Research Article

MODELING AND ANALYSIS OF SINGLE-PHASE INDUCTION MOTOR DRIVE FOR VARIABLE CAPACITY CONTROL OF A REFRIGERATOR COMPRESSOR

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ABSTRACT

A refrigeration system with single-phase induction motor compressor is used to operate the cooling process at constant speed and On/Off control mode. Using a motor driver with this system allows us to utilize variable speed control algorithms, and gives many opportunities to improve energy efficiency. This paper presents developed model simulation results of a single-phase induction motor drive to improve energy efficiency for a refrigerator compressor motor. For this aim, firstly, a household refrigerator compressor and a compatible drive system are determined to obtain the model of the system. Based on the catalog values of a selected real compressor, a model is created. Then, the developed model simulation results are verified with the real compressor data. In the drive system model, scalar control, single-phase full bridge inverter topology and unipolar sinusoidal pulse width modulation methods are employed. Finally, total harmonic distortion and energy consumption of a single-phase induction motor which is driven by the developed driver model are measured. Energy consumption values of the conventional and variable-speed cooling systems which are available in the market are compared with the developed model.
Keywords: Single-Phase induction motor, refrigerator compressor motor, energy efficiency, variable frequency driver, frequency control, sinusoidal pulse width modulation.

1. INTRODUCTION

Refrigeration systems are commonly operated at partial load. For obtaining an efficient system, it is important to use an appropriate method in consideration of the working conditions of the cooling systems in their design. Different capacity modulation methods have been analyzed in partial loadings in previous studies, and increased efficiency is shown when the compressor speed is variable [1-3].

Cooling capacity is an important factor for refrigerators. In order to increase the cooling capacity, most used methods are improving the compressor efficiency, increasing the efficiency of the condenser, increasing the number of evaporator wings, and strengthening the thermal insulation of the system. In variable speed compressor refrigerator systems unlike conventional

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compressors, speed of the compressor can be changed according to the load. This is called capacity control. For the capacity control method, the compressor speed is set to meet the required cooling capacity. The main purpose is to change the refrigerant flow that circulates in the system as needed [4-6].

Capacity control studies were started by Tassou and his colleagues in the 1980's. In these studies, they investigated energy consumption with variable speed compressors, calculated gains according to fixed cycle systems, and tried to make a mathematical model of this system. After this, Tassou worked on capacity control in his studies [7-11]. Lida and others studied capacity control with inverter drivers and showed efficiency improving at 1982 [12]. McGovern in 1988 investigated performance characteristics of a two-cylinder open reciprocating compressor [13]. Ischii and others analyzed mechanical efficiency of a variable speed scroll compressor in 1990 [14,15]. Rice, in 1985, 1988 and 1992 investigated some factors such as motor-slip losses, inverter waveform distortion, inverter type for capacity control and drive control methods [16,17]. In 1996, Qureshi and Tassou published a paper which presents a review of the application of variable speed capacity control for refrigeration systems.

New policies force the cooling industry to develop more efficient and environmentally friendly refrigerators to prevent negative impacts on the environment and reduce energy consumption. Studies in the literature are about high efficient three-phase induction motors and drivers. In the late 90's there were many difficulties to increase efficiency for three-phase compressors, and hence a new kind of compressor which is named linear compressor has been paid a lot of attention by the compressor manufacturers. Firstly, a linear compressor was developed by LG Electronics Company. It was more efficient than a normal induction motor thanks to no end-coil and rotor-bar which caused copper losses. Additionally, this efficiency can be kept nearly constant within normal load variation of the compressor [18,19].

Today, capacity control is a proven method, and is used in commercial refrigerators. As one of the leading compressor companies, Embraco started to produce variable speed compressor in 1998 and linear compressor in 2014. However, implementation of these technologies to the market was not as fast as its development. Currently, 80% of production of refrigerator manufacturing is still with the conventional compressors. Moreover, there are too many refrigerator compressors produced in the past as conventional. Even, there are studies on single-phase motor drives,   there is not any study on conventional single-phase compressor drives in literature. Hence, in this study, conventional single-phase induction motor compressors are considered.

2. MATERIALS, METHODS AND SIMULATION

As mentioned before for cooling processes, single-phase compressors are designed to operate at constant speed and On/Off control mode. Even for a simulation process, to change the control method of the single speed to the variable speed, firstly materials and methods must be defined. The related refrigerator and compressor type must be examined accordingly compressor and drive method of the motor must be evaluated. Inverter topology and modulation technique of simulation must be determined according to these evaluations. In consideration of these evaluations simulation and simulation parameters must be arranged.

2.1. Reference Refrigerator and Refrigeration

Vapor compression refrigeration cycle consists of four main components: compressor, condenser, expansion device, and evaporator. In the scope of this study, conventional On-Off controlled no-frost, double door, household refrigerator is investigated. Specifications of the reference refrigerator are given in Table 1.

Table 1. Reference refrigerator specifications

Manufacturer	Whirlpool Corporation
Description	E2BLH 19213 F
Energy Class	A+
Energy Consumption	381 kWh / year
Total Volume	334 lt
Cooling System	Total No Frost
Type	Bottom-Mounted

The test refrigerator has a conventional On-Off control algorithm. In this method, the compressor works until the fridge and freezer reach the desired temperature levels. Negative Temperature Coefficient (NTC) type sensors are used to detect temperatures of refrigerator compartments. The main purpose is to keep the freezer under -18 C^o and keep the fridge between 0 and +8 ^{o}C. When the compartments reach the reference temperature level compressor stops. Refrigerator air flows between the compartments. This air-flow is supplied by a fan and controlled by a damper between the compartments. Every 48h, the refrigerator operates a defrost cycle that lasts for about an hour. During the defrost cycle, an electrical resistance works and melts ice over the evaporator. In this system, when we consider the energy saving there are many factors affecting the general refrigeration system such as insulation, refrigerant, expansion device, condenser, evaporator, fans and resistances. However, the most important factor is the efficiency of the compressor [1-6].

In this paper, a single-speed compressor is considered. Specifications of this compressor are given in Table 2 [20]. The compressor works constantly near 3000 rpm. If there is not any load change in the system, the operation time of the compressor can be taken as constant.

Table 2. Reference compressor specifications

Manufacturer	Embraco
Description	EM X80CLT
Motor Type	Single-Phase
Nominal Voltage	220-240V
Frequency	50 Hz
Number of Poles	1
Speed	>3000 RPM
Auxiliary W. Resistance	18.65 Ω
Main W. Resistance	13.70 Ω
Locked Rotor Amperage	7.47 A
Run Capacitor	5 – 4 μF 350 VAC

In Fig.1, comparisons of refrigeration cycles with variable speed and constant speed compressors are shown. As seen in the figure, refrigeration system with variable speed compressor reaches the set value faster than constant speed compressor, and it works with minimal temperature fluctuations. However, constant speed compressor has poor temperature control and causes inefficient use of energy.
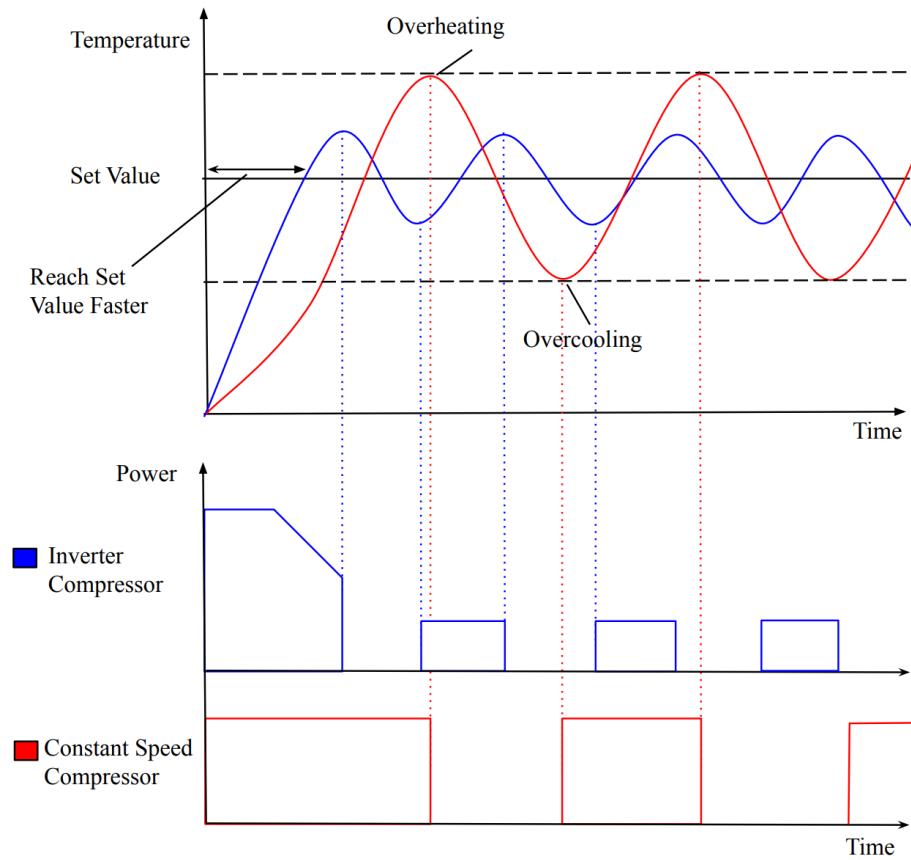
Figure 1. Refrigeration cycles and temperature changes comparison

2.2. Single-Phase Induction Motor

There are several methods to control a single-phase induction motor. Single-phase induction motors are divided into four types according to the starting mechanism: (i) split-phase, (ii) capacitor-start, (iii) permanent split-capacitor, (iv) capacitor-run. In this paper, capacitor-run single-phase induction motor, whose parameters are given in the Table 2, is taken into consideration.

All types of single-phase induction motors can successfully be driven by a variable frequency power supply. Hence, the motor speed can be easily adjusted. While variable frequency drivers allow for a high range of speed, other methods including voltage amplitude control are not allowed. The torque performance of a capacitor-connected motor can be increased in the low frequency range by the scalar (*V/f*) control method. Ba-thunya and others compared various converter and inverter topologies in the literature for the single-phase induction motor drives [21].

2.3. Control Method

We can generally divide induction motor control methods into *V/f* and vector control (field orientation control). In the *V/f* control the speed of the induction motor is controlled by the

adjustable magnitude of stator voltages and frequency in such a way that the air gap flux is always maintained at the desired value at the steady state. On the other hand, the control of frequency, magnitude of current and flux phasor together is known as vector control. It is also known as the "field oriented control". In this method, flux angle is measured or estimated. Depending on the method of measurement, the vector control is divided into two subcategories: direct and indirect vector control. The vector control offers more precise torque control when compared to the scalar control. However, precise torque control is not required for a household refrigeration system. Hence, a simulation of the *V/f* method is selected in this study. The typical *V/f* profile is shown in Fig. 2.

The simplest solution is to increase the voltage slightly at low frequencies so that the motor can give the nominal moment. Hence, the *V/f* profile is not linear. The cut-off frequency (f_c) and the suitable stator voltages can be analytically computed from the steady-state equivalent circuit with stator resistance, $R_s \neq 0$. *V/f* profile follows the constant *Volt/Hz* relationship between f_c and f_{rated}. At higher frequencies, the constant *V/f* ratio can't be satisfied because the stator voltage is limited to avoid insulation breakdown in stator windings. Therefore, the resulting air gap flux is reduced. Otherwise, this may unavoidably cause the decreasing developed torque correspondingly. This region is usually called "field weakening region" [22-24].
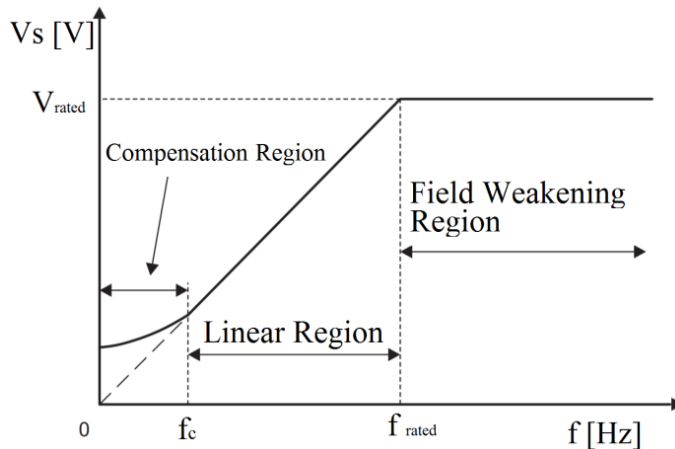

Figure 2. *V/f* control profile

2.4. Inverter Topology

Inverter topology is also a very important factor on motor control. When we look at typical motor control applications, IGBTs have been more preferred at low switching frequencies (<20 kHz) [25, 26]. Hence, we considered IGBT based inverters on our model. Cost of design is a very important factor in deciding inverter topology. Moreover, inverter cost is directly proportional to the number of used IGBTs. Hence, the most logical choice is a topology with 4 IGBT for a single-phase full-bridge Pulse Width Modulation (PWM) inverter which is shown in Fig.3. This topology is enough to meet the requirements of a single-phase compressor drive. However, two-phase semi-full bridge PWM inverter with 6 IGBT and two-phase full-bridge PWM inverter with 8 IGBT can also be considered. On the other hand, this choice will have a big effect on costs.

Here, the motor is connected between "a" and "b". U_a and U_m are motor auxiliary and main windings, respectively. C_{ac} is the starting capacitor.
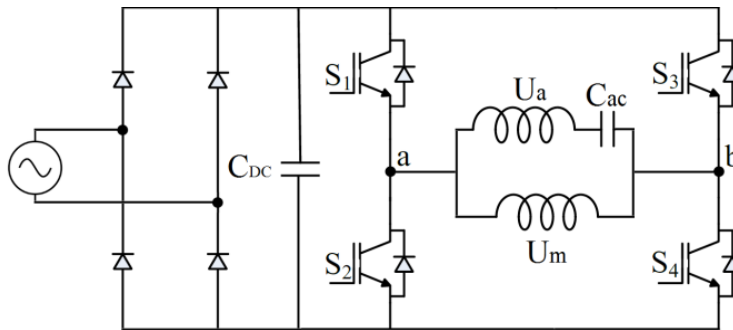
Figure 3. Single-phase full-bridge PWM inverter

2.5. Modulation Technique

An important problem of inverters is that they create harmonics which have negative effects on the electricity network and other electronic devices. Some of these adverse effects include the shortening of the lifespan of the devices, the increasing power losses, and overheating of these devices.

PWM techniques which have been proposed in the literature, can be divided into two main groups: carrier based and non-carrier based modulation techniques. There are also some new techniques which offer improved performance like trapezoidal modulation, stair modulation, staged modulation, and wavelength modulation [24].

- Carrier Based Modulation Techniques
  ○ Single PWM
  ○ Multi PWM
  ○ Sinusoidal PWM (SPWM)
  ■ Unipolar SPWM
  ■ Bipolar SPWM
  ○ Modified PWM
  ○ Random PWM
  ○ Harmonic Injection PWM
  ○ Space Vector Modulation
- Non Carrier Based Modulation Techniques
  ○ Delta Modulation
  ○ Selected Harmonic Elimination

In this paper, unipolar SPWM technique is studied. It is commonly used as a conventional modulation technique and there is the advantage of being easy to control of output voltage without requiring additional components. Moreover, in this method, lower order harmonics can be eliminated or minimized along with its output voltage control, and higher order harmonics can be filtered easily. In Fig.4 unipolar SPWM technique is shown. In this method, a triangular waveform is compared with a controlled sinusoidal modulating signal.
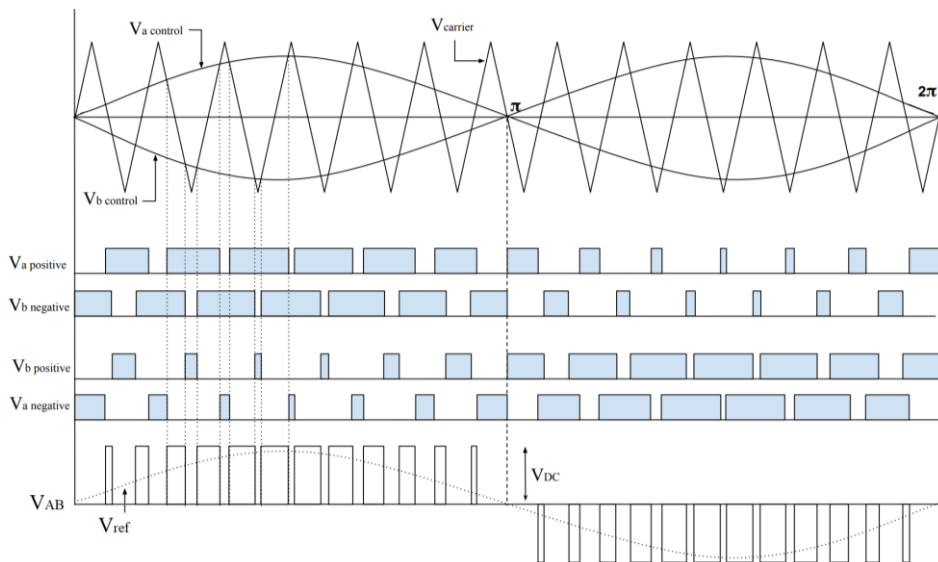
Figure 4. Unipolar SPWM

There are two magnitudes that are effective in adjusting the carrier based PWM inverter output voltage: (i) carrier ratio M_f, (ii) modulation index, M.

Carrier ratio:

$$M_f = \frac{f_t}{f_m} \tag{1}$$

where

f_t : Frequency of the carrier signal
f_m : Frequency of the modulating (information) signal.

Modulation Index:

$$M = \frac{V_m}{V_t} \tag{2}$$

where

V_m : Amplitude voltage of modulating (information) signal
V_t : Amplitude voltage of the carrier signal.

If the voltage in the rectifier is taken as V_{DC}, we can find the voltage which is applied to the motor as in Eq.3. If we divide both sides with frequency, we can see the relationship between *V/f* ratio and modulation index as in Eq.4.

$$V = V_{DC}.M.\frac{\sqrt{2}}{2} \tag{3}$$

$$\frac{V}{f} = V_{DC}.M.\frac{\sqrt{2}}{2}.\frac{1}{f} \tag{4}$$

Carrier frequency is one of the parameter that needs to be determined as well. It is better to use higher frequencies due to harmonic distortion, but in this case the switching losses will be higher. Also, the switching frequency is one of the limiting factors. Hence, different carrier frequencies can be tested by considering these limitations.

2.6. Simulation

The inverter model is developed on the MATLAB® Simulink® as shown in Fig. 5. Gate signals are inverted with a logic "not gate" to prevent short circuits in DC bus.
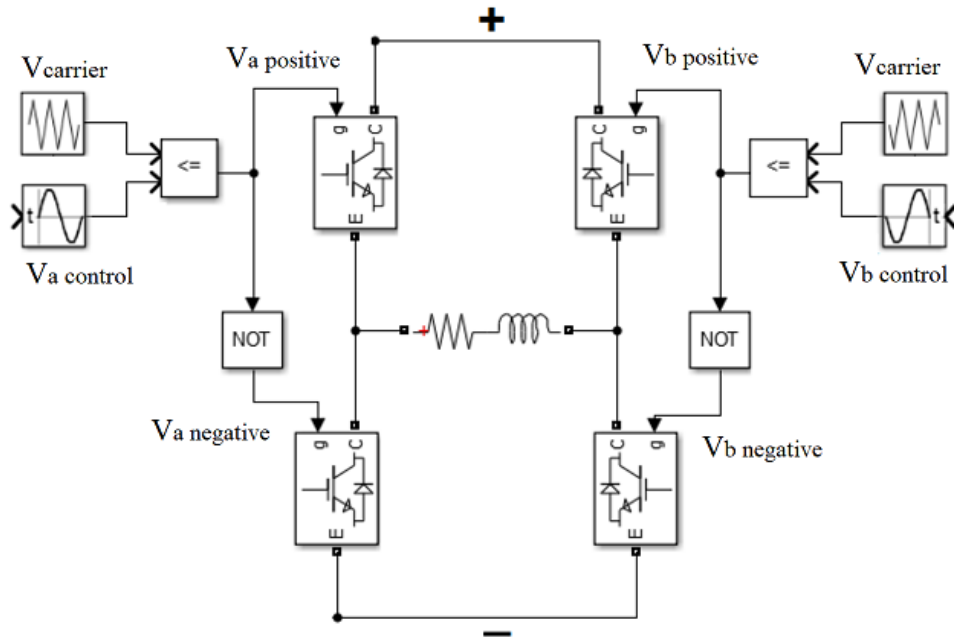

Figure 5. The inverter model

There are four predefined type single-phase induction motor models in Simulink® which can be connected to the inverter model. Most compressors operate with a start capacitor or start-run capacitor. Our reference compressor has a start-run capacitor. Therefore, in this study we consider 2 types of these models, single-phase induction motor with capacitor-start and capacitor-start-run. The model dynamics of a single phase induction machine with squirrel-cage rotor which has been introduced in Simulink® is shown in Fig. 6. Computation method of mechanical system and electrical system can be examined in Mathworks® website [25].
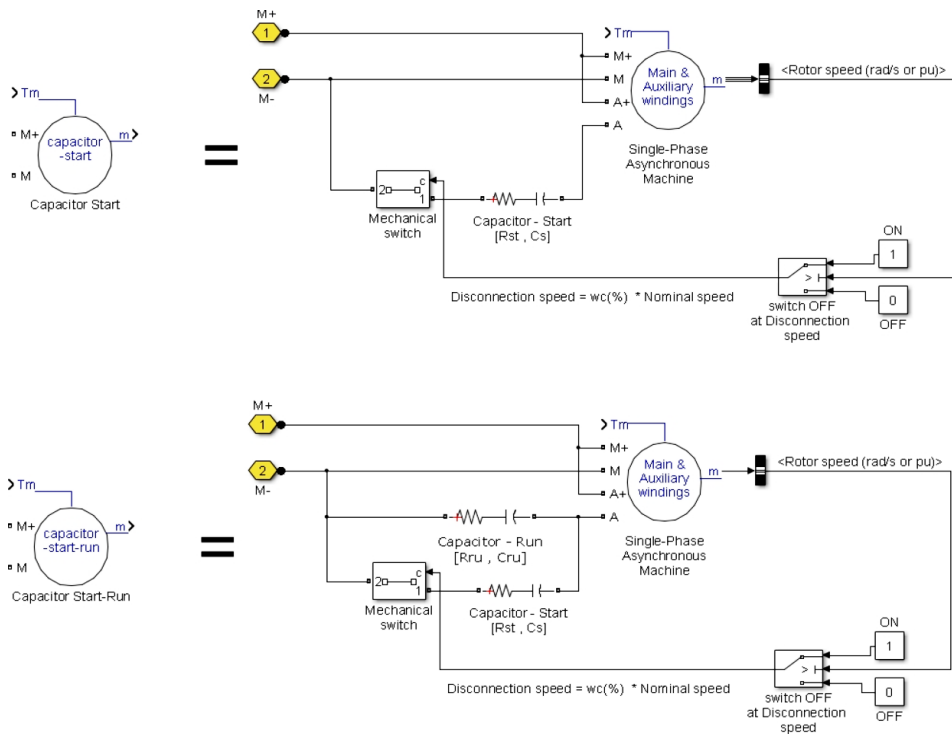
Figure 6. Dynamics model of a single phase induction motor

2.7. Simulation Parameters

Table 3 shows the predefined motor parameters of the Simulink® and the parameters for the selected refrigerator compressor. After implementation of these parameters to motor models, an example simulation is run for the verification. This is an existing example which shows the operation of a single-phase induction motor with capacitor-start and capacitor-start-run operation modes.

Table 3. Motor parameters in Simulink®

Parameter	Definition	Predefined Value	Compressor Value
Rs	Main winding resistance	2.02 Ω	13.7 Ω
RS	Auxiliary winding resistance	7.14 Ω	18.65 Ω
R′r	Rotor winding resistance	4.12 Ω	15 Ω
Lms	Magnetism inductance	0.1772 H	1.8 H
p	Pole number	2	1
J	Load inertia coefficient	0.0146 kg.m2	0.0146 kg.m2
Fr	Load viscous friction coefficient.	0	0
Cs	Start capacitor	254.7 μF	64 μF
C_{run}	Run Capacitor	21 μF	5 μF

2.8. Simulation Parameter Verification

The test results of the operating performance of the compressor have been considered according to ASHRAE standards. These data can be found on EMX80 CLT compressor data sheet. The compressor model simulation results must be compatible with these test results. In Table 4, the compressor power demand versus to evaporating temperature is given.

Table 4. Catalog values of the EMX80 CLT

Evaporating Temperature		Cooling Capacity +/- 5%			Power +/- 5%	Current +/- 5%	Gas Flow Rate +/- 5%"
°C	°F	Btu/h	kcal/h	W	W	A	kg/h
-35	-31	361	91	106	84	0.41	1.13
-30	-22	493	124	145	100	0.49	1.55
-25	-13	660	166	193	117	0.57	2.07
-20	-4	861	217	252	136	0.66	2.71
-15	5	1099	277	322	155	0.74	3.46
-10	14	1375	346	403	176	0.84	4.34

The torque applied to the motor shaft is variable in the refrigerator. It depends on the pressure of the refrigerant gas and varies according to the amount and type of gas, the size of the condenser and evaporator. At the same time, this torque affects the compressor power demand. In this study, we assume that the force acting on the shaft is 0.35 Nm [28]. We also know that this value changes according to gas flow rates. We can assume this change from 0.2 Nm to 0.5 Nm. When the condenser temperature is 55°C, the torque on the motor shaft and evaporator temperature vary as shown in Fig.7.
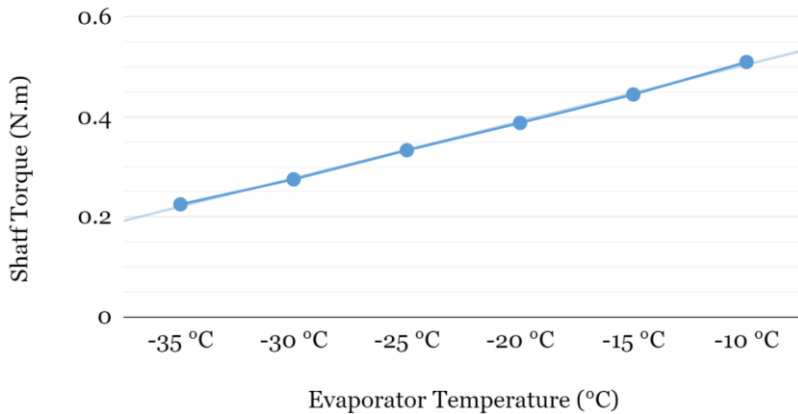

Figure 7. Shaft torque vs evaporator temperature

Simulation verification test results are shown in Fig. 8. As seen in this figure, compressor motor model power values are compatible with the reference compressor catalog values.
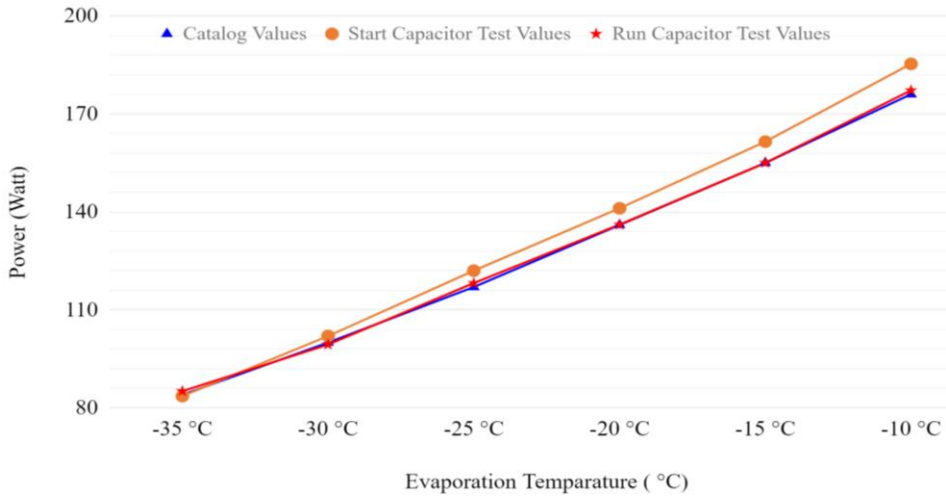
Figure 8. Simulation and catalog values comparison

2.9. Carrier Frequency Determination

The most important factor in determining the carrier frequency is the output of the current signal. In the simulation, it is necessary to draw a varying current between 0.4 A and 0.9 A as shown in Table 4. For this type of systems, the lower the magnitude of the current causes a high harmonic distortion. The current harmonics are observed at the constant modulation index and constant motor frequencies while the carrier frequency ranges from 2 kHz to 8 kHz. The current signal waveforms with the different carrier frequencies are shown in Fig. 9.
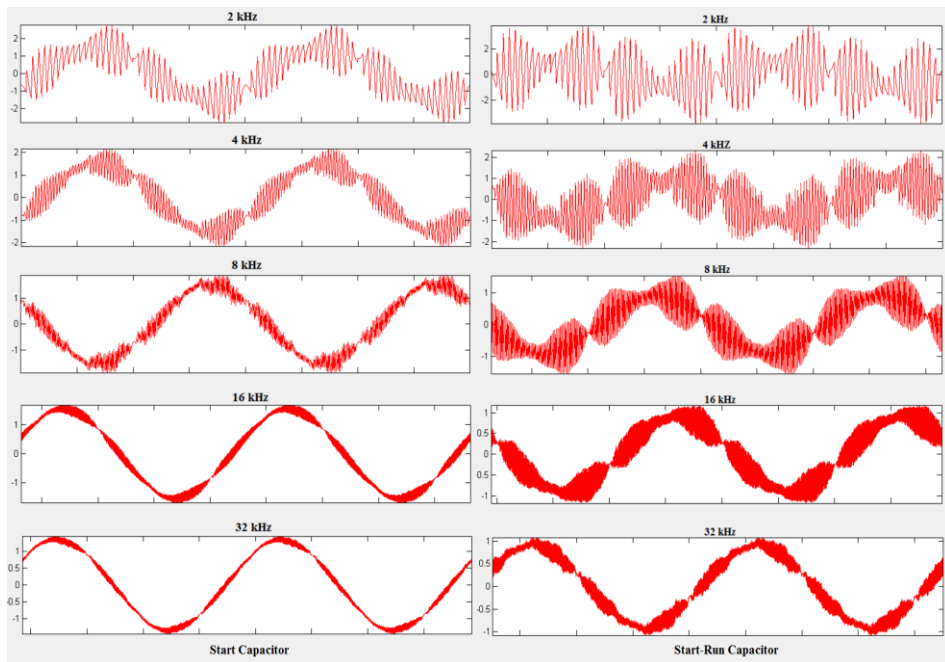
Figure 9. Motor current waveforms

As seen in these figures, higher carrier frequencies create better waveforms. However, there can be seen that the run capacitor has a bad effect on the current waveform.

In Fig. 10, harmonics and Total Harmonic Distortion (THD) values of current are shown. Harmonics occurred at multiples of the carrier frequencies as expected.
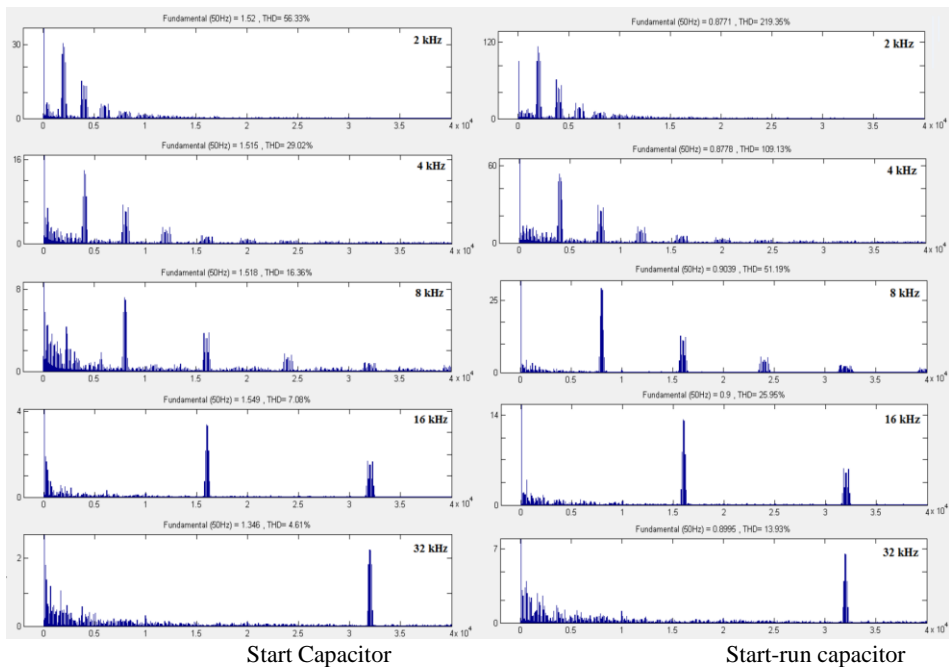
Start Capacitor   Start-run capacitor

Figure 10. Motor current harmonics and THD values

2 kHz and 4 kHz frequencies are low due to the bad current waveform signal. Hence, in our model carrier frequency is selected 8 kHz due to a better simulation speed. 16 kHz level also can be tested. 32 kHz is generally a high value for a motor control application due to the switching losses. Also, IGBT cost must be considered when the 32 kHz signal level is selected.

2.10. Modulation Index and V/f Determination

The rated voltage and frequency of our reference compressor is 220V and 50 Hz. For nominal working at 3000 rpm speed *V/f* ratio is 4.4. When we apply this ratio to Eq.4 with V_{DC}=311 V, the modulation index will be 1. So it will be a good choice to make *V/f =4* to prevent over modulation and standing on the safe side. According *V/f* ratio we can change Eq.4 to Eq.5, and we can determine our modulation index according to frequency. Modulation index changes in the linear region and becomes constant at field weakening region as shown in Fig. 2.

$$M = \frac{8.f}{V_{DC}.\sqrt{2}}$$ (5)

3. RESULTS AND DISCUSSION

Simulation results according to evaporation temperature are presented in Fig.11. The values of the model with a run capacitor which is driven by the inverter is found to be 10% lower than the reference compressor specification values. The reference catalog values have a tolerance of ± 5% in power demand. If we accept the same tolerance for the model, there is not any loss of power demand even at the tolerance limits.
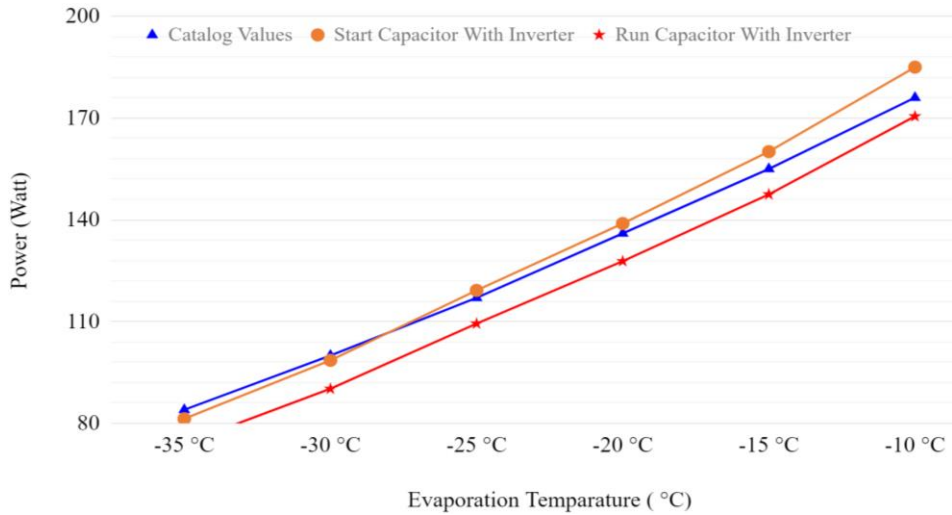
Figure 11. Power demand versus evaporator temperature

Additionally, it is necessary to compare the simulation results with another variable speed compressor. However, as mentioned before, single-phase induction motor compressors are not used as a variable speed compressor in refrigeration. Therefore, a variable speed three-phase induction motor compressor is considered as a reference for comparison. We chose as a reference VESA9C model which is manufactured by Embraco Company and is operated between 1300-4500 rpm speeds. The catalog values of this compressor are given in Table 6.

Table 6. Catalog values of the VESA9C

Motor Speed +/- 5%	Cooling Capacity +/- 5%			Power +/- 5%	Current +/- 5%	Gas Flow Rate +/- 5%	Efficiency Rate +/- 7%
Rpm	Btu/h	kcal/h	W	W	A	Kg/h	W/W
1300	227	57	67	39	0.32	1.49	1.73
1600	282	71	83	45	0.37	1.58	1.83
2000	356	90	104	56	0.45	1.60	1.86
3000	542	159	159	86	0.66	1.60	1.85
4500	762	192	223	131	1.00	1.47	1.71

In Fig. 12, simulation results of the run capacitor which is driven by the inverter and catalog values are compared. The power demand values of the simulation results are 25%, 30% higher than the three-phase compressors. The difference between them also varies according to the speed. However, it is also necessary to consider the cooling capacity when evaluating this result. According to catalog values of compressors at 3000 rpm; while the of the single-phase compressor (EM X80CLT) is 726 Btu/h, three-phase compressor (VESA9C) is 404 Btu/h. Cooling capacity of the single-phase compressor has much more than three-phase compressor; therefore, it is possible to compare them in the same algorithm.
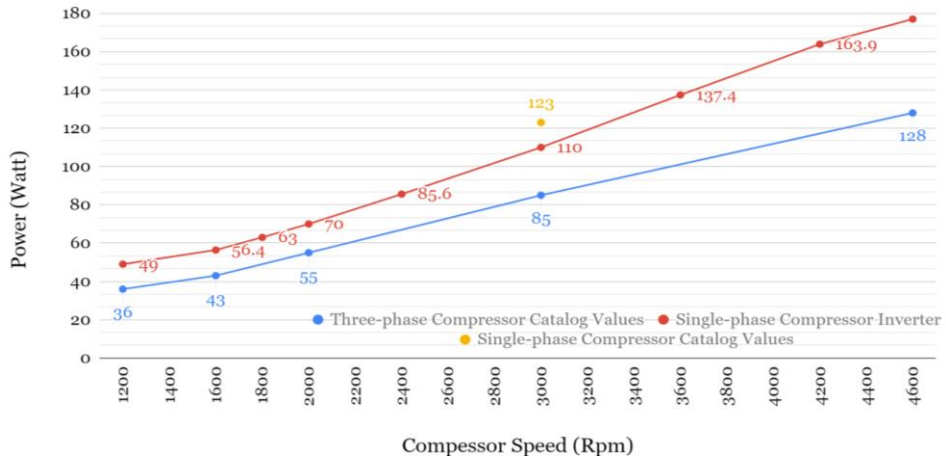
Figure 12. Power demand vs compressor speed

The results obtained in the simulations should be applied to variable speed and constant speed cooling algorithms and the energy consumption should be calculated.

Fig.13 shows the time-dependent variation of the cycles and power demand of a refrigerator with three-phase compressor. For a refrigerator with three-phase compressor, the working time of the compressor is 20 minutes and stopping time is 10 minutes. This algorithm works as long as there is no sudden temperature change in the refrigerator. The power demand is 43W during the normal operation. Compressor operates at about 1600 rpm. The average power demand is 28.67 W.
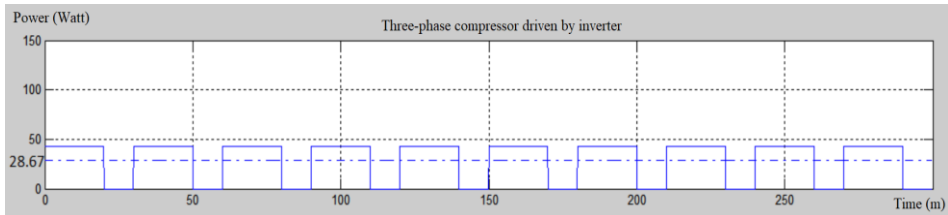

Figure 13. Power demand for a refrigerator with three-phase compressor with inverter

Fig 14. shows the operating algorithm of a refrigerator which has a fixed-speed single-phase compressor. This is a classical working algorithm for most of the refrigerators, and it works 25 minutes and stops 50 minutes. This algorithm is similar for most of the refrigerators. For the selected reference compressor, the power demand is 123W and average power demand is 41 W.
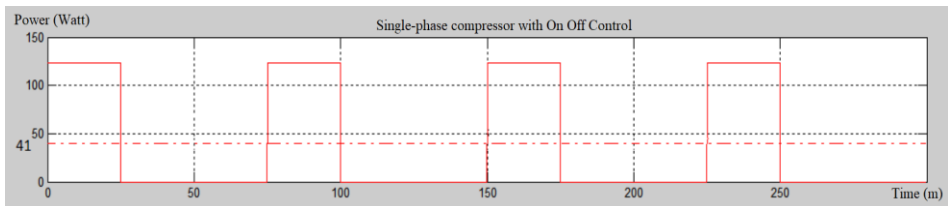

Figure 14. Power demands for a refrigerator with single-phase compressor with on off control

To achieve the same cooling capacity, we can use the three-phase compressor algorithm for our model. There is no need to make any additional operation due to the single-phase compressor having higher cooling capacity at the same conditions as mentioned before. Fig 15. shows the operating algorithm and power demand of a refrigerator with our model. The working time of the compressor is 20 minutes and stopping time is 10 minutes.   The power demand is 56.4W, and the average power demand is 37.3 W.
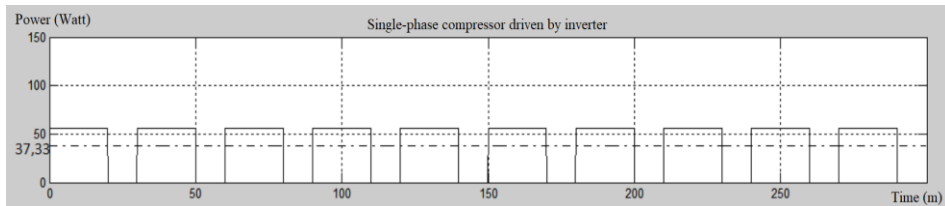

Figure 15. Power demand for a refrigerator with single-phase compressor driven by inverter

As seen in the Fig. 15, the average power consumption of the single-phase compressor driven by inverter is 9% less than the single-phase compressor with on off control and 23% higher than the three-phase compressor with inverter.

There are other cycles in the refrigerator that similarly increase defrost and power consumption. For example, the single-phase compressor runs longer than the normal cycle after defrosting to balance the reference temperature. However, the three-phase compressor is run at a higher speed instead of running longer to balance the reference temperature. In both cases power consumption increases for this reason. Therefore, in the power consumption to be declared, the average instantaneous power consumption of a 48-hour part of an entire test process is calculated. This value gives the hourly average power consumption. Based on this value, daily and annual energy consumption is calculated and declared. As a result comparing the declared consumption values of these refrigerators, this rate changes between 3% and 5% the reason for this defrosting and other power consumption items. This rate may decrease slightly when defrost and other power items are added. However, taking into account that the cooling capacity of the single-phase compressor is higher than the three-phase compressor and with an appropriate working algorithm is created, average power consumption gain of 10% can be achieved.
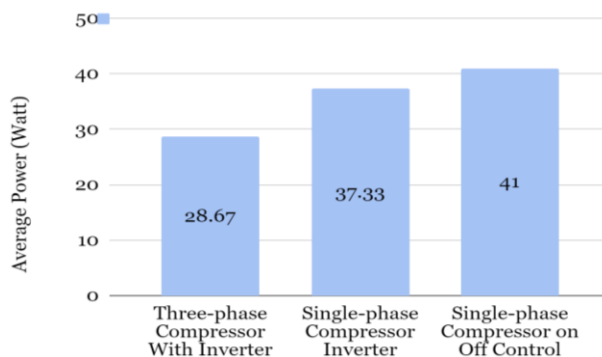

Figure 15. Average power consumption comparison

4. CONCLUSION

In this study, the refrigeration principle and cooling algorithms are examined, and developed single-phase induction motor drive control to improve energy efficiency of a refrigerator compressor motor. For this aim, a household refrigerator compressor parameters are considered to obtain the model of the system. The motor parameters are set to a single-phase compressor motor which is commonly used on the market. Hence, simulation results and real compressor catalog values are compared and so the model is verified. The scalar control method is employed as the control method for the compressor drive system and the corresponding carrier frequency, V/f ratio and modulation index are also determined. While determining these values, harmonics and harmonic distortions are also taken into consideration. Then, power consumption data of the motor are calculated at different evaporator temperatures and at different speeds. Finally, simulation results applied to the cooling algorithms and the energy consumptions are calculated. Defrost system and energy consumptions of other components in the refrigerator aren't considered in the calculations, and the effect of the compressor on the power consumption is examined only in normal operation condition.

Power demand of a conventional A+ refrigerator can be improved 9% with additional inverter and properly selected working algorithm. This energy efficiency corresponds to a change from 30kWh to 40kWh per year. Also, the costs of the inverter and energy consumption improving should be considered together. Refrigeration cycle modifications can be investigated experimentally to determine the more reliable results. However, 9% energy efficiency does not change the energy efficiency class of a refrigerator. For this reason, the experimental stage has not been conducted for this study. Instead, investments can be made to increase the production of the models with three-phase compressors which are already in use.

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