Towards Sustainable Cooling Strategy for Developing Nations: Opportunities for an Off-grid Solar DC Refrigerator

Azem Iqbal Vora, Prashant Kumar Soori, and Prakash K Shetty

[1,2] Heriot Watt University, Dubai, UAE
Email: p.k.soori@hw.ac.uk
[3] A. J. Institute of Engineering & Technology, Mangalore, INDIA
Email: shettyprakashk@ajiet.edu.in

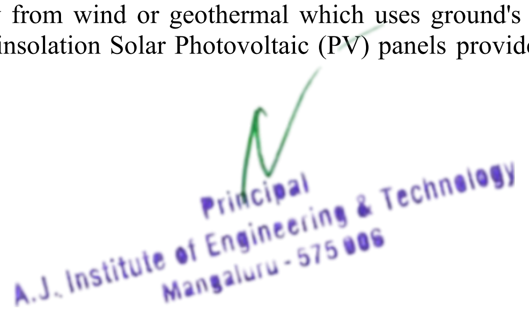
Abstract: The increasing concern of climate change promotes the need to switch to renewable resources. Refrigeration is integral in day-to-day life to store perishable goods, life-saving drugs and vaccines in hospitals and clinics. Refrigeration consumes significant amount of energy as they are required to operate throughout a day. Solar-powered refrigerators is a promising alternative to reduce carbon emissions while providing cooling. An additional benefit is its ability to use off-grid solutions; hence, integral in improving the quality of life in developing nations where electricity is not readily available. Furthermore, it shall aid better quality of life for the economically backward societies by having life-saving medicines reliably available. Providing solar refrigerators in rural areas shall help people store food for longer durations thereby elevating food wastages.

The novelty of the proposed work is to convert a conventional AC-refrigerator into a DC-refrigerator by retrofitting AC compressor with a DC compressor. Furthermore, the Internet of Thing (IoT) implementation is incorporated to enhance the user experience by remotely controlling and monitoring the performance of the refrigerator. Designed prototype is tested to determine its energy consumption. It is concluded that the fabricated prototype is found to be more energy-efficient than the conventional AC refrigerator.

Keywords: Current spikes, DC compressor, Vapour Compression Refrigerator

1 Introduction

The ever-increasing concern of climate change due to increased use of fossil fuels is promoting interest in researchers to study and improvise the ways of harnessing clean energy. There are various ways to produce clean energy such as the use of wind turbines to produce energy from wind or geothermal which uses ground's heat, but due to abundance of solar insolation Solar Photovoltaic (PV) panels provide a better alternative to fossil fuels.



Solar PV panels have no moving parts and require minimal maintenance, hence making it an easy energy source to use. Continuous research and development in the PV technology have enabled companies to reduce the price of solar panels, meanwhile increasing their efficiency. The graph shown in Figure 1 indicates the decrease in cost per Mega Watt hour (MWh) as the technology matures (IEA, 2019). The graph also indicates a further decrease in cost in the following years.

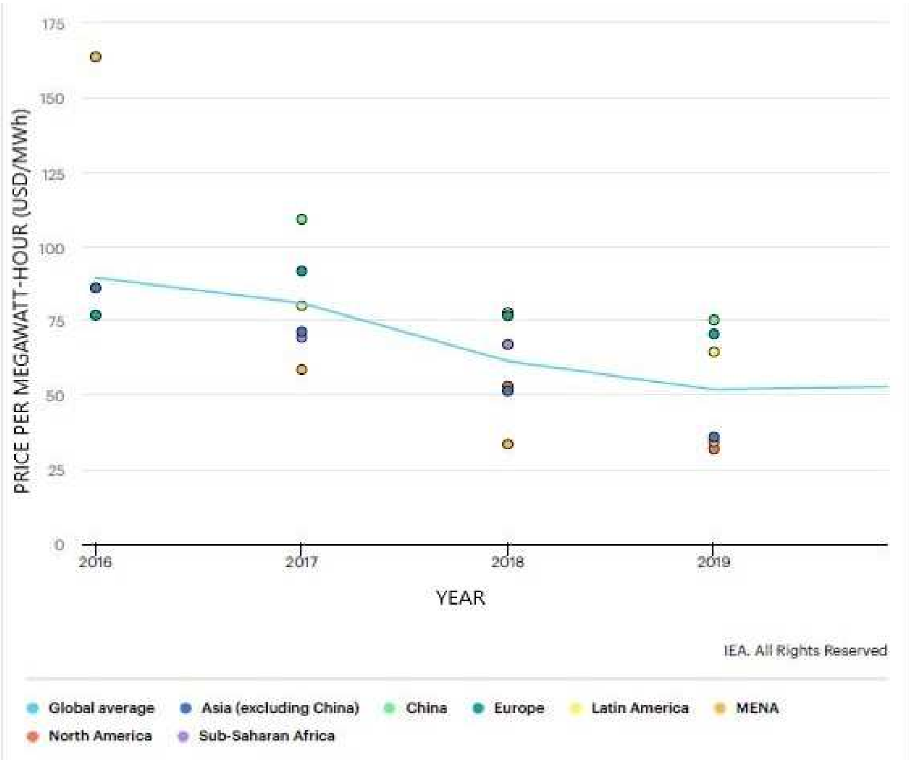


Figure 1 Price Per MWh of Solar Generated Power

Energy consumed by commercial and residential sector was around 39% of the overall energy produced in the United States of America (USA) and from that almost 35% of the energy was used for cooling and heating purposes. This is depicted in Figure 2. Further breaking down the numbers obtained, refrigeration utilizes 51% of the energy used by residential buildings (EIA, 2018).

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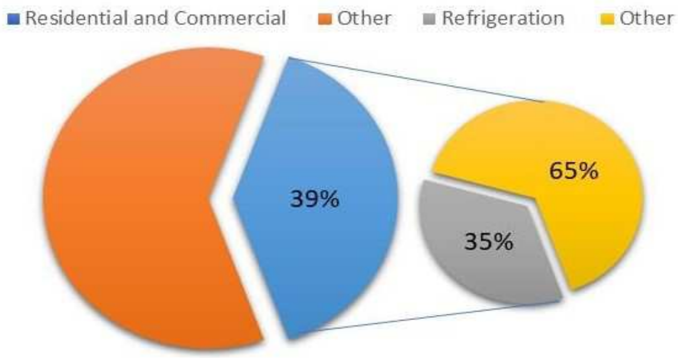

Figure 2 Energy Consumption by Refrigerators in Residential and Commercial Buildings

The rapid progress in developing countries leads to more energy usage in the buildings, the majority of which is used in refrigeration. The increase in energy usage increases carbon emissions and contributes to climate change. The refrigeration systems can utilize renewable energy such as Solar energy to decrease the use of energy generated by fossil fuels and thus reducing the carbon emissions. Furthermore, Solar run refrigeration systems can be utilized off-grid in places such as Sub-Saharan countries where the electricity is scarce, relying on diesel-generators for powering the various electrical appliances (G. Nakweya, 2019). The overall quality of life shall improve as refrigeration is essential to store perishable goods, particularly in hospitals, where constant refrigeration is required to store life-saving medicines, blood and vaccines.

The refrigeration system utilizing solar energy can be implemented either using a Vapour Compression Refrigeration (VCR) system or Vapour Absorption Refrigeration (VAR) system. VCR consists of a compressor, condenser and a control unit running on Alternating Current (AC) (using DC-AC converter); meanwhile, VAR system consists of an absorber, pump, generator, evaporator and condenser. The mature technology, along with ease of use, compact size and minimal maintenance, making the VCR systems ideal for refrigerators utilizing solar power. The solar power produced by Solar PV panels is DC power; therefore, the DC VCR system can be utilized in the prototype as no inverters are required. An added benefit of utilizing DC VCR is decreased power spikes compared to AC VCR system as depicted in Figure 3 (Opoku et.al, 2016).

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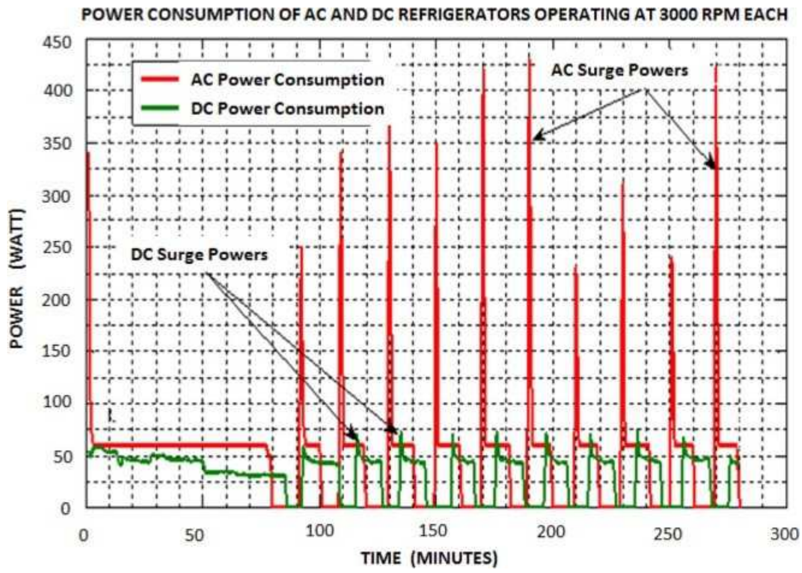

Figure 3 AC Versus DC power Surge during operation

The novelty of the presented work is to design and implement a refrigerator capable of running directly on Solar Power by utilizing 24V DC VCR with variable speed control and micro-controller with sensors and display for smart control and operation.

2 Literature Review

The compressor in the VCR system can be operated using Direct Current (DC) or Alternative Current (AC). Researchers analyzed the overall performance of the refrigerator using AC and DC power (Opoku et.al, 2016). The two systems were tested in Sub Saharan countries to determine their efficiency and cost-effectiveness. The methodology used by researchers was to initially test the power consumption of two identical refrigerators with AC compressor and then determine the battery, inverter, and PV panel rating. It was followed by replacing AC compressor to 12V DC compressor. Voltage and current were monitored for a day for both the refrigerators in the same environment, and the data were logged on a data logger. The data from the experiment showed higher power consumption (over 20%) in the AC compressor in comparison to DC compressor. Furthermore, during startup of the compressor, the power surges in the AC compressor were in the range of 250-400W. In contrast, in DC it stayed at around 75W.

Researchers reported an efficient 12V DC Compressor based refrigerator with PV panels, solar charge controller and deep cycle Lead-Acid batteries (Tsado et.al, 2018). The prototype was tested for a day to determine its performance. It was noted that after the initial startup, the power consumption reduced to a minimum throughout the testing phase.

El-Bahloul et.al used a DC refrigerator and conducted tests with and without phase change material (PCM) in hot arid conditions to study the difference the PCM makes in off-grid applications (El-Bahloul et.al, 2015).

Kaplanis and Papanastasiou (2006) substituted AC compressor in FV100 refrigerator to utilize DC compressor. They found that daily energy consumption reduced from 4.4kWh/day to 2.2kWh/day. Additionally, insulation was added inside the refrigerator to reduce the heat loss resulting in a 30% decrease in volume. There were two tests performed, first test to determine the voltage to speed ratio and starting compressor current, and the second test was done with the load to determine the maximum power utilized by the system. The maximum power consumed was 102W initially, dropping to 84W at steady state at 3000rpm. It was observed that power consumption was highly dependent on rpm and the set temperature (Kaplanis and Papanastasiou, 2006).

Researchers used a conventional AC refrigerator and paired it with an inverter to run from solar panels along with a solar charge controller and two 12V batteries (Modi et.al, 2009). The test was conducted to determine the feasibility of using a refrigerator on solar energy. It was determined that 140Wp was enough to run 165L refrigerators even in a high ambient temperature of about 40^{o} Celsius. Although the system performed well, it was reported that the payback time was high, and subsidies are required to bring down the cost.

Another experiment with AC refrigerator coupled with inverter was done by Alshqirate et.al (2015). The researchers used 50L refrigerator powered by two solar PV panels of 70W.

Wang and Yu (2018) proposed the idea of using STM32 micro-controller running on Android as an operating system to read the data from the sensors and transmit them to a mobile device to display the data. The proposed project is meant for domestic consumers, but this could be particularly helpful in the medical application where medicines, vaccines or blood are stored.

Nasir et.al (2018) used Arduino UNO as the micro-controller to collect data from a DHT11 temperature and humidity sensor along with MQ3 gas sensor. The data is analyzed, and the user is alerted via SMS when measured data is different from set parameters.

3 Proposed Methodology

Figure 4 shows the block schematics of the proposed Solar-powered DC refrigerator. The prototype consists of 55L refrigerator, 24V DC compressor and Brushless Direct Current (BLDC) motor controller. DHT11 Temperature and humidity sensor, three Load sensors, ESP8266 WiFi Module, Arduino Mega and a TFT Display was added for IoT application. All these features were added to make Smart VCR system capable of running directly on DC power without the use of any other converters.

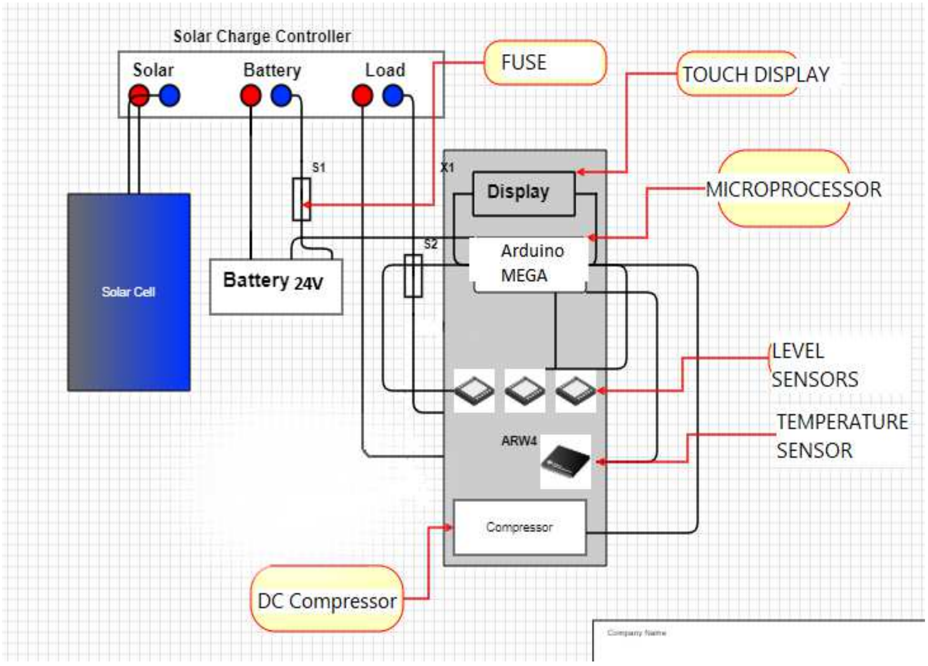

Figure 4 DC refrigerator Schematics

Initially, the existing AC compressor in the 55L refrigerator is replaced with a 24V DC compressor. Furthermore, evaporating coil, condenser coil and two 24V DC fans are also added to the refrigerator. This is followed by electrical and IoT part of the project, which is divided into two sections:

- Compressor Control Using Arduino MEGA and BLDC motor controller.
- Controlling refrigerator using TFT Display and Mobile Application.

3.1 Compressor Control Using Arduino MEGA and BLDC motor controller

The compressor control using a micro-controller (Arduino Mega) was done with the help of temperature and humidity sensor (DHT11) placed in the refrigerator. The micro-controller monitors the cabinet temperature continuously and cross-checks with the set temperature. When temperature difference was noted, it determines the difference between the temperature and accordingly varies the duty cycle of the Pulse Width Modulated (PWM) signal to the BLDC motor controller. The sequence is depicted in Figure 5.

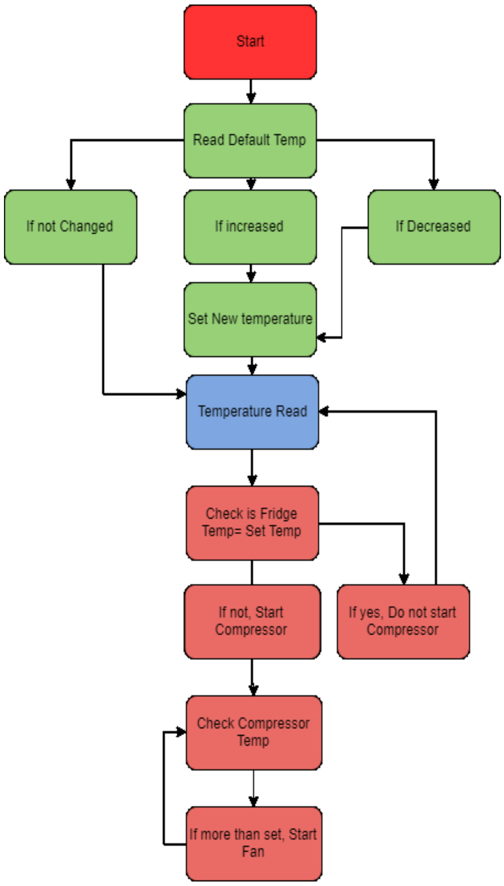

Figure 5 Compressor Control Flowchart

3.2 Controlling refrigerator using TFT Display and Mobile Application

Following successful control of DC compressor using a micro-controller, TFT display, Load Sensors and WiFi module were connected to Arduino. The TFT display is a UART display which allows serial connection with Arduino Mega; hence, the display works as a slave to the micro-controller. The display was programmed to show temperature and humidity from the DHT11 sensors, vary the set temperature and Load sensors values. The WiFi module was configured in the Arduino code, and the interface was developed using RemoteXY open-source software (Remotexy, 2020). The WiFi module enabled control of refrigerator remotely from a connected mobile device. Figure 6 shows the system block diagram.

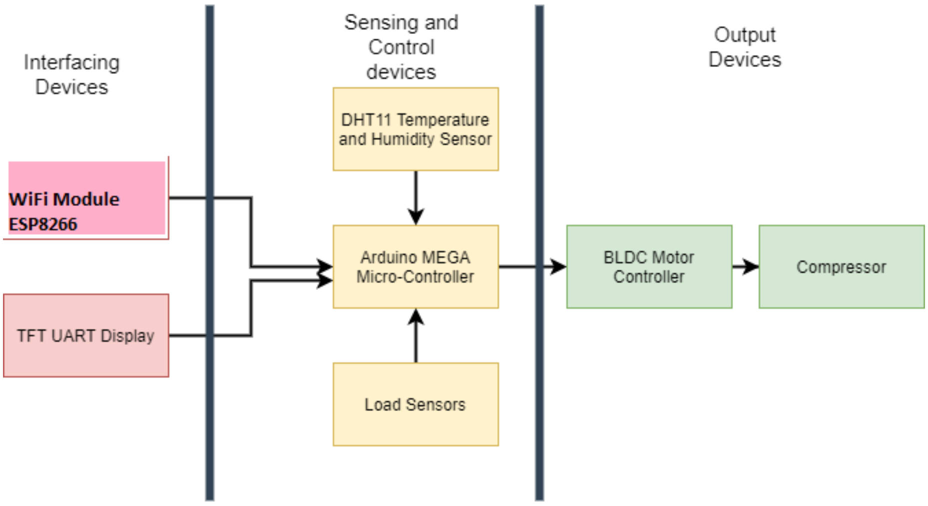

Figure 6 System Block diagram

3.3 Testing of the prototype

The power rating of the entire system was calculated to compare the developed system with an existing AC refrigerator. Figure 7 shows a schematic of the test rig-up used. The testing of the system was done using a high precision Digital Multimeter (DMM 4020), a Windows PC with putty and LabVIEW installed, Solar PV panel and 24V battery. Digital Multimeter (DMM4020) is a high precision multimeter which can measure current and voltage and can be operated via a computer using RS-232 interface. For the purpose of this experiment, only current was measured as the voltage was constant. The accuracy of the DMM is ±0.18A at 10Amps and 23^{o} Celsius. Labview software was used to read the data from DMM and store it in a database. Along with that, putty was used to store serial interface data from the microcontroller. The microcontroller sends temperature and humidity data which was essential for data analysis.

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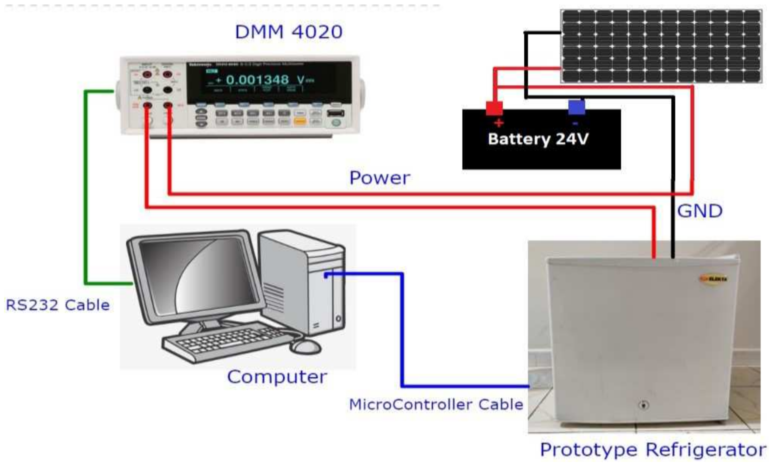

Figure 7 Test-Rig Setup

Two test experiments were conducted. The purpose of first test was to determine the current consumption of the prototype when the temperature inside the cabinet was dropped from 22º to 4º Celsius. The second test was conducted to determine the time taken to drop cabinet temperature from 22º to 4º Celsius. The first test was essential to determine the average power consumption by the prototype. Average power consumption helps to determine ratings of Solar Panels, Batteries, and solar charge controller. Both the tests were conducted at No-Load at temperature of 23º Celsius.

4 Results and Discussions

Figure 8 shows the developed Smart DC refrigerator. Fabricated Acrylic parts were added to house the BLDC motor controller, Arduino MEGA micro-controller, and TFT display. The swapped compressor was bolted on to the refrigerator body to reduce vibrations during operation. Figure 9 shows the display and mobile application interface.

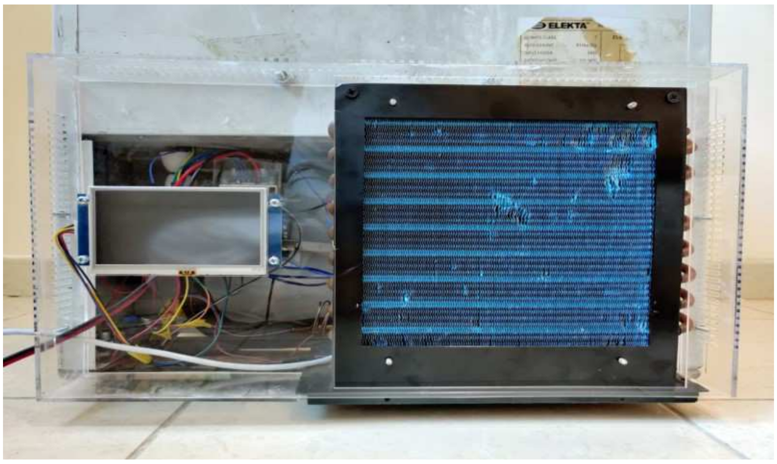

Figure 8 Completed Prototype

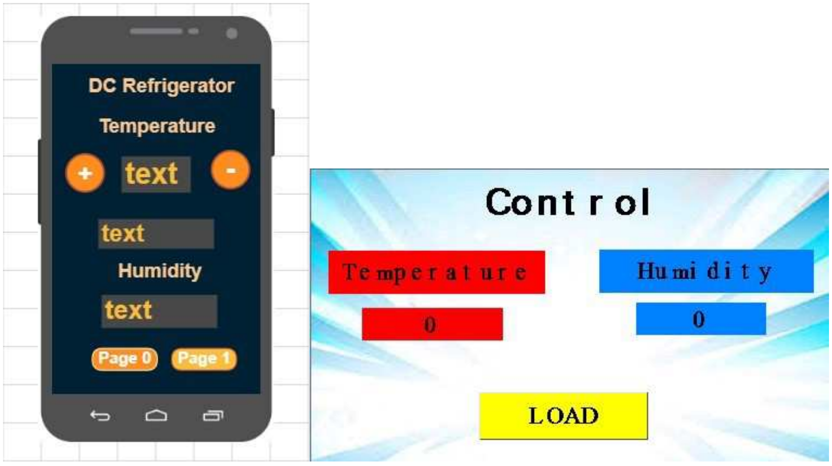

Figure 9 Mobile and Display GUI

4.1 Testing Results

The testing results from DMM 4020 were stored by LabVIEW software on the computer and sorted in Microsoft Excel to produce the graph shown in Figure 10. It can be noted that the voltage remained constant at 24V as the unit was powered by a DC source. Meanwhile, the current varied depending on the compressor operation.

Initially, the current was low as the microcontroller initializes all the variables and starts the compressor after noting the difference in temperature from the set temperature. The compressor operated for 11.8 minutes until the cabinet temperature reached 4^{o} Celsius, as shown in Figure 11. After the initial pull-down phase, the system maintained the internal cabinet temperature. High peaks can be seen at the time of the start of the compressor unit. The average current is found to be 5.6 A, but at the starting, the current reading was up to 8 A.

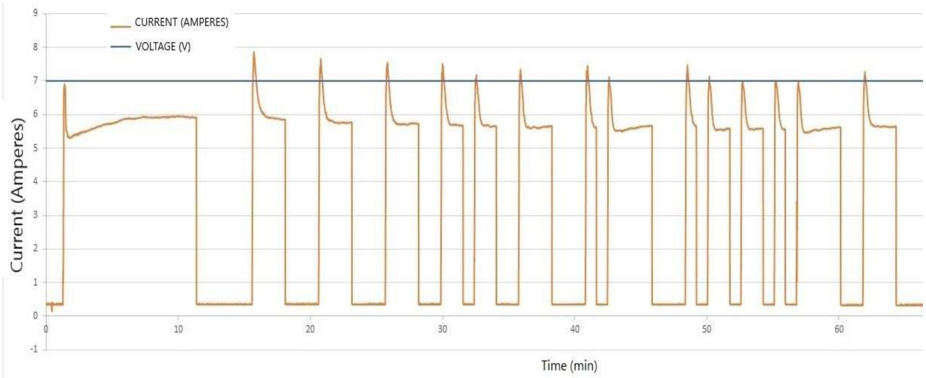

Figure 10 Current and Voltage Graph

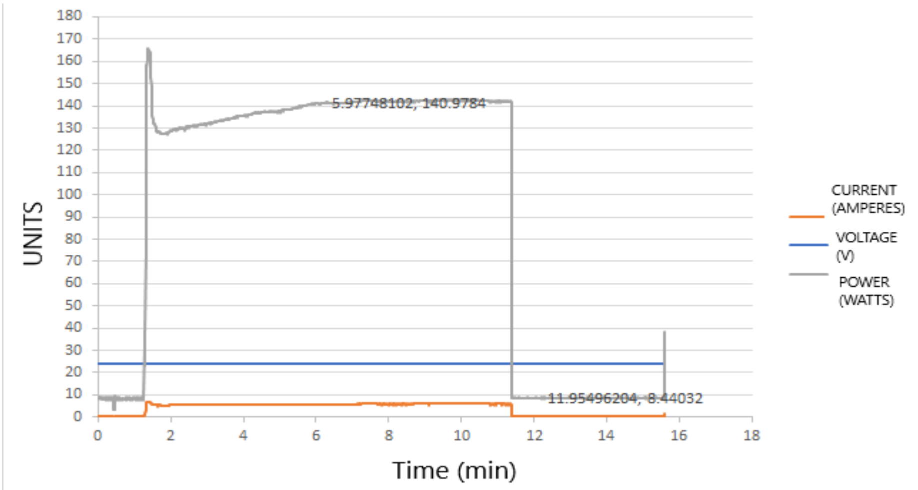

Figure 11 Power Graph during start up

The second test was conducted to determine the temperature variation over time, and it is shown in Figure 12. The data was taken from the microprocessor using putty and plotted using Microsoft Excel. The initial temperature was 22º Celsius, and the temperature gradually reduced to 0º Celsius in 14 minutes at no load. It was observed that, the variation of one-degree temperature resulted in compressor operation again.

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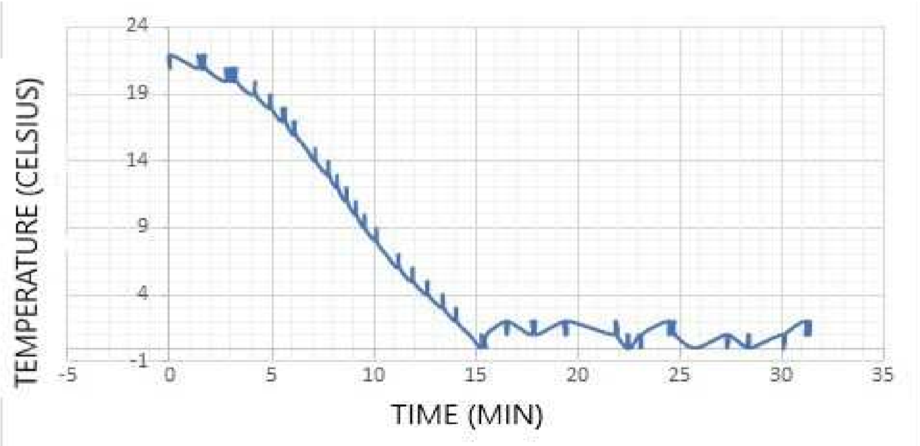

Figure 12 Temperature Variation over time

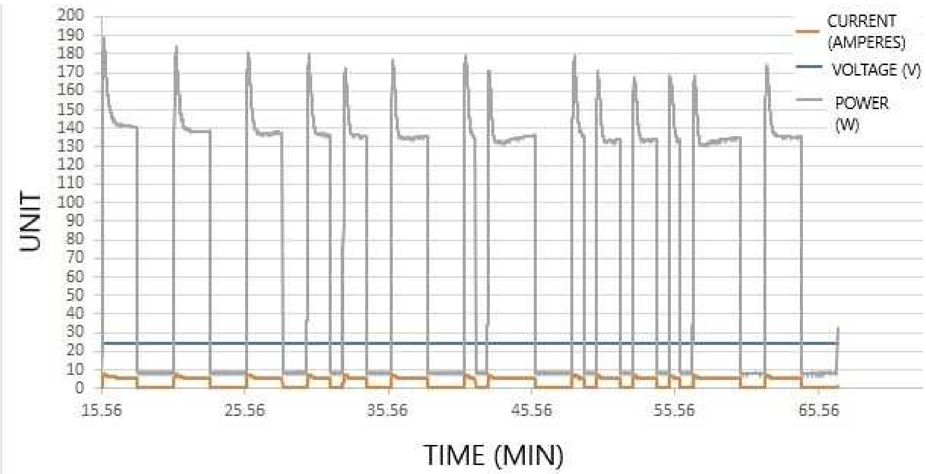

Figure 13 Power Graph when maintaining temperature

Figure 13 shows the power consumption graph. The average power consumption of the fabricated prototype was found to be 139.12 Watts. The duty cycle, which depicts the ratio of compressor operation time over total run time, was calculated to be 0.555. The daily energy consumption was found to be 1.85kWh. Hence, the annual energy consumption of the fabricated prototype was expected to be 676.4kWh under No-load condition.

5 Conclusions

The average power consumption of the developed prototype is in line with conventional AC refrigerator available in the market. The main advantages of using a DC compressor is the reduced current spikes at the starting of the compressor. A conventional refrigerator could have current spikes 100-150% higher than normal current usage, which would elicit a higher rated inverter (Opoku et.al, 2016). The duty cycle of the developed refrigerator was in line with the AC refrigerators. Additionally, added display, WiFi Module and load sensors allow constant control and monitoring of the refrigerator using a paired mobile device. Further advancements such as improved insulation or addition of PCM can be done to improve the efficiency of the developed refrigerator. To conclude, a Smart DC refrigerator prototype was successfully built and tested, which proved to be better suited to work in conjunction with a Solar PV system.

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