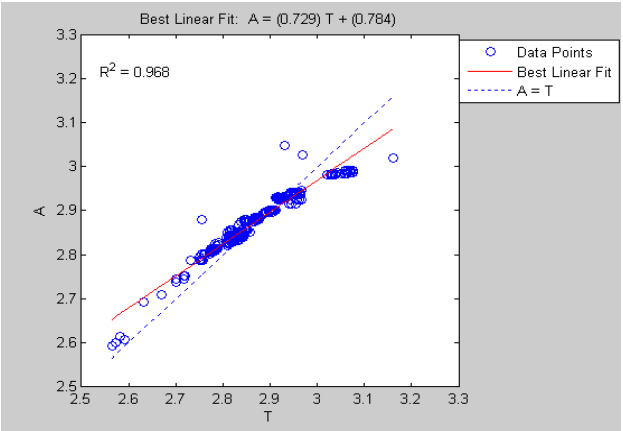

Figure 16 Network regression analysis of Case 2 test samples

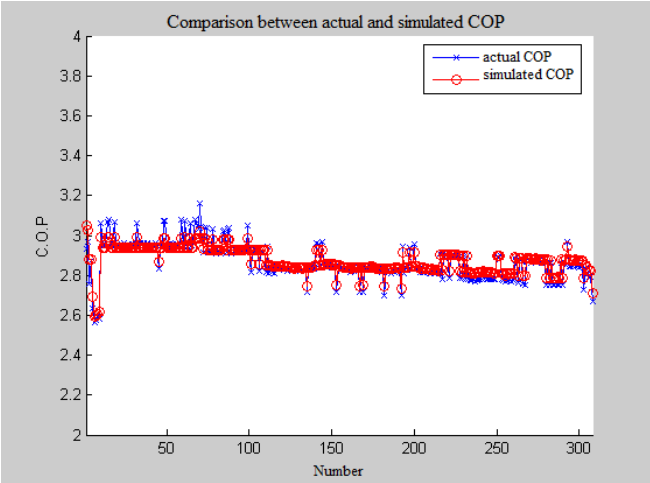

Figure 17 Line chart of actual COP and simulated COP of Case 2 test samples

3.2.3 Method 3: Genetic neural network

The accuracy of the genetic neural network established by training samples is judged, the mean error rate is less than 0.1%, the linear regression analysis is shown in Figure 18. The line chart is shown as Figure 19. The generation number convergence map is shown as Figure 20. The optimum weighted value and bias value searched out by genetic algorithm are shown in Table 11. The error analysis of test samples is shown in Table 12.

Table 11 Optimum weighted value and bias value searched out by genetic algorithm of Case 2

IW{1.1}	0.8275 -0.7403 0.1050 0.1369 -0.2503 0.7505 0.2591 -0.5241 0.1368
b.{1}	0.0889 0.7273 0.2687
LW{2.1}	0.7508 0.9813 0.8209
b.{2}	0.9764

Table 12 Error analysis of Case 2 test samples

Date of training samples	Date of test samples	RMSE	Cov	EEP	MBE	Mean error (%)

2008/05/27~ 2008/06/07	2008/06/08	0.0255	0.0089	0.0081	0.0009	0.0010

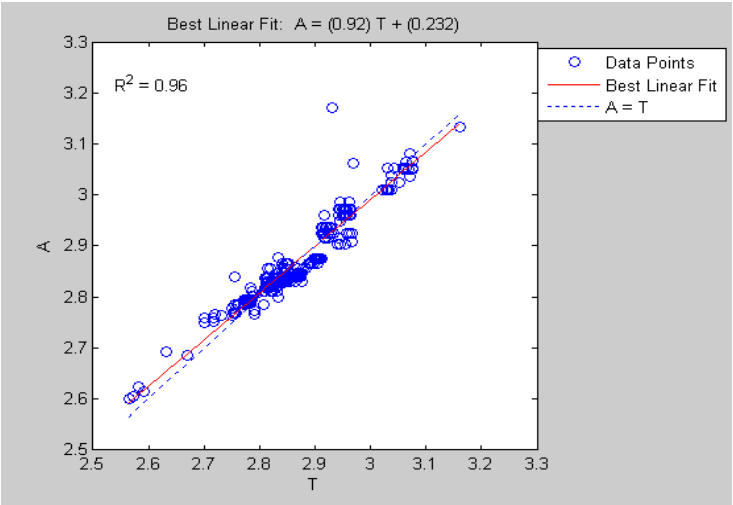

Figure 18 Network regression analysis of Case 2 test samples

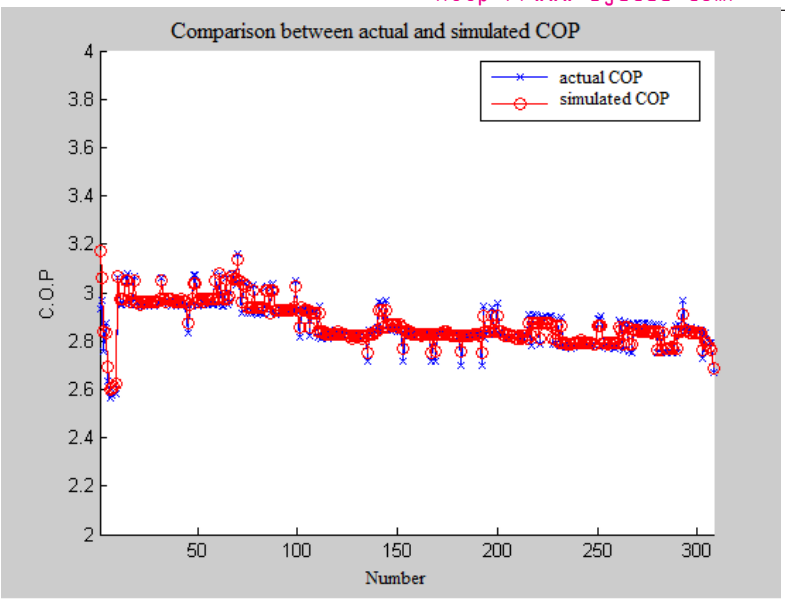

Figure 19 Line chart of actual COP and simulated COP of Case 2 test samples

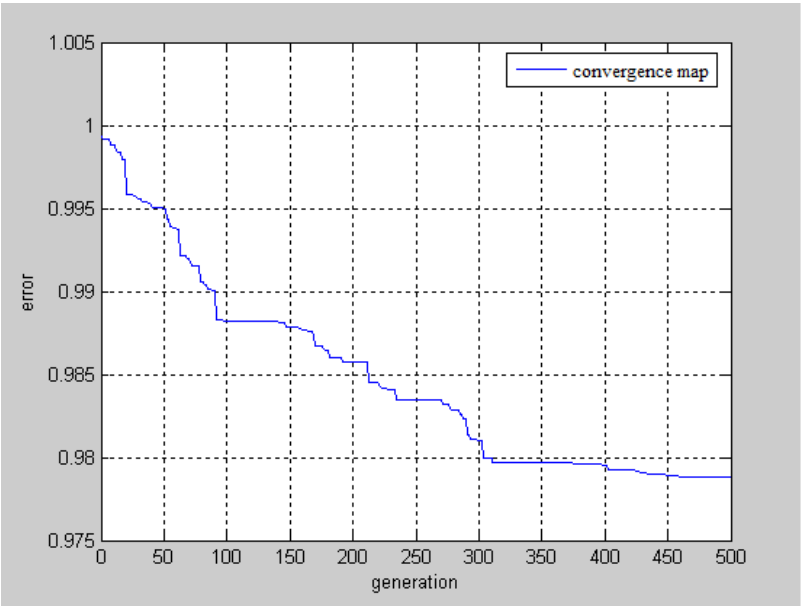

Figure 20 Convergence map of 500 generations of Case 2

The test sample result comparison analysis is shown in Table 13. The result shows the mean error obtained by using genetic neural network model for modeling is the lowest among three methods, proving that the accuracy rate of this model is reliable and effective.

Table 13 Result comparison analysis of test samples of Case 2

Method	Date	Actual average COP	Simulated average COP	Mean error (%)
Regression model	June 8, 2008	2.8685	2.8752	0%(0.0023)
Backpropagation network model		2.8685	2.8742	0%(0.0020)
Genetic neural network model		2.8685	2.8713	0%(0.0010)

Afterwards, the genetic neural network model is used to simulate the COP after the condenser is cleaned. The condenser was cleaned on June 10, 2008, so the 1144 data collected and analyzed during June 11, 2008 to June 19, 2008 are used as the data samples after the condenser is cleaned, the analysis result is shown in Figure 21.

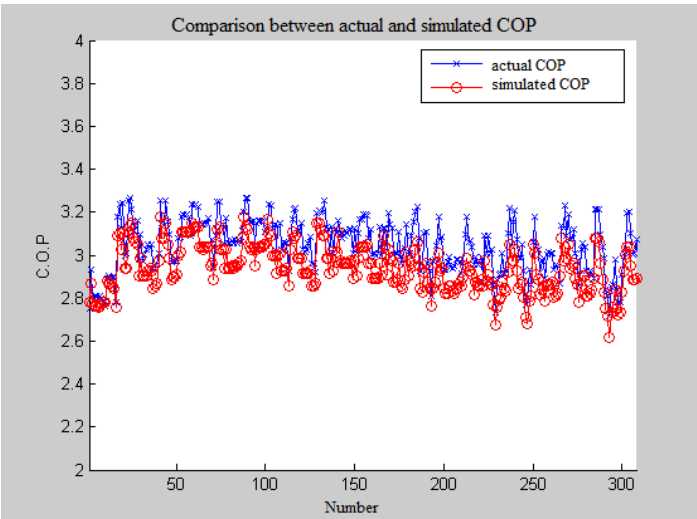

Figure 21 Comparison between actual COP and simulated COP after the condenser is cleaned of Case 2

The analysis result shows that when the genetic neural network analysis method is used. During June 11, 2008 to June 19, 2008, the COP after the condenser is cleaned is increased by 3.78% in average, meaning that the COP can be improved effectively by cleaning the condenser. The analysis result of data samples before and after cleaning of Case 2 is shown in Table 14.

Table 14 Result comparison analysis of data samples before and after cleaning of Case 2

Method	Date	Average COP after actual cleaning	Average COP before simulated cleaning	Mean error (%)
Genetic neural network model	June 11, 2008-June 19, 2008	3.0489	2.9337	3.78%(0.0378)

4. Conclusion

The traditional backpropagation network uses gradient descent method to train the weighted value and bias of neurons, it often falls into local optimum. Therefore, this study integrates genetic algorithm into neural network to search for the global optimum weighted value and bias value. This method can search for multiple targets in the space simultaneously, it seeks for the global optimal solution efficiently. The experimental method of Case 1 uses electrode scale treatment machine to adsorb scale, and uses genetic neural algorithm to analyze the COP in 1 month and 2 months after the scale is cleaned out, which is increased by 1.16% and 3.82% respectively. Because the experimental equipment of Case 1 has been used for almost 10 years, the equipment is old, and the improvement effect is presented apparently after a long time. The experiment of Case 2 cleans condenser and uses genetic neural algorithm to analyze the COP before and after the condenser is cleaned, which is increased by 3.78%. The improvement effect is obvious promptly after the cleaning of Case 2, because the heat-exchange rate before the condenser is cleaned of Case 2 is not too bad, and the performance can be improved effectively after a few days. According to the above two cleaning methods, cleaning the condenser is more efficient, the COP is improved effectively. Therefore, it is more effective to use genetic neural algorithm to analyze the improved COP before and after the condenser is cleaned.

References

[1] Bureau of Energy, Ministry of Economic Affairs., Taiwan Green Productivity Foundation, Office Building Economy Manual, 2009.

[2] Bureau of Energy, Ministry of Economic Affairs., Taiwan Green Productivity Foundation, Air Conditioning System Management and Energy-Saving Manual, 2009.

[3]Taiwan Patent Search, Publication No.: 200839204, Patent: air conditioning system energy-saving verification method, Application No.: 096111363, Applicant: Yung-chung Chang

[4]Lin, H.L, Chen, C.T., Applied statistics second edition, Yeh Yeh Book Gallery, 2002.

[5]Su, M.C., Chang, H.T., Machine Learning Neural Network, Fuzzy System and Genetic Algorithm, Chuan Hwa Book, 1997.