American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-10, Issue-8, pp: 271-275
www.ajer.org
Research Paper Open Access

Decision Analysis Model for Optimizing the Operation of Refrigeration Compressor Units

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Abstract
This study applied the mathematical planning method of system optimization technology to obtain the minimum energy consumption of the refrigeration unit. Adjustments to the operating state of each compressor unit in the system were primarily based on actual requirements for refrigeration capacity at the load end. According to the actual running performance and operating state of each unit, a decision analysis model for the optimal control of refrigeration compressor units was constructed. To meet the requirements for refrigeration capacity of a refrigerated (frozen) warehouse, the proposed model adopted an optimization framework and algorithm to obtain the optimal operating performance of each compressor unit and thereby achieve optimal operation performance of the refrigeration unit. Finally, this model structure and calculation method were used to develop a decision support system for optimizing operation of refrigeration compressor units to meet the requirements of rapid modeling and analysis. This system can provide relevant designers and operators with objective support for determining optimal controls and settings for refrigeration units.
Keywords: *refrigeration compressor unit, system optimization, mathematical planning, decision support system, energy efficiency*

Date of Submission: 07-08-2021 Date of acceptance: 21-08-2021

I. INTRODUCTION

Designs for refrigeration systems must meet certain requirements, particularly in Taiwan, where the climate is characterized by four distinct seasons. To account for the considerable seasonal variations in temperature, various refrigeration capacities should be obtained by modifying operating points to meet different refrigeration requirements. Therefore, refrigeration systems are often designed as multiple refrigerant compressor units to flexibly provide cold energy for refrigerated (frozen) warehouses.

Conventionally, a refrigeration compressor unit is operated based on the operator’s experience, Proportional-Integral-Derivative (PID) control of the refrigerant temperature or pressure, or direct digital control (DDC) for setting and adjusting the operating states of each compressor unit in the system. These methods lack a basis in science, systemization, and optimization. This shortcoming prevents refrigeration units from achieving optimal operation performance and causes excessive energy consumption. An advanced operation and control method requires a suitable decision model for the refrigeration unit in order to analyze the dynamic behavior of the unit, and optimal operation strategies should be developed based on the behavior of the system to maintain the unit operation at the optimal operating point. Because of the complexity of refrigeration compressor unit, establishing a decision analysis model for optimal control remains a topic of research. Few studies have focused on developing optimal control strategies.

Using the optimization principle to design and analyze the optimal control mode for the refrigeration compressor unit can improve conventional operation methods and enhance energy efficiency and refrigeration quality. In the current research field of air conditioning systems, numerous studies have been conducted on the optimal design, operation, and control methods of chillers, air handling units (AHU), ice-storage air conditioning systems, and chiller plants to obtain maximum effectiveness for meeting the requirements of energy conservation and user comfort. However, little progress has been made in the field of industrial refrigeration systems, and related research is scarce. Taiwan is located in a subtropical region, where the preservation of vegetables, fruits, and fish heavily relies on refrigerated (frozen) warehouses. Therefore, optimizing the operation of refrigeration compressor units to improve system operating efficiency and thereby establish the system as economical and reliable is a critical topic worthy of research and development. This topic is also the direction and focal point of this study.

II. CONTROL OF CONVENTIONAL REFRIGERATION COMPRESSOR UNIT

2.1 Experience-based operation

Experience-based operation is the least scientific and least precise control method and primarily relies on the on-site operator of a refrigeration system. Each compressor unit is set and adjusted according to the weather conditions, use conditions of the refrigerated (frozen) warehouse, and operator's experience. Operators usually excessively increase the operating capacity of the refrigeration system to ensure that the warehouse can obtain a sufficient amount of cold energy. This method relies on the subjective judgment of the operator and lacks an objective and scientific operation procedure, which renders the operation inaccurate and unstable and thus leads to excessive energy waste.

2.2 Control based on temperature or pressure variables

The most commonly applied control modes in refrigeration systems are PID control and DDC embedded with network and PID controllers. The control logic for these two modes is based on the detection of changes in temperature or pressure of the refrigerant in the system and setting and adjusting the operating status of each compressor unit accordingly. Figure 1 presents the schematic of PID control. The controller determines the temperature or pressure value of the refrigerant in the system, receives the feedback signal (system feedback temperature or pressure value), and uses internal ratios, integrals, and differential algorithms to derive a control signal. This signal is used to reset and adjust the operating state of the control unit to enable the control variable (temperature or pressure) output from the system to reach the set point.

Advancements in digital and network technology have enabled the original PID control logic to be embedded in the DDC module, and these control modules are sequentially connected through the Internet. The operator can easily use computers or smart mobile devices (e.g., smartphones or tablets) for remote monitoring, determining the operating state of each compressor unit in the refrigeration system, and resetting the PID parameters to improve the monitoring efficiency of the refrigeration system.

However, neither PID control nor DDC embedded with network and PID controllers can achieve optimal control of the refrigeration system. The reasons are as follows. (1) The control mode that uses PID as the basic control logic only adopts independent control variables (e.g., temperature or pressure) to set and adjust the operating state of each compressor unit (usually these independent control variables are not directly related to energy efficiency optimization). This control mode does not consider the operational correlation among each unit from the perspective of overall energy efficiency optimization; thus, it cannot effectively coordinate and integrate the operation between different units, leading to low efficiency in the refrigeration system operation. (2) Typical PID feedback control is based on the values of set point and feedback signal. By using proportional, integral, and differential algorithms, a proportional value can be obtained; the proportional value is then used to reset and adjust the operating state of the controlled units. This value does not consider the operating performance of the unit; thus, when the refrigeration system is required to achieve optimal operating performance, the optimal proportional value is not easily obtained. The overall refrigeration system then operates in a nonoptimized state, resulting in excess energy consumption. Notably, the operating efficiency of the refrigeration system can potentially be improved by continually adjusting the control set points of each unit (resetting the PID parameters). However, this procedure leads to unstable operation and excessive operation time.

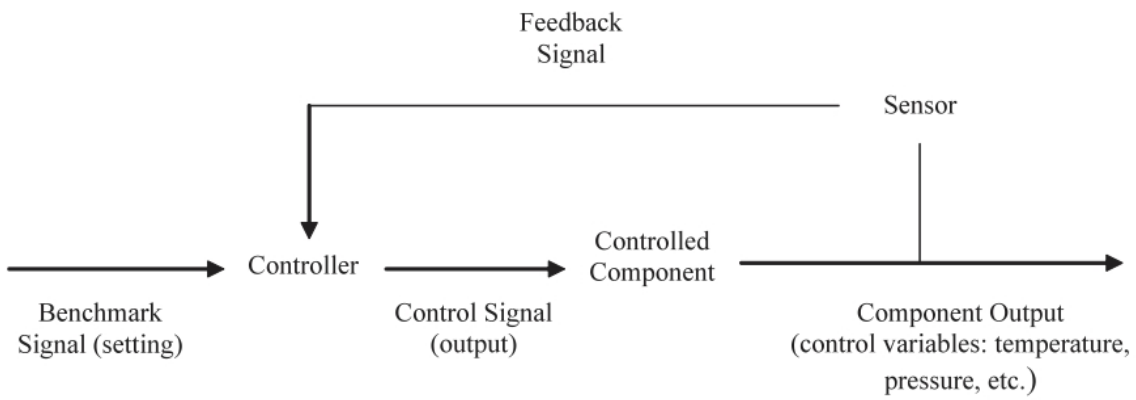

Figure 1: Basic diagram of PID control

III. DECISION ANALYSIS SYSTEM FOR OPTIMAL CONTROL OF REFRIGERATION COMPRESSOR UNITS

Studies on strategies for energy conservation of refrigeration systems in refrigerated (frozen) warehouses have primarily focused on the optimal control of the solenoid valve operation in refrigeration systems. The solenoid valve in a refrigerated (frozen) warehouse is effectively regulated to enable the overall refrigeration system to achieve a favorable operating coefficient of performance. However, the operation setting and control mode of refrigeration compressor units currently used in refrigeration systems continue to implemented with inadequate scientific and manual control or with a control mechanism lacking an optimized logical background. Moreover, an insufficient number of studies (or reports) have been conducted on methods for optimizing the operation modes of each compressor unit to obtain an energy-efficient system. Therefore, the present study referred to a method proposed from a decision analysis of an optimal chiller operation strategy. The human–machine interaction mode of the information system guides the designer or operating personnel to establish the energy optimization model and solution for the compressor unit system. This assists personnel in exploring the optimal start–stop status and operating capacity of each compressor unit under different requirements for frozen storage capacity in the warehouse, thereby providing an adequate basis for designing (setting) the optimal control schedule of each unit and minimizing the operating energy consumption of the unit. The construction steps and methods of the decision analysis system for optimal control of the refrigeration compressor unit are listed as follows:

Step 1: Measure and collect the operation information (data) of the refrigeration system and the associated compressor units using the monitoring system (or related instruments), and then compile the data.

Step 2: Establish a running performance function for each compressor unit of the refrigeration system using the neural network method.

Step 3: Establish a decision analysis model for optimal control of the overall refrigeration compressor units by adopting mathematical planning methods.

Step 4: Solve the decision variables in the optimal decision-making analysis model of the refrigeration compressor units using the particle swarm optimization (PSO) and harmony search (HS), and compare the effectiveness of the solution methods.

Step 5: Establish a decision analysis system for optimal operation/control of the refrigeration compressor unit using the technology of a decision analysis support system.

In summary, this study developed a decision analysis (support) system for optimal control of refrigeration compressor units that can be adapted for rapid modeling and analysis to provide relevant designers and operation managers with objective assistance when units are operated under optimal control settings. The developed system can sufficiently improve the operating state of each compressor unit in a refrigeration system; consequently, the operating state can approach the optimal parameter values, thus enabling the unit to maintain optimal levels of energy efficiency during operation. The primary function of the system is to help users simulate the optimal start–stop mode and optimal operating capacity status of each compressor unit under different cold energy requirements (unit: refrigeration ton [RT]). The system can also calculate the optimized total power consumption and provide accurate information on objective improvements for users to acquire control over the refrigeration unit.

IV. CASE STUDY AND ANALYSIS

This study conducted relevant tests and analyses on the refrigeration system of a fruit and vegetable market under operation by the Farmers Association in central Taiwan. The refrigeration system is simultaneously operated by four 30-HP reciprocating compressor units to provide a sufficient amount of cold energy for 12 refrigerated warehouses. Each compressor unit has a rated cooling capacity of 20 RT and uses R-22 refrigerant. Currently, the number of compressor units of the refrigerated warehouse is set according to the following simple rules:

- When cooling 1–3 chambers, one compressor should be operating.
- When cooling 4–6 chambers, two compressors should be operating.
- When cooling 7–9 chambers, three compressors should be operating.
- When cooling 10–12 chambers, four compressors should be operating.

The control rules indicate that one compressor can supply a cooling load sufficient for three refrigerating chambers. The ON/OFF switching of the compressor is controlled through the interface module of the main monitoring computer in the control room. The on-site operator determines the operation settings of the specific compressor unit (or multiple units) according to the operator’s experience and preference.

4.1 Decision analysis (support) system for optimal control of the studied case

This study collected data from the studied case, including operation data of the refrigeration system, operation modes, hourly cold energy requirements during the test period, and related restrictive conditions. In accordance with the aforementioned methods and procedures, the collected data were used to construct a program and interface for the optimal control decision of the optimal control decision analysis (support) system for the refrigeration system of the studied case. The program and interface were based on the associated inverted neural network model, nonlinear mathematical planning, and the principle and solution of the heuristic optimization algorithm (HS and PSO). Borland C++ Builder (BCB) 6.0 produced by Borland was used to construct the related programs and interfaces. The system mainly consisted of database modules for data transfer (input) and storage as well as modules such as model library modules and human–machine interface modules for calculation, analysis, and simulation.

4.2 Comparison of efficiency (effectiveness)

Figure 2 presents a comparison of power consumption before and after optimization of the operating states of the refrigeration system compressor unit from July 1–31, 2016. The total power consumption before system optimization was 37,467.56 kWh. The simulation results indicated that if the developed decision analysis system for optimal control operation of the refrigeration compressor unit was used for optimizing the operation mode of the original system, then the total power consumption of the overall refrigeration unit could be reduced to 34,928.11 kWh under the same hourly cooling energy requirement. The system saved 2,539.44 kWh, and the rate of power conservation was 6.78%.

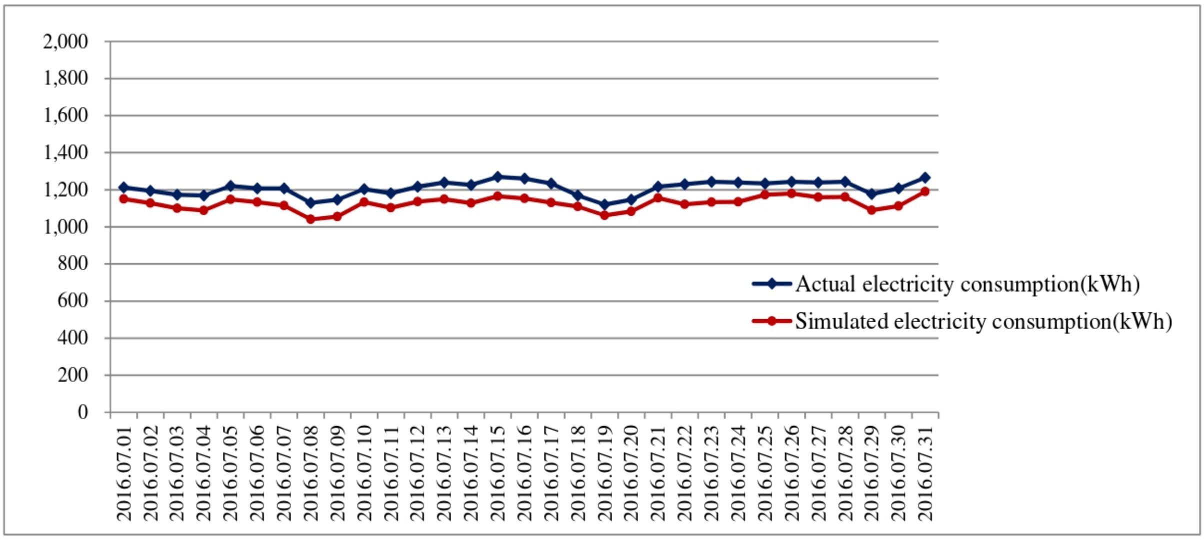

Figure 2: Comparison of electricity consumption before and after optimization of the refrigeration unit

This study also compared the operating states and power consumption of each refrigeration compressor unit under the cold energy requirements of 18, 30, 55, and 72 RT. As expected, the start–stop status and operation load rate of each unit were different before and after optimization, and their rates of power consumption were also significantly different. The results are listed in Table 1

.

Table 1: Comparison of operating states and power consumption of the compressor units before and after optimization under different cooling energy requirements.

Number of refrigerating rooms (RT)	Actual (before optimization)			Simulation (after optimization)		Power saving	Power saving rate
	Refrigeration compressor unit	Load ratio	Power	Load ratio	Power		
3 rooms (18RT)	1	0.9	17.1 (kW)	×	16.2 (kW)	0.9 (kW)	5.26 (%)
	2	×		×			
	3	×		×			
	4	×		0.9			
5 rooms (30RT)	1	0.75	28.05 (kW)	×	26.03 (kW)	2.02 (kW)	7.2 (%)
	2	0.75		0.65			
	3	×		×			
	4	×		0.85			
9 rooms (55RT)	1	0.91	51.25 (kW)	×	47.35 (kW)	3.9 (kW)	7.61 (%)
	2	0.91		0.92			
	3	0.91		0.88			
	4	×		0.95			
12 rooms (72RT)	1	0.9	66.9 (kW)	0.77	62.55 (kW)	4.35 (kW)	6.5 (%)
	2	0.9		0.95			
	3	0.9		0.88			
	4	0.9		1			

The performance of the solution and number of PSO and HS iterations were tested. In this study, the convergence speed of each algorithm was indicated by the number of iterations. Fewer iterations indicated less time required for both convergence of the solution and achievement of the optimal value. We discovered that HS exhibited favorable energy efficiency and calculation speed compared with PSO. Although the refrigeration unit that adopted HS consumed a slightly greater amount of electric power than that using PSO at 30 and 55 RT, the number of operations in the solution was favorable in HS compared with PSO. Therefore, the HS algorithm had the advantage of solving the problem of control optimization of the refrigeration compressor unit; thus, adopting HS is cost-effective. This study also used the HS algorithm as the solution method for the decision analysis (support) system for optimal control of the refrigeration unit.

V. CONCLUSION

This study used the developed decision analysis (support) system for optimal operation to determine the original temperature and humidity quality and thereby achieve the goal of maintaining equal cooling capacity without modifying any refrigeration equipment or affecting the refrigerated warehouse. The optimal operating state for the compressor units of the original refrigeration system was determined, which led to reduced operating energy consumption. The solution performance and convergence time of the PSO and HS algorithms were also comprehensively compared. The method that employed the HS algorithm exhibited optimal effectiveness (efficiency) and was determined to be a comprehensive and operation-friendly solution model.

ACKNOWLEDGEMENTS

This study received funding from the Ministry of Science and Technology (MOST-104-2221-E-492-035-). The authors thank the Ministry of Science and Technology for its support, which enabled this project to be conducted successfully.

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Chun-Wei Chen, et. al. "Decision Analysis Model for Optimizing the Operation of Refrigeration Compressor Units.”*American Journal of Engineering Research (AJER)*, vol. 10(8), 2021, pp. 271-275.