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# Preface

In order to realize a low-carbon society and electric power system renovation, new energy service technology for air-conditioners, which accounts for about half of the power consumption of buildings, is increasingly expected. Variable Refrigerant Flow (VRF) air-conditioner is a distributed-type air-conditioning system originating in Japan. In recent years, VRF air-conditioners have been installed in most commercial buildings. According to statistics from the Japan Refrigeration and Air Conditioning Industry Association, there are 1.5 million units installed nationwide, and the total rated power consumption is estimated to be around 15 GW, equivalent to 15 nuclear power plants.

Until now, most technical books on building air-conditioning were based on the traditional central type. With the central type, the building facility designer selects each component and builds the entire system, so such specialized books were necessary. On the other hand, VRF air-conditioners are also called packaged air-conditioners, as all the components are packaged. If you only want to operate the air-conditioner just for simple cooling and heating operation, you can just install it as is. That is why there was no need for specialized books on control and management of VRF air-conditioners.

However, with the recent development of energy services and IoT technology, there is increasing need for optimal control and management of air-conditioning power from the building energy management system (BEMS) or the cloud service provider. There will be a desire for more sophisticated control and management that goes one step or two beyond the conventional simple centralized control provided by air-conditioner manufacturers.

For example, the future will require cutting-edge energy service control, such as high-speed demand response that will support the smart grid power supply and demand adjustment. It goes without saying that for energy service control in the near future, there will be a need for technology that enables high-speed and precise energy control of VRF conditioner groups distributed over a wide area via a wide-area network.

In addition, because of its high-speed and precise data communication, the database for multi-air-conditioners for buildings in the near future will be of an unimaginable scale. AI methods will become an indispensable technology for extracting useful knowledge for electric power services from this huge time series operation database and for dynamic characteristic predictive modeling.

Under the above-mentioned circumstances, when energy management system designers and future power service system integrators try to study new energy service control technology for VRF air-conditioners, next-generation energy service control for distributed air-conditioners I realized that there are no standardized specialized books.

Each air-conditioner manufacturer provides information in its catalogs and technical documents, but it is limited to old and simple control details such as routine stoppages and set temperatures. Rather than such old and simple control, it seems that there is a demand for a technical book on cutting-edge energy service control that makes full use of IoT and AI in the near future.

This book describes a new energy service control for VRF air-conditioning systems for commercial buildings in the near future of the mid-21st century. In other words, it provides an easy-to-understand introduction to cutting-edge technologies for next-generation distributed building air-conditioner energy service systems, from IoT cloud control to AI optimal control, and even standards for the smart grid supply and demand adjustment market.

The structure of this document is shown below.

Chapter 1 describes the background of next-generation power energy services that monitor and control the short period power of VRF air-conditioners for commercial buildings using IoT and AI.

Chapters 2 and 3 explain BACnet and LON, which are de facto communication standards for facility control, and discuss their interconnection with communication dedicated to VRF air-conditioners.

Chapter 4 describes a Web cloud monitoring system that monitors and controls VRF air-conditioners from the cloud, which is the “Internet” side of IoT.

Chapter 5 introduces the “virtual power meter’” method, which apportionments power consumption by building area from time series data on the operation of VRF air-conditioners, as a basic technology for future IoT-based power energy services.

Chapter 6 introduces a method for constructing a power consumption prediction model using deep learning neural networks, a representative AI technology.

Chapter 7 describes a power reduction prediction model for VRF air-conditioners and the smoothing effect in mass aggregation, aiming at future power system services such as high-speed demand response.

Chapter 8 introduces the standardization document from the Institute of Electrical Engineers of Japan for negawatts from VRF air-conditioner in the smart grid power supply and demand adjustment market.

Chapter 9 presents an implementation example of demand response communication using the OpenADR smart grid communication standard.

Chapter 10 considers the optimal operation of power and room temperature tradeoffs for VRF air-conditioners in order to adapt to the future real-time electricity rate system.

Chapter 11 describes the optimal operational control of VRF air-conditioners using reinforcement learning, an AI method, in order to further advance optimal operation.

I received the cooperation of many people in writing this book. I would like to express my deep gratitude to Mr. Hiroyuki Otake, Mr. Seiji Kondo, and Mr. Junji Morikawa of Mitsubishi Heavy Industries Thermal Systems, Ltd., for supporting the academic research that is the basis of the written content. I would like to express our gratitude to the members of the Smart Grid Technology (SGTEC) Committee of the Institute of Electrical Engineers of Japan, for providing a great deal of information. Finally, I would like to thank Yoshifumi Aoki, Specially Appointed Assistant Professor, and other members of the Ninagawa Laboratory at Gifu University for their patience and continued research.

We hope that this book will be useful in planning and constructing innovative next-generation energy service systems for VRF air-conditioners.

Nagoya, Japan Chuzo Ninagawa

# Contents

# Chapter 1
# Innovations in Air-Condition Energy Control

## 1.1 Air-Conditioning Energy Services in the Near Future

### *1.1.1 Innovative Energy Services*

This book explains advanced control and management systems for Variable Refrigerant Flow (VRF) air-conditioners by applying the latest IoT and AI technologies. Without a doubt, one of the main purposes of these systems will be innovative energy management in the background of the world decarbonization movement. In order to associate with the background, this book often refers to situation of Japan. This is not only because of the VRF's birthplace but also because of the author's actual application experiences in the country. But we would like readers to replace by the background of each country since the aim is common throughout the world.

For example for the background, the Japan prime minister's declaration that "Japan aims to be a carbon neutral society by 2050" has attracted a great deal of attention. The government will now formulate various measures to realize this goal. In order to realize a carbon–neutral society, there is no doubt that the whole country needs to take on the challenge of innovative changes in energy use.

In developed countries, reductions in energy consumption have been promoted considerably in the manufacturing and transportation sectors, but energy consumption reductions in the business and commercial sectors are not as great as in other sectors. This may be due to the increase in electricity consumption resulting from the accelerated increase in IT equipment and the increase in air-conditioning load caused by global warming, despite improvements in equipment efficiency.

Air-conditioning power consumption has always been said to account for a significant portion of energy consumption in office buildings. Therefore, improvements in air-conditioning equipment have been strongly promoted since the end of the twentieth century, resulting in significant improvements in the efficiency of equipment hardware.



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However, to promote energy consumption reduction in the business and commercial sectors as described above, further improvements are still expected in air-conditioning power consumption in office buildings. Although there is a sense that energy efficiency of VRF air-conditioning equipment has already been sufficiently improved, there may still be much untapped potential for energy efficiency improvement in terms of control operation.

Today, in many areas of society, the importance of services has begun to shift from devices to services. For example, automobiles are shifting to mobility services, and music CDs are shifting to downloading services. Traditionally, air-conditioning power consumption has been regarded as a result of operation and not an object to be controlled. However, there may be a service that not only reduces energy consumption but also creates innovative value by changing the way of thinking and controlling air-conditioning power consumption.

Most of the energy consumed by modern air-conditioning equipment is supplied by the commercial power grid, with the exception of some equipment. Therefore, it is very much related to the power system reform that has started in Japan, which aims for a low-carbon society. Innovative services for air-conditioning operation should be consistent with the low-carbonization of the electric power system, so that the vectors match, leading to a carbon-free society.

Until now, the contribution of air-conditioning to energy conservation and low-carbon emissions has been limited to the rated efficiency and seasonal efficiency of the equipment itself. Little consideration has been given to the coordination of air-conditioning operations from time to time. However, load operation coordination for consumers, which will be required by the reform of the electric power grid system, is necessary for energy conservation and low-carbonization of society as a whole.

The key to power system reform is the shift from fossil energy, mainly thermal power generation, to renewable energy. When renewable energy becomes the main power source, it will become extremely difficult to balance supply and demand on the supply side and the demand side from time to time. In such a near-future power system, there is a possibility of creating an innovative service that has never been thought of before, which improves the energy efficiency of the entire power grid system by optimally controlling air-conditioning power consumption in accordance with the short-time supply and demand of the power system. To achieve this, it is necessary to adjust VRF air-conditioning power consumption at high speed in a fine-tuned manner.

The VRF air-conditioner, also called building multi-type air-conditioner [1], is a distributed air-conditioning system originated in Japan. In this type of air-conditioner, many indoor units are connected to one outdoor unit as shown in Fig. 1.1. It is characterized by the fact that many indoor and outdoor units can be operated independently of each other, which is the reason why it is called a decentralized air-conditioning system. The compressor speed of the outdoor units is continuously controlled by an inverter because the refrigerant flow rate required by each of the indoor units fluctuates from moment to moment. Therefore, it can be said that the system is originally equipped with a mechanism to control power consumption from moment to moment.

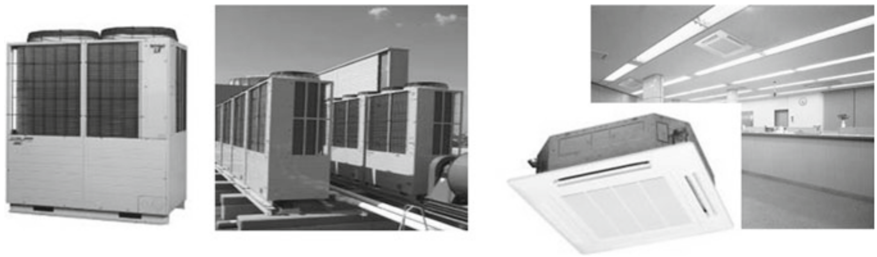

**Fig. 1.1** Variable refrigerant flow (VRF) air-conditioner, also called building multi-type air-conditioner

Since the original function of building-use air-conditioners is not to control power consumption, the technology to optimize the trade-off with temperature control and allowable power consumption control has not yet been developed. This would require advanced operation technology that adjusts the factors of many complex air-conditioning target conditions and refrigerant circuit conditions. This is the paradigm shift that this book addresses toward innovative operation that is distinctly different from conventional air-conditioning technology.

The two technological foundations supporting this paradigm shift to innovative operations may be the Internet of Things (IoT) [2] and artificial intelligence (AI) [3]. Instead of embedding operational service control software into embedded controls at the time of manufacture, IoT enables precise and high-speed communication control from the cloud. AI enables complex and uncertain operational conditions to be handled beyond each operator's skill and knowledge.

With the development of IoT in recent years, there is an increasing need to control air-conditioning power and comfort from building management systems and cloud-based service providers. Advanced control that goes one or two steps beyond the standard remote controller provided by air-conditioner manufacturers will also be desired.

Innovative market systems of electric energy for smart grid [1] is being developed in some countries. Cutting-edge energy services such as precise and fast power consumption control that correspond to this market development trend will be required in the future. Needless to say, such near-future power consumption control services will require IoT communication technology for precise and fast control information from the cloud via wide-area networks.

The advancement of industrial application of AI technology has also been remarkable in the past decade. The IoT has made it easy to collect and store vast amounts of time series data, which may lead to revolutionary changes in data utilization technology. It is indisputable that the accumulation of sufficient quantity and quality of data and its utilization technology are the fundamentals that support AI. The time is ripe for innovation in air-conditioning energy management and control systems for the twenty-first century, which will be powered by IoT and AI, which are like the two wheels of a car.

Currently, we believe that there is a need for a specialized book focused on the VRF air-conditioning facility that explains the state-of-the-art energy control technologies using IoT. But in reality, no appropriate VRF-specialized book can be found. Therefore, this book describes the VRF air-conditioning energy control technology for the new era using IoT and AI.

### *1.1.2 Electric Power System Reform and Air-Conditioning Control*

(1) **Renewable Energy and Electric Power System Reform**

With the exception of some gas engine models, the energy source for VRF air-conditioners is a commercial electric power system (i.e., power grid). At the beginning of the twenty-first century, this power system is undergoing a once-in-a-century transformation.

According to the Japanese government Energy White Paper, its total electricity consumption has been almost 1 trillion kWh per year in recent years [4]. This is more than twice the amount consumed during Japan's period of rapid economic growth, such as in 1973. It can be said that electric energy has supported Japan's economic development, which is unprecedented in the world.

However, the Great East Japan Earthquake of 2011 marked a turning point in Japan's electric energy supply. Since the earthquake, nuclear power plants have been shut down one after another, either because they could not operate due to the disaster or because of a review of safety standards. Since then, until 2021, thermal power generation has been the dominant source of electric energy supply in Japan.

As is well known, Japan has very scarce energy resources such as oil and natural gas that can be used for the latest thermal power plants and are almost entirely dependent on imports. Coal is also a resource that exists in Japan, but it cannot be relied upon to a large extent in terms of $CO_2$ emissions.

In 2012, a preferential treatment, Feed-In Tariff (FIT) was established as a preferential measure for the spread of solar power generation, and since then, solar power generation has been introduced in large quantities.

Photovoltaic (PV) and wind power generation is a clean and safe power generation method that does not emit $CO_2$. Of course they should be included in Japan's future main power sources. However, the output of PV and wind power generation frequently fluctuates greatly depending on solar radiation conditions.

Large-scale hydroelectric power plants are also included in what are called renewable energy sources, but they are controllable and non-volatile sources from the perspective of the power system. PV and wind power, on the other hand, are both renewable energy sources and naturally variable power sources. This essential characteristic of natural variability is the technological core of power system reform.

Maintaining the system frequency is the most important factor in an AC electric power system. As previously shown in Fig. 1.2, the basic physical characteristic of

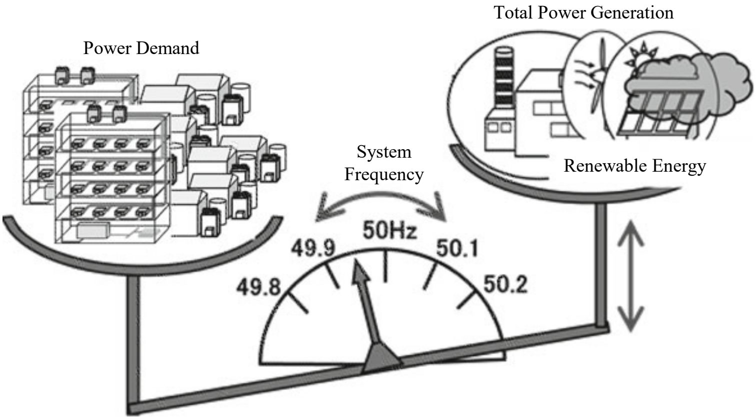


**Fig. 1.2** AC power system supply–demand balance and resulting system frequency

an electric power system is that the system frequency is determined by the total generation-consumption balance between the supply and demand of electric power in the entire system [1].

In the modern power system, the central power supply control center of the electric power manufacturer issues commands to adjust power generation from time to time, second to second, to large thermal power plants to maintain the supply–demand balance. However, as more and more power is generated by solar and other naturally variable sources, it is becoming increasingly difficult to maintain the supply–demand balance by controlling power generation on a moment-by-moment, second-by-second basis.

As one of the countermeasures, we have been developing technologies to absorb fluctuations generated by renewable energy sources using storage batteries installed on the electricity supply side. In any case, consumers, who are the users of electricity, have not been able to operate in a coordinated manner for short-time supply–demand balances of a few minutes to several tens of minutes. There is a late-night electricity discount system for long periods of time during the night, but it is too late to be used for controlling the supply–demand balance from time to time.

In other words, the demand side has always been able to use electricity whenever it wanted, as much as it wanted with perfect quality. This is a paradigm in which voltage and frequency, which are qualities of electric power, are assumed to be perfect and are entirely controlled by the supply side.

However, in addition to controlling the amount of electricity supplied on the supply side, there is also the possibility of controlling electricity usage on the demand side. This is the function known as “Demand Response (DR)” [1]. This is a function in which the demand side controls the amount of electricity consumption by responding to requests from the supply side from time to time by utilizing a computer network.

A precise and large-scale IT system will be expected to balance the fluctuations in power generation and power usage from moment to moment throughout the entire power system. This is called a “smart grid” or “next-generation power system”.

### (2) Power System Reform and VRF Air-Conditioners

Air-conditioners were originally regarded as simple loads that only consumed power on the demand side from the power system side’s perspective. This is the value of electricity from its energy aspect alone. In fact, this is true when viewed as the effective amount of electricity that actually becomes energy and ultimately heat.

However, as mentioned above, from the perspective of maintaining and controlling the balance between generation and load in the power system, i.e., maintaining and controlling the system frequency by precisely matching supply and demand, controlled demand suppression is equivalent to generation acceleration.

Therefore, the ability to control the suppression of power consumption will be useful. The controlled suppression of power consumption at the required timing, at the required speed, and for the required amount in line with the power system conditions creates the value. In Europe and the USA, this ability to adjust supply and demand is called “flexibility”.

Originally, air-conditioners, including but not limited to VRF air-conditioners, have been regarded simply as electric power loads. In that sense, they are “consumers” because they are in the position of being consumers of electric energy.

However, in an advanced power system, as described above, the controlled suppression of demand can also be regarded as a virtual amount of electricity generated, called a “negawatt” (Negative watt), in the sense of negative electricity generation. In the sense of generating such negawatt, loads that are capable of controlled power suppression are sometimes positioned as producers. It is sometimes called a “Prosumer” because it can play the role of an electric power consumer at one time and an electric power producer at another time.

Of course, to function as a power system, it must have more than just the simple characteristic of being able to suppress and control power consumption. The key is the presence of service providers that aggregate the demand-responsive loads dispersed over a wide area. In addition, the providers have to be based on strict specifications of DR rules from the power system agency, maintaining the required suppression amount, response speed, and duration.

The power loads that can be prosumers have a decisive feature. It is that DR by power suppression control must be performed at the request of the power system side, not at its own convenience or timing. This cannot be done with power load facilities whose original purpose cannot be sacrificed even for a moment or a minute amount. In the case of VRF air-conditioners, the thermal inertia of a building, such as a large office building, makes it possible to operate them while suppressing power consumption for a short period of time without compromising air-conditioning comfort. For this reason, air-conditioning equipment has been included as a target load for DR in the past.

**Table 1.1** Value of power control services for smart grid

| | kWh | ΔkW |
|---|---|---|
| Essence | Energy accumulation | Control change value |
| Future value trends | 10 yen or less/kWh | More than a few hundred yen/kWh |
| Purpose of use | Base energy | Sales to the electricity supply and demand adjustment market |
| Management control perspective | Energy-saving management | Supply and demand adjustment service |

In order for air-conditioning to function as it should, it is necessary to be able to maintain comfort. There is the problem of possible time periods and possible durations for power suppression. In this respect, as mentioned above, the ability to control power suppression for a short period of time with high speed and precision at the right time is valuable. Table 1.1 shows the new value of controlled power suppression (ΔkW) in comparison with the conventional value of power accumulation (kWh). The new value ΔkW is neither the amount of electricity consumed by the load (kWh) nor the instantaneous absolute amount of electricity at that moment (kW), but the controlled change in a short period of time.

This ΔkW is required, for example, in a situation where photovoltaic power generation provides a sufficient amount of power during the day, but rapidly decreases as the sunsets. In this case, the outdoor air temperature is generally decreasing, and the VRF air-conditioning heat load is also on a downward trend during the time period near sunset. Therefore, this is the time when the required power by the air-conditioner decreases. There is a high possibility that the side effects of the room temperature caused by the power suppression can be avoided.

In the future, the ΔkW service will be very valuable for controlling the suppression of electricity demand at high speed and with precision during a short period of time at "the right moment" from the viewpoint of the power system. However, the amount of adjustment for each individual air-conditioner in a building is small and uncertain in terms of the scale of the power system. Therefore, the large-scale, high-speed, and precise IT system is a decisive factor. In the case of VRF air-conditioners, it is important to have such an IT service provider that stands between the power system and the VRF air-conditioners.

## 1.2 Distributed VRF Air-Conditioning Energy Services

### *1.2.1 Characteristics of VRF Air-Conditioners*

(1) **VRF Air-Conditioners as a Decentralized Air-Conditioning System**

Air-conditioning systems for commercial buildings can be divided into two main types according to their basic heat source: centralized heat source type and distributed heat source type.

The centralized heat source type is a large-scale air-conditioning machine installed in the basement of a large office building or commercial facility. On the other hand, the distributed heat source type is a group of VRF air-conditioners installed throughout the entire building. In recent years, they have become common especially in buildings of medium size. This document describes the distributed air-conditioning system, that is, the VRF air-conditioning system for commercial buildings.

As shown in Fig. 1.3, VRF air-conditioning systems have spread rapidly since the beginning of this century. Nowadays in some countries in the world, including Japan, almost all commercial buildings of medium size or smaller are now occupied by VRF air-conditioning systems. The data is based on the statistics of the Japan Refrigeration and Air Conditioning Industry Association [5]. The number of outdoor units shipped over their 13-year legal service life is estimated to be about 1.5 million units. Assuming that the power consumption of an average model is simply 10 kW, although not all of them are in operation or all of them may not operate at the same time, the equipment load of 1.5 million units reaches 15 GW.

Similar to residential room air-conditioners, the components of VRF air-conditioners are based on indoor and outdoor units connected by refrigerant piping. However, VRF air-conditioners differ from room air-conditioners in that several to several dozen indoor units are connected to one outdoor unit by branched refrigerant piping. The term “multi” refers to the connection of multiple indoor units.

Generally, outdoor units are installed on the rooftop of a building. The large box-shaped outdoor units can often be seen lined up on the roof of an office building. The total length of the refrigerant piping system may reach about 1000 m because the refrigerant piping branches from the outdoor units on the rooftop to the numerous indoor units on each floor. The total length of the refrigerant piping system may reach about 1000 m. In some cases, the long piping paths that extend throughout

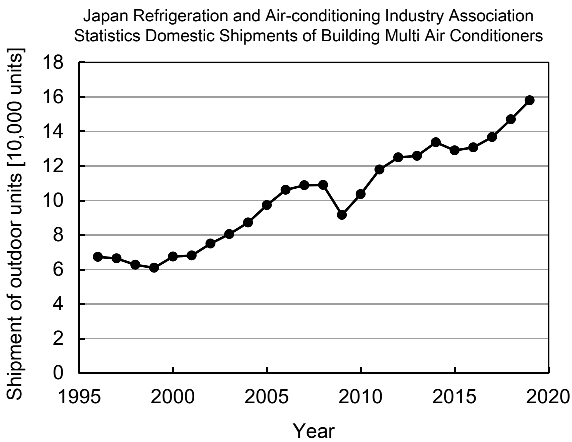


**Fig. 1.3** Statistics on shipments of VRF air-conditioners in Japan [5]