2004

The Components and Control Methods for Implementation of Inverter-Controlled Refrigerators/Freezers

Wen Ruey Chang
Industrial Technology and Research Institute

Der Yeong Liu
Industrial Technology and Research Institute

San Guei Chen
Industrial Technology and Research Institute

Nan Yi Wu
Industrial Technology and Research Institute

THE COMPONENTS AND CONTROL METHODS FOR IMPLEMENTATION OF INVERTER-CONTROLLED REFRIGERATORS/FREEZERS

Wen-Ruey CHANG*, Der-Yeong LIU, San-Guei CHEN, and Nan-Yi WU

Energy and Resource Laboratories (ERL),
Industrial Technology and Research Institute (ITRI),
Chutung, HsinChu, Taiwan, R.O.C.

* Corresponding author. TEL.886-3-5914221, FAX 886-3-5820250,
E-mail: wrchang@itri.org.tw

ABSTRACT

This article describes the difference in performance of household refrigerators/ freezers operated by one constant speed and one variable speed controlled compressors respectively, especially for their storage temperature control methodology and energy efficiency potential. The inverter-controlled refrigerator/freezer with one variable speed controlled compressor allows rapid cooling function for customers. While this type of refrigerators/freezers under low-speed operation, energy loss due to on/off cycle is reduced, so the energy consumption is saved. From the testing results, the inverter-controlled refrigerator/freezer has more energy-saving potential compared to that of fixed frequency type by 22~34% under ambient temperature at 15 and 30°C, respectively. Some control components were applied to the inverter-controlled refrigerators/freezers in recent years, including variable speed compressor, brush-less DC motor/fan for evaporator/condenser, chilled air flow damper driving by one stepping motor, and one more thermostats for temperature control. Each component has its specific function and signal control methods. An inverter-controlled refrigerator/freezer should be operated with microchip and also the power electronic board, so it is easy to adopt digital intellectual control methodology. Under different operation modes and conditions, the central control unit of the inverter-controlled refrigerator/freezer provides optimal performance by complying the pre-designed control logistics. This article also gives a preliminary introduction of these components and control methods for inverter controlled refrigerators/freezers.

1. INTRODUCTION

According to the statistic data, the household refrigerator/freezer takes up with 17% of the total household energy consumption as 38 billion kWhr/year in Taiwan. To improve energy utilization and minimize carbon dioxide emission, some governments around the world are tending to establish increasingly strict regulation on energy consumption for household appliances. Some strategic methods were proposed to reduce energy consumption for household refrigerators/freezers, including with increase of thermal insulation thickness for walls, improvement of thermal insulation material or applying vacuum insulation panels, using a high-efficient compressor, and optimization of the refrigeration system etc. To reduce energy consumption greatly for refrigerators/ freezers, novel inverter controlled technology for the variable speed compressor with a brush-less DC (BLDC) motor is paying attention in recent years, especially in Asia area. The inner structure diagram and disassembled photo of a four-pole BLDC motor is shown in Figure 1. The energy-saving potential was evaluated about 30 to 40% in some published literatures and press medium. The DC motor inside the variable-speed compressor is driven by a digital signal processing (DSP) controller, one sensor-less power electronic circuit with pulse width modulation (PWM) regulation vs. its driving machine codes, a switching power supplier, and some peripheral communication circuits. The control sequence diagram for one six-step driving inverter is indicated in Figure 2, and the PWM waveform is described in Figure 3. This type of controller described previously is implemented as an inverter, and the product is generally named as variable frequency refrigerators/freezers in Asia area. The compressor rotation speed is modulated through power frequency feedback control, what helps to realize intellectual control, increase power efficiency and energy saving. The rotation speed of compressor is usually controlled within 1600~4800 rpm for normal operation. At high speed, the refrigerator/freezer can reach the setting storage temperature during a short time; so the rapid cooling function can be achieved. Sometimes, the refrigerator/freezer would not be opened for a long time, and the low speed operation methodology can reduce the energy consumption and also ensure low noise. Therefore, temperature stability is improved by smart feedback control, and so food freshness is maintained. Besides, as the on/off switching frequency of the compressor is reduced, the running life of the electric appliance can be also improved.

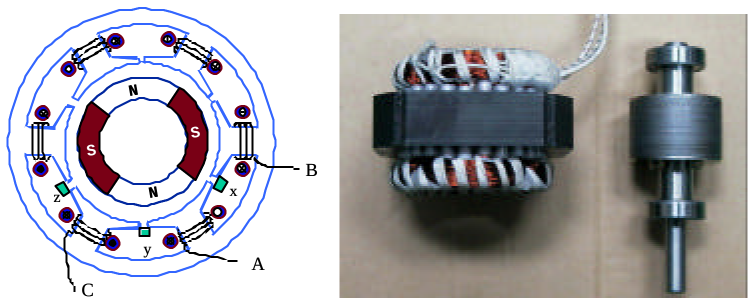

Figure 1: Inner structure and photo of four-pole brush-less DC motor.

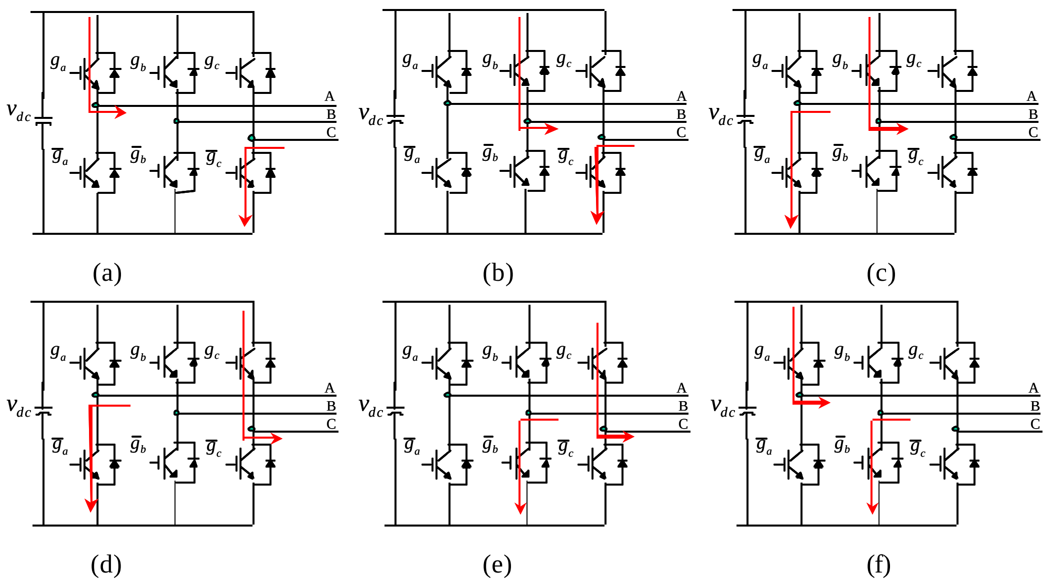

Figure 2: (a)-(f) Control sequence diagram for six-step driving inverter.

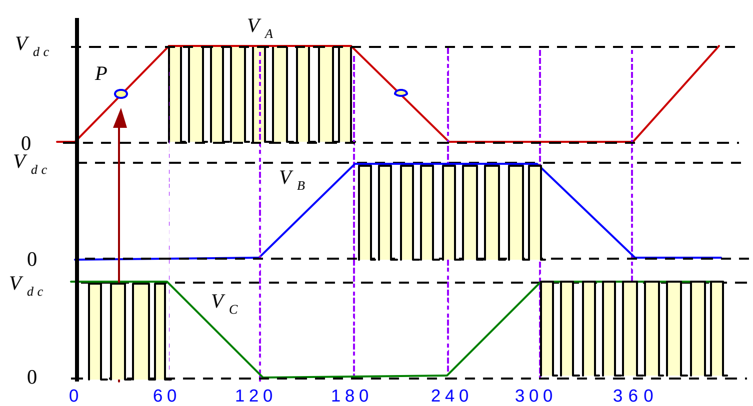

Figure 3: Pulse width modulated voltage waveform.

A traditional refrigerator/freezer uses one AC induction motor/compressor with a constant frequency and a respective fixed rotation speed. The on/off operation mode is used to maintain its refrigeration storage temperature. Within an acceptable setting temperature range, the compressor turns on and off following the signal of thermostat relay inside the refrigeration/freezer cabinet. For on/off control method by using an ac compressor, the storage temperature of fridge fluctuates vastly and the energy consumption is more than that by inverter-controlled product, generally. The refrigeration capability of inverter-controlled refrigerators/freezers can be adjusted through variable speed regulation; so the main power turning on/off frequency could be reduced greatly, and the energy consumption could be also decrease due to the increase of refrigeration cycling efficiency.

2. ADVANTAGES AND ENERGY-SAVING POTENTIAL FOR INVERTER-CONTROLLED REFRIGERATORS/FREEZERS

From the second law of thermodynamics, the coefficient of performance for one refrigeration system can be improved as by continuous running, if possible, compared to intermittent on/off operation under the same condition. The whole summation of each cycling loss could occupy a large percentage of household energy consumption. The percentage running time R', defined as $d'/D' \times 100$, is usually 40 to 50% for apparatus with on/off control for the refrigerating source, where d' is the duration of the refrigerating system operation during an operation cycle, and D' is the total duration of operation cycle minus the duration of the defrosting cycle for refrigerators/freezers. In general, the storage temperature of refrigerator/ freezer is maintained by turning on/off for thermostat relay of AC compressor/motor. Such control method causes cycling loss and reduces its energy efficiency. Under off-cycle state, refrigerant inside pipeline of refrigeration system will flow through capillary tube from condenser at high pressure vs. temperature into evaporator at low state. As the motor stops and refrigeration system is in equilibrium, evaporator temperature will increase due to pressure balance. Although the natural convection heat quantity is small inside refrigeration cabinets, it does not affect food preservation. But when the system is turning on again, warmer refrigerant vapor in the evaporator of freezer compartment will exhaust additional refrigeration capacity during starting instance. The system needs to re-establish the pressure potential between condenser and evaporator, for the refrigerant reaching normal conditions. Coulter et al. (1997) studied the starting and steady state cycling losses of refrigerators/freezers experimentally at room temperature from 60 to 100°F. The starting operation caused refrigeration loss of system by 3 to 17%, the energy consumption increased by 1 to 9% and the COP reduced by 5 to 25%. Wicks' study (2000) indicated that the variable speed control of compressor would reduce temperature variation than that by on/off control for a refrigerating system. For one system with refrigeration capability rated by 12000 Btu/hr operating under partial load of 6000 Btu/hr, variable speed control would save more energy than that by on/off control by 41% from the analysis of thermodynamic second law. On the other hand, energy consumption of refrigerators/freezers would be decreased by reduction of pressure potential cross compressor's discharge and suction lines. From the study by Woodall et al. (1997), the energy efficiency of refrigerators/freezers improved by 10.5% due to decrease of temperature difference between the condenser and evaporator, as the rotation speed of compressor decelerating from 3600 rpm to 2400 rpm under steady-state operation.

The energy efficiency potential was also studied experimentally in this paper with one variable frequency refrigerators/freezers, with BLDC motor/compressor noted by 'B', compared to one fixed frequency type, installed with AC induction motor/compressor noted by 'A'. The fixed frequency sample, 'A' was made on 2001 by local manufacturer in Taiwan with storage volume rated 480 liters. The inverter type 'B' with 470 liters of rated storage volume was imported from Japan, manufactured on the same year. The testing procedure used here is following CNS-2062 standard (2001) used in Taiwan, similar to ISO 8561 (1995) and ANSI/AHAM HRF-1-1988 (1988). The room ambient temperature is fixed at 15 and 30°C, standing for winter and summer condition respectively. The relative humidity is controlled at 75%, and the storage temperature is set at -18±0.5°C for frozen food compartment and 3±0.5°C for fresh food compartment. Refrigerators/Freezers 'A' and 'B' were tested under the same condition concurrently in an environmental controlled room. From the testing results, variable speed product 'B' had higher energy efficiency than that of fixed frequency product 'A' by 22% at room temperature of 30°C. As the room temperature was set down to 15°C, the energy efficiency potential was raised up to 34%.

Table 1: Comparison for Energy Consumption of Testing Refrigerators/Freezers at Ambient Temperature of 15/30°C.

Ambient Temperature	30°C		15°C	
Type	Energy consumption (kWh/yr)	(B-A)/A	Energy consumption (kWh/yr)	(B-A)/A
Fixed Frequency Product 'A'	932.5	-	474.0	-
Variable Frequency Product 'B'	725.8	-22.15%	311.9	-34.2%

3. CONTROL METHODS FOR INVERTER CONTROLLED REFRIGERATORS/FREEZERS

In digital era, intellectual control function is the inevitable trend for home appliance development. The controller of variable frequency refrigerator/freezer can adjust some rotating components, including the BLDC motor/compressor, to fit the best operation under discrepant environment condition and customer's propensity. This smart controller should be including with digital signal processor with PWM modulation, sensor-less control circuits and driving machine codes for refrigerant compressor, power supply and transformer with power factor correction, ability to defense of electromagnetic interference, and some peripheral analog sensors or communication. The controller's methodology provides flowchart of physical information and corresponding judgment of inter devices for smart appliances. Better control methods could serve with optimal performance and behave friendly for any kind of consumers of household appliances. The control methods applied in variable frequency refrigerators/freezers are described in Figure 4, where the input signals are coming from temperature transducers, electro-switches like doors or function bottoms, and timer for defrosting or adaptive control. The output signals, which are processed by DSP controller with smart methodology, could regulate suitable actions for the BLDC compressor, Fan/motor, chilled flow electro-damper, and defrosting heater. Sometimes, the amplitude of these control signals is decided following consumer's propensity, especially for homemakers, e.g. quick freeze for meat or fresh sea food after market. These normal control parameters or special functions should be built as a database from a lot of performance testing data and electro-mechanical debug consideration.

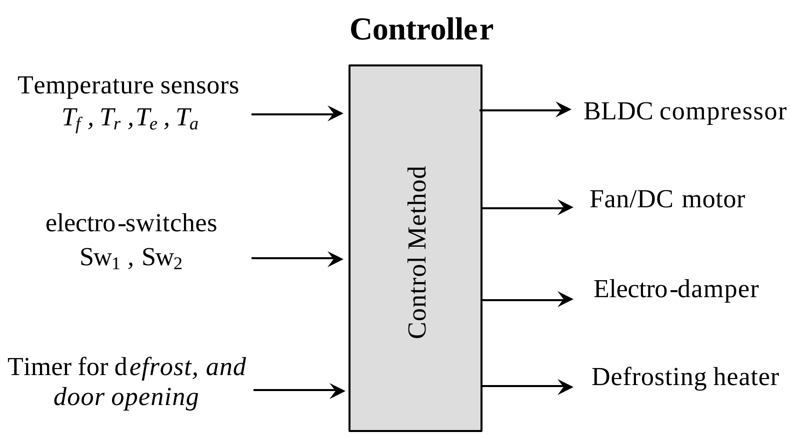

Figure 4: Control methods for variable frequency refrigerators/freezers.

In general, basic control methods of variable frequency refrigerators/freezers include temperature control method, defrosting heater control method and door opening control method. Depending on additional functional requirements, more control methods can be established and flashed as machine codes in the DSP micro-controller. Some common control methods are describing in this paper as following.

3.1 Frozen Food Storage Temperature Control Method

For some fixed frequency types of refrigerators/freezers, the frozen food storage temperature is maintained by turning on/off for compressor from the criteria of freezing temperature difference DT_f between setting value of compartment bottom T_{fs} and actual value read T_f by thermostat inside the freezer compartment. Variable frequency refrigerators /freezers use a pre-defined methodology to maintain constant freezing temperature and also reduce the cycling loss. A functional relationship between freezing temperature difference DT_f and compressor rotation frequency, *Fz*, was established by experiment during product development as $Fz=f(DT_f)$ shown in Figure 2. The controller sends out digital signal following this relationship to driver of compressor, and then the suitable rotation speed can be achieved. Under stable temperature control requirement, large DT_f will react with quick rotation speed of compressor for quick freezing function, and lowest speed control will provide low noise and low running percentage with almost the same efficiency with BLDC motor driver. For different operation conditions, such as door open/closed, energy saving/ fast cooling mode and defrost, variable speed compressor will implement different control functions for customers.

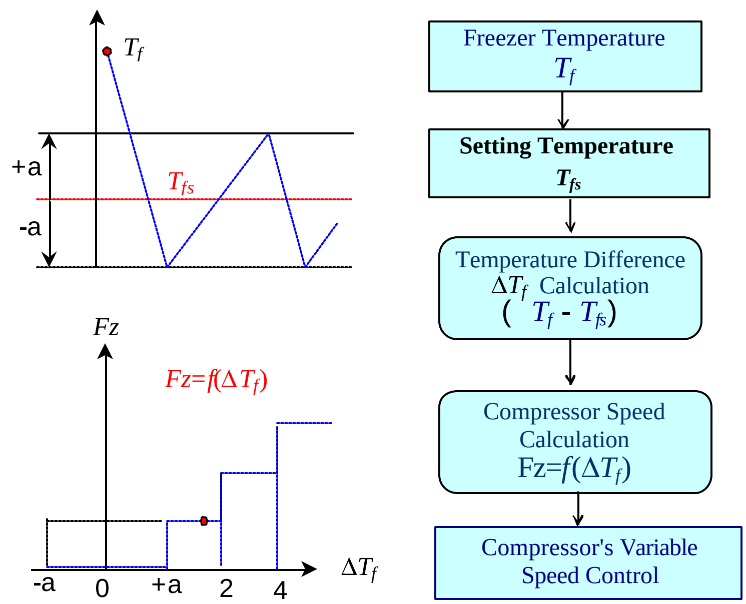

Figure 5: Frozen food storage temperature control flowchart.

3.2 Defrost Control Method

The key technology for defrost control method is determination of starting time and defrosting duration for electrical heater below the finned tube evaporator in freezer compartment. The power specification of defrosting heater will also affect this procedure. There are many ways to judge the starting time for defrosting. For example, use fuzzy algorithm to determine with pre-established database, or put different types of sensors inside the evaporator and detect frost thickness or temperature difference between frost and fins. The relay dominated by a timer is usually applied to defrost for household refrigerators/freezers. The frost's formation is very complicated and this simple method by regular defrosting cycle usually consume more energy than that of actual necessary. Novel variable frequency refrigerators/freezers use defrosting methodology induced from theoretical study and performance testing database. In recent years, a lot of patents were proposed to optimize the defrosting process. For example, a new idea with compressor's running speed as a weight index for induction of defrost interval was implemented in some inverter-controlled refrigerators/freezers. Under variant door opening, season changes or costumer's operation, frost formation in the evaporator behaves with more uncertainty. Basic defrosting control method is summarized as in Figure 6, where the flowchart describes the control sequence for each component associated with defrosting, including with compressor, fan/motor of evaporator, timer and defrosting electric heater.

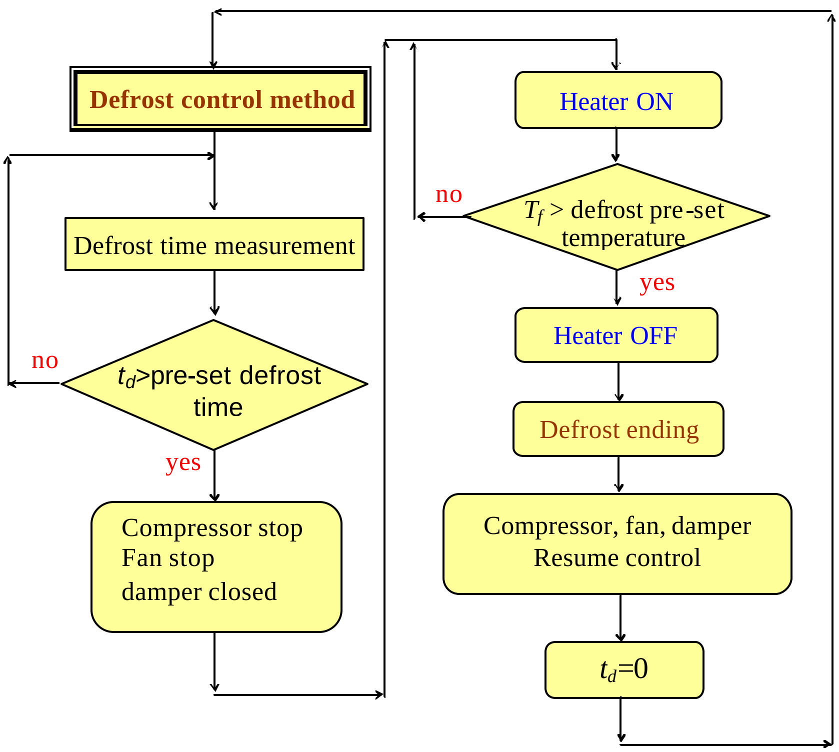

Figure 6: Defrosting Control Method

3.3 Door Opening Control Method

When the door of refrigerator/freezer is open, moist and warm air entrance into the refrigerator/freezer compartment and will also increase the heat load compared to that of door-close condition. If the chilled space opened to ambient for a long period, e.g. over a half minutes, and there is no proper control mechanism to maintain refrigeration/freezing temperature, the freshness of storage food will be affected. If door is open shortly, the cooling capacity by the running compressor can compensate the entrancing thermal load, so the storage temperature variation is small. If door is open too long, refrigerator/freezer needs additional cooling capability to cope with additional heat load. The BLDC compressor of variable frequency refrigerators/freezers has a potential for wide range speed operation with keeping almost the same efficiency. As the doors are open for a long time, action of door switches will start the clock inside controller to judge the compressor's speed to provide available cooling capacity. Different door opening status results in different thermal load of refrigerator/freezer. For example, the thermal incursion for freezer's door opening is larger than that for refrigerator's door opening. So control method is a little different for variable door opening situation and door opening time period.

For door opening control method, switch detects door-opening status. To prevent thermal entrance from ambient, circulation fan in compartments will be stop as the door is open. Meanwhile, the controller starts to calculate door opening time, and regulates the necessary running speed and corresponding frequency for inverter controlled compressor. When both door opening time and temperature variation exceed the pre-set values, the highest speed should be maintained to overcome the continuous thermal entrance. After door is closed, the fan motor will be resumed and the door opening time will be reset to zero. Some notice alarm or voice function for costumers is built-in to confirm the doors being close after using. Some available control method after door opening is shown in Figure 7.

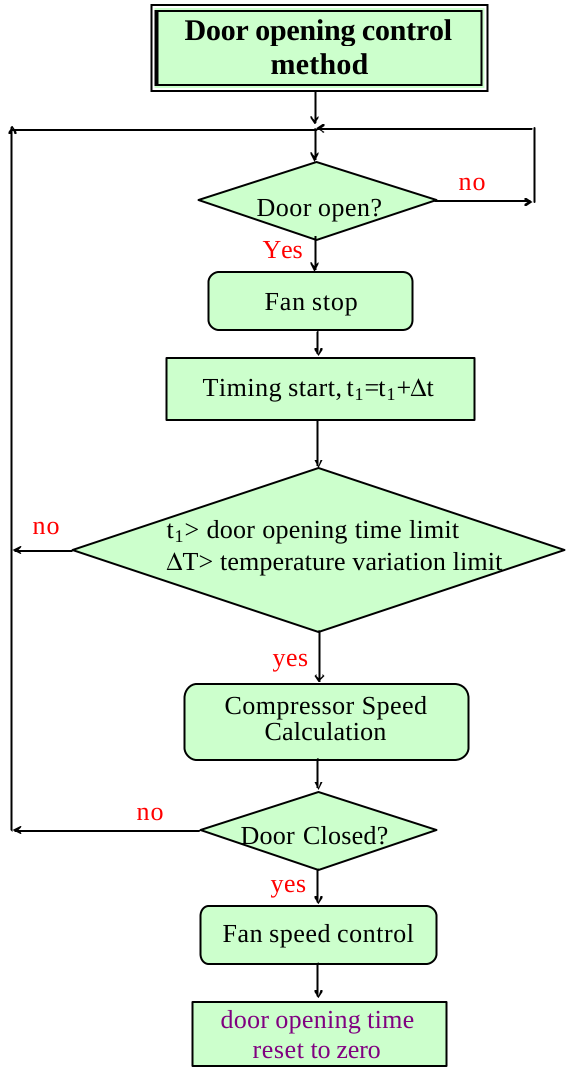

Figure 7: Door Opening Control Method.

3.4 Other Control Methods

Proper control methods can improve the efficiency of electrical products and some friendly user-orientated function will encourage the usage of smart home appliances. Due to acceptable price for DSP microchip and memory IC, more and more convenient functions will be implemented in these years, including home networking by home electric appliances. Digital controlled inverter refrigerator/freezer is sometimes focused as a representation product for the future home communication. In some product exhibitions, there were some spotlighted refrigerators/freezers with internet-communication and multi-function control ability, which were propagating the coming digital communication era. Based on user's habit operation, the novel product will self-learn and behave friendly to provide multiple service automatically. Such demand or control method can be converted to control method. For example, at night or when nobody home, the variable frequency refrigerators/freezers will turning to energy-saving state automatically due to the long term status of doors close. Some odor detection function will tell its master by notice music or LED display to handle the destroy food inside cabinet. The development for multiple temperature storage zones is also the other popular feature for manufacturers, which uses double evaporators with different evaporation temperature for refrigerant to maintain the storage conditions for fresh food and frozen food, respectively. The refined temperature or moist regulation for different compartments is sometime carried out by electric heater, which is dominated with solid stated relay or CMOS inverter. So, the fresh vegetable and fruit compartment can be providing the long-term storage service with warmer condition than that of cheese or frozen food.

4. CONCLUSIONS

In recent years, the price for digital signal processing micro-controller has been gradually dropping and gaining market competitive advantage. Therefore, home appliances can realize the idea of digital control. With the same mechanical and electrical configuration, many complicated control methods only need to expand software program and memory to process peripheral signals or drive key components in appliances, such as BLDC motor in compressor, fan motor and electric heater, so the need of optimization can be satisfied. Even by software upgrade, the newest control program can be copied to appliance through communication port. Consumers can enjoy updated and more convenient services. Development for inverter-controlled refrigerator can be considered as a revolutionary advancement for white appliances. It not only has low noise, constant temperature control, fast cooling and freshness preservation and energy saving. Variable frequency control even makes refrigerator intellectual. It adjusts compressor speed and puts control over other components according to various conditions. Variable frequency refrigerator needs proper control method to obtain good performance. It also needs integration among all components to achieve optimization in speed and temperature control under different input conditions.

Variable frequency control method uses designer's framework and works with system simulation. To verify or adjust control parameters, it usually needs a long-term performance test under different ambient conditions to establish the database for reliable control or empirical formula for parameter control. Intellectual control is the development trend for appliances. Low cost electrical and electronic components are available to help realize the idea of implementing software into appliances. Inverter controlled refrigerator adopts digital control, so refrigerator temperature control becomes more accurate than before. Through different control method planning, consumer needs in food freshness, low noise and humanistic control can be satisfied.

REFERENCES

William H. Coulter and Clark W. Bullard, Experimental analysis of cycling losses in domestic refrigerator-freezers, ASHRAE Transactions, Vol.103, No.1, 587-596, 1997.

Frank Wicks, 2nd law analysis of ON/OFF vs. Frequency modulation control of a refrigerator, Proceedings of the Intersociety Energy Conversion Engineering Conference, Vol.1, 340-344, 2000.

Terrence R. DuMoulin and Douglas A. Collings, Higher efficiencies by means of variable-speed technology in a domestic refrigeration application, ASHRAE Transactions, Vol.104, No.2, 652-657, 1998.

Robert J. Woodall and Clark W. Bullard, Simulating effects of multispeed compressors on refrigerator/freezer performance, ASHRAE Transactions, Vol.103, No.2, 630-639, 1997.

National Bureau of Standards: Chinese National Standard. Electric refrigerators and freezers, General No. CNS 2062, Classified No. C4084, 2001.

ISO, ISO 8561, Household frost-free refrigerating appliances - refrigerators, refrigerator-freezers, frozen food storage cabinets and food freezers cooled by internal forced circulation - Characteristics and test methods, 1st ed., 1995.

AHAM, ANSI/AHAM HRF-1-1988, American National Standard Household Refrigerators/Household Freezers, April 7, 1988.

ACKNOWLEDGEMENT

The authors would like to thank the Energy Commission, Ministry of Economic Affairs, Taiwan, for the support of this study under the Energy R&D funding.