APPLICATION OF ARTIFICIAL INTELLIGENCE TO REFRIGERATION SYSTEMS

Fernando Cerdán Cartagena[1], Mario Pérez Gomariz[1] and Antonio López Gómez[2]

1: Department of Information Technologies and Telecommunications, ETSIT - UPCT Antiguo Cuartel de Antigones, Plaza del Hospital 1 30202-Cartagena (Spain): 2: Department of Agricultural Engineering, ETSIA-UPCT, Paseo Alfonso XIII 48 30203-Cartagena (Spain)

Fernando Cerdán Cartagena
fernando.cerdan@upct.es

Abstract: *Refrigeration systems currently use 20% of the total electrical energy, and this consumption is expected to increase by more than 30% between now and 2050. The optimization of these systems makes it possible to minimize CO2 emissions, increase energy efficiency and reduce costs. However, refrigeration system optimization problems are complex and time consuming. This is where sensorization and artificial intelligence come into play. Not many years ago, refrigeration systems were controlled with analog thermostats, and centralized supervision by SCADA systems using the data from sensors. Currently, we are in a completely digitized world thanks to massive sensorization, which is possible due to the development of the IoT (Internet of Things). The fundamental premise of the IoT is to connect the unconnectable by enabling new services and experiences. Complex machines and systems such as refrigeration systems can be measured comprehensively, down to the component level, and their data streams studied in real-time analysis systems. In this case, artificial intelligence can take the data to drive decision-making.*

Keywords: Internet of things, Energy saving, Big data, Cloud computing, Experience-based models

1. INTRODUCTION

Energy efficiency is currently one of the highest priorities for countries and companies. Energy saving is a necessity for modern societies as resources become limited and the consequences of climate change highlight the need of urgent and effective measures to mitigate these effects. Industrial refrigeration systems play a very important role in this scenario since it is estimated that 20 % of the energy generated worldwide is consumed by refrigeration systems.

Historically, the control of industrial systems has been designed from a functional point of view without considering factors such as energy efficiency. The control algorithms of most traditional refrigeration systems are based on the control of the temperature of the air in the refrigeration chamber. Over time, more complex control systems have been designed in order to optimize and achieve greater efficiencies in terms of both consumption and production. This improvement was mainly based on two factors: firstly, new technologies for designing and building more efficient machines and devices (new generation of compressors, electronic valves, etc.). On the other hand, the efficiency of refrigeration systems has been enhanced by an improvement of the control systems. New techniques of mathematical optimization and modeling of refrigeration systems, such as those presented in [1], have made possible to characterize the elements that make up the system in order to assist in their design and control. The modeling of these systems is mainly carried out with statistical methods that, using optimization techniques, are able to model refrigeration systems with great accuracy. However, not all models can be implemented into real operating environments due to their complexity. Most of the models are highly dependent on the elements that make up the refrigeration system as well as a number of assumptions adopted when designing the model. This means that, often, the models are not directly applicable to the control systems since these are not able to accurately adapt to the dynamics and real operating conditions that characterize most refrigeration systems. In production environments, control systems are mainly based on simplified models and PID (proportional, integral and derivative) controllers that, with proper parameterization, determine the optimal operating point of a system based on different variables. Often the tuning of these control systems is complex and it is required a great deal of experience and knowledge.

In recent years, new advanced control techniques based on data have been adopted in the management of refrigeration systems. In this article we will address this new trend, the interest of this new type of techniques in resource management and energy efficiency and how they can be used in refrigeration systems. The rest of the document is organized as follows, section 2 cover the new paradigm shift in the industrial sector towards massive information management and artificial intelligence (AI), the industry 4.0. We will analyze the scenario in which this trend emerges and why it has had such a great impact on industry, a historically conservative sector. In section 3, we will discuss the key factors in applying data-driven AI models for energy savings in refrigeration systems. The main methods used will be presented, as well as the different target variables that have been used for energy optimization in refrigeration systems. Finally, section 4 reviews the evolution of AI in industrial refrigeration systems and discusses new trends on how artificial intelligence can improve the performance and energy efficiency of refrigeration systems in the future.

2. PARADIGM SHIFT. INDUSTRY 4.0

In the last decade, industrial sector has experimented a great revolution due to the adoption of new strategies based on the improvement of technologies of information and communication (TIC) and digitization. New technologies such as system virtualization, IoT, Big Data, cloud computing or AI have shaped what is known as Industry 4.0 or fourth industrial revolution. All these technologies support the three fundamental bases of Industry 4.0, which are the interconnection of systems and devices, the massive acquisition of data and the processing and treatment of this information.

2.1. Internet of Things

The emergence of more efficient and higher capacity wireless communication protocols and improvements in electronic devices have enabled intelligent hypersensitization in several industrial sectors. IoT consists of the interconnection of all kinds of devices and objects in a data network so that they can exchange information with others. These devices range from simple sensors or actuators, equipped with communication systems, to more complex systems. The use of IoT devices in the industry has intensified nowadays because this technology makes possible to acquire new data, both process and external, that were not collected before, either because they were difficult to access or because they were magnitudes that were not used by the control system. In this new scenario, machines would be continuously sending large amounts of data in real time to networks that must have the capacity to store and process the information.

2.2. Big data & Cloud computing

Big data is a technology used for processing large volumes of information. Due to technologies such as IoT, we have an increasing volume of data in industries. All this information generated by the different nodes of the network must be collected and stored in a structured way for analysis. This data is part of the assets of companies and provide great added value for them, therefore it is important to have technologies that facilitate the collection, processing and visualization of huge volumes of information. In addition to big data, cloud computing technologies are used together to carry out all these actions in remote servers, facilitating access to the data and improving the security and integrity of information in an environment in which software and hardware are virtually interconnected.

2.3. Artificial Intelligent

As the quantity and quality of data available in industrial processes increases, new methods of information processing and control are needed. Just as experts in certain sectors have been analyzing the behavior of industrial systems for years in order to know and be able to operate them in an optimal way, the massive amount of information handled today makes it necessary the use of new techniques for handling this information. AI algorithms have the ability to analyze large amounts of information to learn from the data and use this knowledge to perform certain tasks without the needed of program explicitly each possible scenario. In this way, AI gives machines the ability to learn autonomously to detect complex patterns and trends in data, draw conclusions and act accordingly, just as an expert would.

One of the major potentials of artificial intelligence systems is their ability to extract new information with great added value from data that, a priori, are not related. AI is capable of finding complex relationships between data that, despite being dependent variables, have low or zero degree of correlation. These algorithms are able to find trends or relationships between data that are impossible to detect through a quantitative analysis of the information or that would be highly complex to model with traditional methods.

3. IA IN REFRIGERATION SYSTEMS. ENERGY EFFICIENCY

In the literature we can find different articles such as [1] that highlight the increasingly use of IA algorithms for modeling and optimizing industrial refrigeration systems in terms of energy efficiency. Firstly, the complexity of modeling refrigeration systems due to factors such as their stochastic nature have led to the search for new, more effective and efficient modeling techniques. On the other hand, the greater knowledge we have about these systems and the easy acquisition of data using IoT, have facilitated the application of artificial intelligence algorithms in the industrial sector and specifically in refrigeration systems.

Mainly the modeling of refrigeration systems is based on the resolution of a mathematical problem in which it seeks to optimize one or more parameters of the system by reducing the cost of an objective function. In energy efficiency problems, these parameters are related to the energy performance of the system such as the coefficient of performance (COP) or the energy efficiency ratio (EER). We can distinguish two main types of IA models for refrigeration system optimization: experience-based and data-driven models.

3.1. Experience-based models

Experience-based artificial intelligence models have the ability to establish relationships and understand a system based on prior knowledge of the system. These modeling techniques are based on statistical models that can take into account physical laws, properties or dynamics of the system under certain conditions. They can also be based on laws or rules that gather the knowledge of an expert or facts that represent the current knowledge of the system in a specific case or experiment. In short, the use of these AI techniques is conditioned by the prior knowledge of the system, whether mathematical or empirical. In this field, different IA techniques have been successfully used to solve energy optimization problems in industrial refrigeration systems. Some of the most commonly used methods are fuzzy logic, genetic algorithms (GA), expert systems and stochastic optimization methods.

Studies such as [2] use optimization techniques based on fuzzy logic in order to optimize the control of a refrigeration system and make it more robust and responsive to variations in system operating conditions. For this purpose, they control the compressor operating mode and the position of certain valves. Other studies such as [3, 4] focus on the optimization of the power consumption. The proposed models, based on fuzzy logic, are able to keep the temperature of the refrigeration room constant by acting on valves, fans and other elements of the system. In [4] the authors achieve energy savings of more than 30% per day by applying these control techniques.

One of the most widely used algorithms in optimization and modeling problems of refrigeration systems are genetic algorithms [1]. Different AI models based on GA have been proposed as a control strategy to increase the energy efficiency of refrigeration systems. In [5] the authors propose a GA model that achieves energy saving of up to 8% in an industrial vapor compression refrigeration system. The proposed model is based on the optimization of the total operating costs based on several variables such as mechanical constraints, interaction between components, environmental conditions and refrigeration demand of the system. On the other hand, in [6] a control strategy has been designed by which, using GA, it is possible to reduce the energy costs of an air conditioning system. The model, by monitoring the following five elements: thermal comfort, energy consumption, room air quality, air relative humidity and ventilation flow level, is able to optimize the overall performance of the system by reducing the energy consumed.

In addition to genetic algorithms, other stochastic AI models have been successfully applied for the optimization of refrigeration systems. Some of them are Simulated Annealing [7] or Particle Swarm Optimization [8] in which the authors improve the energy efficiency of industrial refrigeration systems. All model shown so far are based on experience and they require a great deal of prior knowledge of the system for its application.

3.2. Data-driven models

Like other industrial systems, refrigeration systems are involved in a deep revolution, the industry 4.0. These systems increasingly have major sensorization and, therefore, greater potential for control due to the knowledge we have about them. The more information we have about a given system, the greater the capacity to act on it in order to make it more efficient. This is why classical mathematical modeling algorithms are giving way to data-driven models. Data-driven artificial intelligence algorithms have the ability to model a system exclusively based on the correlation between input and output data, without any prior information or knowledge of the system. This set of techniques is known as machine learning (ML) and among them, neural networks stand out.

Artificial neural networks (ANN) are algorithms composed of a set of interconnected nodes creating a network as shown in figure 1. These nodes are called neurons. Each neuron receives inputs and provides outputs based on different characteristics such as weights associated with the inputs and an activation function that relates the neuron's input to its output depending on a threshold. Like other ML algorithms, ANN learn by examples, therefore, they need a previous training process. This process consists of selecting the weights and thresholds of each of the neurons that make up the network. These parameters are calculated using different optimization algorithms on a cost function that, over a number of iterations, will adjust each of the weights based on the set of data provided in the network training phase.

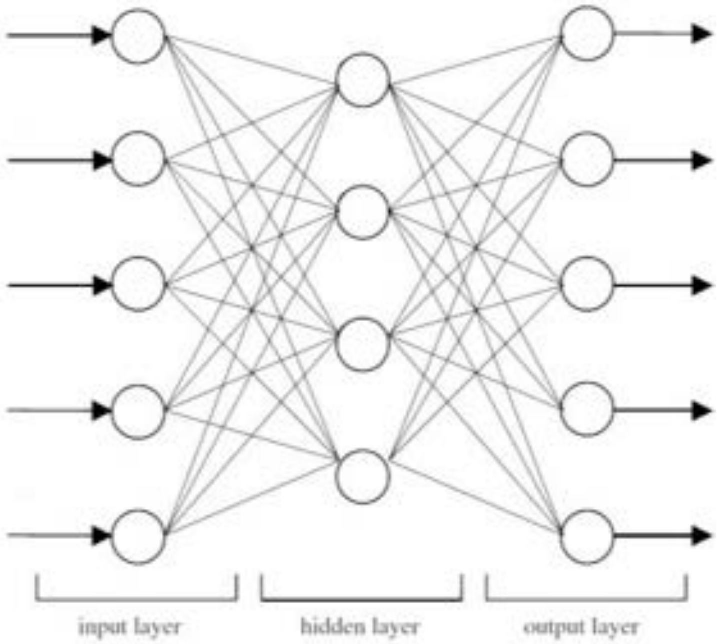

Figure 1. Structure of an artificial neural network.

Due to the potential of this technology to model complex systems based exclusively on empirical data, ANN are increasingly used in the modeling of industrial refrigeration systems for energy saving. In [9] the authors use an ANN to predict the refrigeration demand of an industrial refrigeration system by monitoring the chamber temperature. This information is used by the control system to command the action of the compressor and the different evaporators in the refrigeration room. In this way, the authors balance the refrigeration demand of the system in order to reduce peak demands. The model guarantees product quality while achieving energy savings of up to 17%. Other studies such as [10, 11] train different types of neural networks in order to model the power consumption of various refrigeration systems. For this purpose, using different variables such as those summarized in table 1, they predict the COP. In [10] the authors monitor a large number of refrigeration system variables such as evaporator temperature, condenser temperature and ambient temperature among others. They also monitor four system pressure points such as refrigerant pressure in the compressor, condenser and evaporator. After comparing six data mining techniques, the authors conclude that they obtained better results using ANN. Other variables such as condenser water flow in [11] have been used for COP prediction using ANN.

Table 1. Variables used for energy saving in refrigeration systems.

Variables	Description
Temperature and relative humidity	Air temperature and relative humidity in the cooling chamber
Condenser temperature	Condenser surface temperature
Evaporator temperature	Evaporator surface temperature
Condenser pressure	Refrigerant pressure in the condenser (high pressure)
Evaporator pressure	Refrigerant pressure in the evaporator (low pressure)
Age of the equipment	Age or level of wear of system elements
Thermal characteristics	Thermal characteristics of the refrigerated area
Refrigerant characteristics	Properties of the refrigerant used in the refrigerant circuit

Product quantity	Presence of material in the refrigerated area
Solid waste level	Particle meters. Frost level
Failure history	Log of equipment failure events in the system

On the other hand, studies such as [12] analyze two AI systems for increasing the energy efficiency of a refrigeration system. First, the authors propose a hybrid knowledge-based model using fuzzy logic and a PID controller; second, they design an ANN. Both models are used to control the system based on input variables such as the indoor and outdoor temperature and air relative humidity of the refrigeration room, as well as EER. Finally, the authors conclude that no significant energy savings were achieved with the first model; however, the use of the ANN in the control system increased the overall energy savings by more than 7%.

Among the applications of AI in refrigeration systems, the use of ANN for the evaluation of the state of the machines that make up the systems stands out. By using telemetry data from the different elements of the system, diagnosis and anomaly detection models can be trained to reduce the number of system failures. This information can be used for the implementation of new data-driven industrial maintenance techniques, better known as predictive maintenance. Several studies such as [13, 14, 15] have shown that by applying predictive maintenance techniques in industrial refrigeration systems, it is possible to reduce the overall energy consumption of the system. This fact is based on the idea that the equipment works in optimal conditions for a longer time, thus increasing the energy efficiency and the performance of the machines [14]. In [13] the authors propose a model for fault detection based on monitoring the operation of a refrigeration system. For this purpose, they train an ANN based on the temperature of the cold room and the history of system events that produce anomalous performance. The output of the neural network is used by an expert system that decides whether or not to trigger an alarm. Due to the early ability of the system to detect malfunctioning episodes, different actions can be taken to bring the system back to a normal operation mode reducing the power consumption of the system. On the other hand, [15] focus on refrigerant leak detection using ANN. Refrigerant losses in refrigeration systems contribute greatly to inefficient operation, increasing power consumption. To design the model, the authors rely on the temperatures of the refrigerant at different elements of the system, the flow rates of the refrigerant liquid and the energy consumption of the compressor. As in [13], the authors use a combined expert system for decision making.

4. CONCLUSIONS AND FUTURE TRENDS

This paper review and evaluate the state of the art of the use of AI techniques for the efficiency increase and energy saving of refrigeration systems. Throughout the literature revision, it is shown how different types of AI algorithms have been used for the modelling of refrigeration systems with the purpose of predicting, optimizing, controlling and diagnosing the behavior of industrial refrigeration systems from the point of view of energy efficiency. Different stochastic models such as genetic algorithms have been widely used in refrigeration system modelling for solving complex mathematical optimization problems.

Industries are undergoing a profound paradigm shift focusing on control, automation and digitalization. This is increasing the use of advanced data acquisition systems with IoT technologies in industries. The acquisition of a larger number of process variables in refrigeration systems has enabled the use of new data- driven artificial intelligence algorithms in the industry. These algorithms stand out for their ability to learn from system data. In this way, control systems can be trained to operate the system and adapt optimally to the needs of the system. Therefore, ML techniques such as ANN are increasingly used in the industrial sector. For this transformation, professionals from different sectors such as AI systems, software engineering and refrigeration system experts will work together in order to design advanced control systems for energy saving in refrigeration systems.

The IA methods used in industrial refrigeration systems are mainly based on process information such as temperature, air relative humidity and pressure in different elements of the refrigeration system. This information has been used in various types of refrigeration systems to detect and correct errors in real time or optimize system operation for energy saving. New trends and AI models are expected to come from deep learning, where more and more data will be used to model refrigeration systems more accurately. The use of hybrid AI algorithms techniques is also expected to grow, allowing the most complex problems to be solved. In addition, new external variables are expected to be used in the modelling of future intelligent control algorithms for refrigeration systems. Energy tariffs, weather data, event history such as door opening, product handling or operation schedules will be used together with process information in order to efficiently manage the system and reduce the energy consumption of industrial refrigeration systems.

REFERENCES

[1] AHMED, Rasel, et al. Artificial intelligence techniques in refrigeration system modelling and optimization: A multi-disciplinary review. Sustainable Energy Technologies and Assessments, 2021, 47: 101488.

[2] SILVA, F. V.; NEVES FILHO, L. C.; SILVEIRA JR, V. Experimental evaluation of fuzzy controllers for the temperature control of the secondary refrigerant in a liquid chiller. Journal of food engineering, 2006, 75(3): 349-354.

[3] AL-AIFAN, Bader, et al. Performance evaluation of a combined variable refrigerant volume and cool thermal energy storage system for air conditioning applications. International Journal of Refrigeration, 2017, 76: 271-295.

[4] CHU, Chi-Min; JONG, Tai-Lang; HUANG, Yue-Wei. Thermal comfort control on multi-room fan coil unit system using LEE-based fuzzy logic. Energy Conversion and Management, 2005, 46(9-10): 1579-1593.

[5] ZHAO, Lei, et al. Model-based optimization for vapor compression refrigeration cycle. Energy, 2013, 55: 392-402.

[6] WANG, Shengwei; JIN, Xinqiao. Model-based optimal control of VAV air-conditioning system using genetic algorithm. Building and Environment, 2000, 35(6): 471-487.

[7] CHEN, K.; LIN, G. T. Optimization of multiple-module thermoelectric coolers using artificial-intelligence techniques. International journal of energy research, 2002, 26(14): 1269-1283.

[8] LEE, Wen-Shing; LIN, Lung-Chieh. Optimal chiller loading by particle swarm algorithm for reducing energy consumption. Applied Thermal Engineering, 2009, 29(8-9): 1730-1734.

[9] CIRERA, Josep, et al. Improving the energy efficiency of industrial refrigeration systems by means of data-driven load management. Processes, 2020, 8(9): 1106.

[10] CHOU, Jui-Sheng; HSU, Yu-Chien; LIN, Liang-Tse. Smart meter monitoring and data mining techniques for predicting refrigeration system performance. Expert Systems with Applications, 2014, 41(5): 2144-2156.

[11] YILMAZ, Sezayi; ATIK, Kemal. Modeling of a mechanical cooling system with variable cooling capacity by using artificial neural network. Applied Thermal Engineering, 2007, 27(13): 2308-2313.

[12] LEE, Dasheng; TSAI, Fu-Po. Air conditioning energy saving from cloud-based artificial intelligence: Case study of a split-type air conditioner. Energies, 2020, 13(8): 2001.

[13] KUŽNAR, Damjan, et al. An intelligent system to monitor refrigeration devices. Expert Systems, 2017, 34(5): 12199.

[14] ZHAO, Yang, et al. Artificial intelligence-based fault detection and diagnosis methods for building energy systems: Advantages, challenges and the future. Renewable and Sustainable Energy Reviews, 2019, 109: 85-101.

[15] TASSOU, S. A.; GRACE, I. N. Fault diagnosis and refrigerant leak detection in vapour compression refrigeration systems. International journal of refrigeration, 2005, 28(5): 680-688.