HVAC System Operation: Enhancing Energy Efficiency and Reducing Costs

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To Cite this Article
MOHAMMED ABDUL JABBAR[1], SYED JUNAID UDDIN[2], Dr. MOHAMMED NOOR ALAM[3], "HVAC System Operation: Enhancing Energy Efficiency and Reducing Costs "*Journal of Science and Technology, Vol. 07, Issue 10, Oct 2022, pp191-208***

Article Info
Received: 24-09-2022 Revised: 02-10-2022 Accepted: 10-10-2022 Published: 20-10-2022

ABSTRACT

A/C energy savings has recently emerged as a hot issue in practical energy research, with a focus on creative management and effective OS usage. The primary goal of energy-efficient air conditioning system design is to provide thermal comfort with lowest usage. When temperatures are high, the air conditioner is a major energy consumer. In order to achieve and maintain the targeted degree of thermal comfort, it is crucial to have a well-thought-out air conditioning operating system. This study aims to provide a novel operating system architecture that can simulate and experiment with the thermal performance of air conditioning systems for two similar residences in the Dhahran region of Saudi Arabia. Here, two distinct HVAC operating systems were considered in developing the thermal model for the two homes. Several physical features and factors, including weather and heat gain/loss within the home, have been included in the study. To model the ON/OFF and VFD controller systems for air conditioning, we utilize Matlab/Simulink software. In order to track weather and power use in real time, the experimental effort makes use of the LabView platform, which has data collecting capabilities.

Keywords: *Air-Conditioning, Energy Savings, Variable Frequency Drives VFD, ON/OFF Cycle, Modeling*

INTRODUCTION

To save energy and make better use of cooling systems, thermal units need to be designed creatively so they can fulfill demand while still providing sufficient comfort. There has been a lot of recent interest in the performance of systems with variable refrigerant flows and in best practices for minimizing waste energy [1-2], and a number of methods have been suggested to develop energy efficient systems [3-6]. Hot and humid weather is typical in many residential locations around the globe, including parts of the United States, the Arabian Gulf, Africa, South America, and Southeast Asia. As an example, in Saudi Arabia, HVAC systems utilize the most energy, accounting for almost 60% of total household energy usage [7]. Because of the very hot weather, high humidity, and dust storms, space-conditioning has become increasingly commonplace across KSA, leading to an increase in energy usage. Ensuring thermal comfort and lowering energy usage are major concerns when developing HVAC systems. In order to assess the energy consumption of the HVAC system, it is necessary to create thermal models and simulations of the home. Here, we will go over two different ways the system might operate. The first HVAC system uses an on/off cycle, whereas the second uses a variable speed driver (VFD). Salsbury and Diamond investigated the idea of doing energy analyses and validating the performance of HVAC systems using simulation [8]. They detailed one use of the new technique that involves using data monitoring simulations set up to mimic optimal performance. We can validate the system's performance and analyze its energy consumption by comparing the monitored outputs to the performance objectives provided by the simulations. They demonstrated the outcomes of implementing the ideas into a large San Francisco office building's dual-duct air-handling unit. In order to estimate the amount of energy needed to achieve a comfort level, Muratori et al. used Matlab/Simulink to account for the expected temperature change [9]. They checked their findings against those of the IEA BESTTEST, which is a building energy simulation test. The findings are further confirmed using real data from home meters. Home HVAC systems may have their heating and electric energy usage modelled using a basic physically based model all year round. They rely on using principles of thermodynamics and heat transmission to control the home's air volume. For the purpose of implementing the model, Matlab readily replicates diver situations. In their research, Karmacharya et al. [10] validate their model using real data from American Electric Power (AEP) on residential metered loads. Using these findings, Wen and Burke created a thermal model of the home [11]. To get the HVAC system's predicted state, they employed the autoregressive model with exogenous inputs, often known as the ARX model. Through the use of the GE Nucleus energy management system, which aggregates data and implements algorithms, the suggested solution is tested in a specific residence. They verify and simulate their data using an ARX model and a thermostat regulator. Residential energy use has been and will continue to be a major focus of academic inquiry. Zhu has evaluated several energy-saving methods in a case study he ran using simulation code. The simulation may provide a reusable tool for energy efficiency study, according to the researcher [12]. In order to lower the building's energy usage, Zhou and Park [13] looked at another case study that used the control optimization technique. A research for a low-energy-use building envelope was presented by Yu et al. for a residential structure in China's hot-summer-cold zone. According to their findings, energy modeling may be used to assess how different envelope designs affect AC energy consumption, which in turn can help establish the most effective approach for HVAC energy savings [14]. An experiment was carried out by Nasution et al. to determine the energy efficiency of a centralized air conditioning system with a variable speed driver. A traditional on/off controller and a PID controller allowed them to regulate the HVAC system's variable speed compressor. By comparing the two controllers' energy use, we find that a variable speed compressor provides superior temperature control and energy savings [15]. The energy consumption of the HVAC system is evaluated by experimental and computational thermal analyses that include the ON/OFF controller and the VFD controller. While building the experimental setup with a data collection monitoring and measurement system based on Lab-View, we simulated the house's temperature and included several types of air conditioning system controllers (ON/OFF, VFD units) in the model. The measurements verify the accuracy of the predicted HVAC power consumption. Provided are analyses pertaining to the evaluation of energy consumption, energy savings, cost, and payback time.

ANALYTICAL MOLDING

Thermal Model of the House

In developing strategies to minimize energy consumption in houses, it is crucial to understand the dynamics of working, heat energy generation and losses [16]. This section aims to investigate some of the contributions of heat generation and losses through the developed empirical models. From these models, a thermal model is derived to allow the researcher to build the relationship of heat flows with the variations in temperature [10]. The developed models have adjustable parameters corresponding to different contributions of the heat budget by understanding the form of variation temperatures. Therefore, we aim to determine the most important factors in the energy consumption and production within the house.

The thermal model of a house is presented in Figure 1 [17, 18]. The aim of this section is to show the parameters extracted in real-time were a reasonable representation of the house, in that they could be used to control the cooling plant of a real house. This means that, at any instant, the model would have to represent the thermal aspects of a house in its present condition, thus allowing predictions to be made.

The proposed thermal model of the house includes three layers for the wall, roof and windows. The temperature can be found at each desired point on the surface or center of the plaster, concrete, and outside wall of the plaster or stucco. Moreover, using three layers can enhance the thermal house parameters such as the type of building materials and thickness depending on the desired temperature in the house.

Thermal energy absorbed by air in the house, heat transfer via floor, wall and windows are represented in following equations.

$$Q_{\text{Absorbed in the House Air}}(t) = \frac{dT_H}{dt} \times C_{\text{Air}} \tag{1}$$

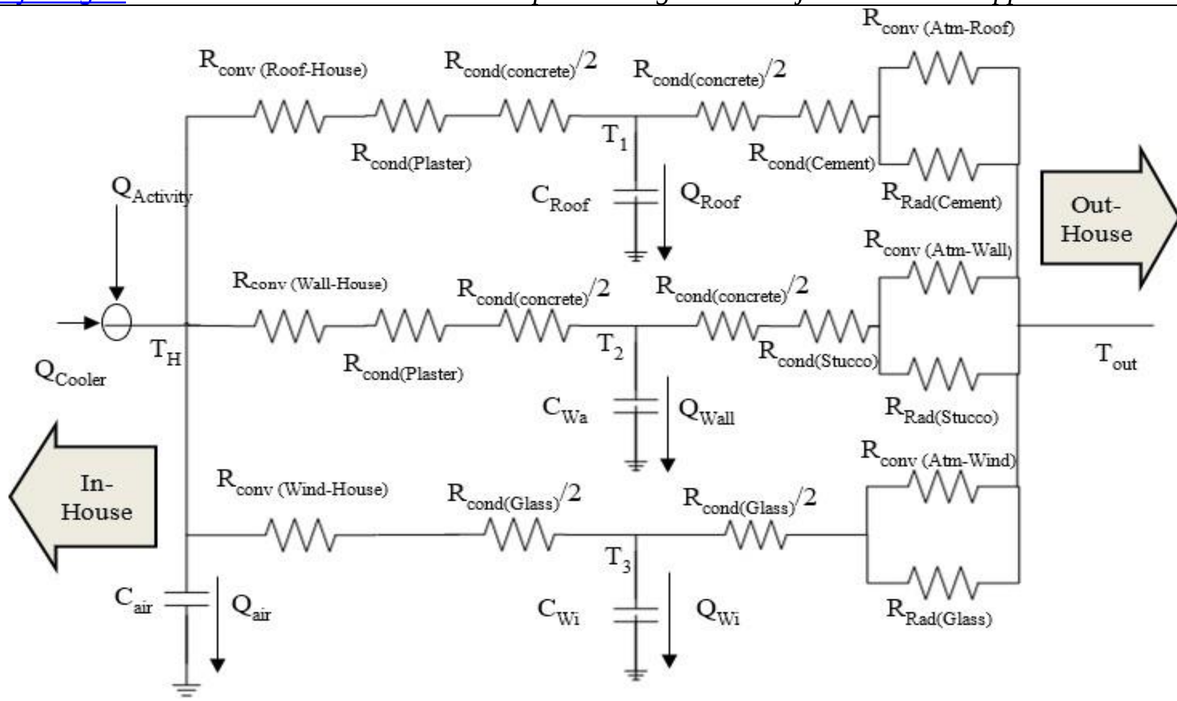


Figure 1. Thermal circuit model of house

$$Q_{\text{Absorbed in the Roof}}(t) = \frac{dT_1}{dt} \times C_{\text{Roof}} \quad (2)$$

$$Q_{\text{Absorbed in the Walls}}(t) = \frac{dT_2}{dt} \times C_{\text{Wall}} \quad (3)$$

$$Q_{\text{Absorbed in the Windows}}(t) = \frac{dT_3}{dt} \times C_{\text{Window}} \quad (4)$$

$$Q_{\text{Absorbed in the House Air}}(t) = (Q_{\text{Heat Passes to the House}}(t) + Q_{\text{Heat Sources in the House}}(t) - Q_{\text{Cooler}}) - (Q_{\text{Absorbed in the Roof}}(t) + Q_{\text{Absorbed in the Walls}}(t) + Q_{\text{Absorbed in the Windows}}(t)) \quad (5)$$

The heat transfer through the roof, walls and windows and the absorbed heat in roof, wall and windows are expressed in the following equations:

$$Q_{\substack{\text{Heat Passes}\\ \text{to the House}}}(t) = Q_{\substack{\text{Heat Passes}\\ \text{though Roof}}}(t) + Q_{\substack{\text{Heat Passes}\\ \text{through Walls}}}(t) + Q_{\substack{\text{Heat Passes}\\ \text{through Windows}}}(t) \quad (6)$$

$$Q_{\substack{\text{Heat Passes}\\ \text{though Roof}}} = Q_{\text{Absorbed in the Roof}}(t) + U_{11}(T_1(t) - T_H(t)) \quad (7)$$

$$Q_{\substack{\text{Heat Passes}\\ \text{though Walls}}} = Q_{\text{Absorbed in the Walls}}(t) + U_{21}(T_2(t) - T_H(t)) \quad (8)$$

$$Q_{\substack{\text{Heat Passes}\\ \text{though Windows}}} = Q_{\text{Absorbed in the Windows}}(t) + U_{31}(T_3(t) - T_H(t)) \quad (9)$$

Finally, the following equations present the thermal model incorporating the parameters related to the house:

Journal of Science and Technology
ISSN: 2456-5660 Volume 7, Issue 10 (Oct -2022)
www.jst.org.in *DOI:https://doi.org/10.46243/jst.2022.v07.i10.pp191- 208*

$$Q_{\text{Absorbed in the House Air}}(t) = U_{11}\left[T_1(t) - T_H(t)\right] + U_{21}\left[T_2(t) - T_H(t)\right] + U_{31}\left[T_3(t) - T_H(t)\right] + Q_{\text{Heat Sources in the House}}(t) - Q_{\text{Cooler}} \quad (10)$$

$$\dot{T}_H(t) = \frac{1}{C_{Air}}\left(U_{11}T_1(t) + U_{21}T_2(t) + U_{31}T_3(t) - T_H(t)\left(U_{11}+U_{21}+U_{31}\right) + Q_{\text{Heat Sourcesin the House}}(t) - Q_{\text{Cooler}}\right) \quad (11)$$

$$\dot{T}_1(t) = \frac{1}{C_{Roof}}\left[U_{12}\left(T_{out}(t) - T_1(t)\right) - U_{11}\left(T_1(t) - T_H(t)\right)\right] \quad (12)$$

$$\dot{T}_2(t) = \frac{1}{C_{Wall}}\left[U_{22}\left(T_{out}(t) - T_2(t)\right) - U_{11}\left(T_1(t) - T_H(t)\right)\right] \quad (13)$$

$$\dot{T}_3(t) = \frac{1}{C_{Window}}\left[U_{32}\left(T_{out}(t) - T_3(t)\right) - U_{31}\left(T_3(t) - T_H(t)\right)\right] \quad (14)$$

Factors Affecting Cooling Load

The amount of cooling required depends on a large number of factors. These include the dimensions of the house, outdoor temperature, lights, the outdoor humidity, wind speed, the level of insulation in the house, the amount of air leakage in the house, the amount of southern, eastern, and western facing glass in the house, whether this glass is single, double, or triple glazed, and whether window treatments (curtains or blinds) are kept closed or open. Other factors include the amount of shading from trees, roof overhang, awnings, or buildings and how much heat is generated in the house by people during cooking, sleeping and some electric equipments inside the house that produce heat [19].

The operation electrical load by the compressor in one hot day in Dhahran city (KFUPM Campus) has been studied by taking into account the cooling effective factors. Figure 2 shows the outdoor temperatures of the same hot day which is measured for 24 hours. It can be observed that the temperature starts around 35 ºC, and it goes up dramatically to 51 ºC at midday, and then it drops slowly until it reaches to 33 ºC at midnight. Figure 2 also presents the daily internal heat load for one hot day in the house as there are only two people living in it.

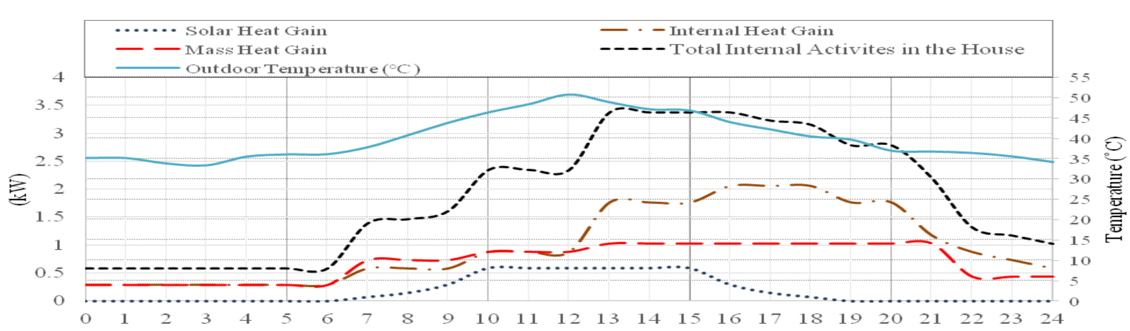


Figure 2. Outdoor temperature with daily internal heat load

House Thermal Model Using Simscape Physical System

The thermal model of both identical houses is built by applied Simscape Physical components in Simulink/Matlab as shown in Figure 3. The model is developed with four thermally distinguishable parts: inside air, house walls, windows, and roof. The house exchanges heat with the environment through its walls, windows, and roof. Each path is simulated as a combination of a thermal convection, thermal conduction, and thermal radiation. This model has been integrated with two different units of an air conditioning system; the 1st house has been equipped with VFD HVAC unit and the 2nd house has been equipped with an ON/OFF HVAC unit.

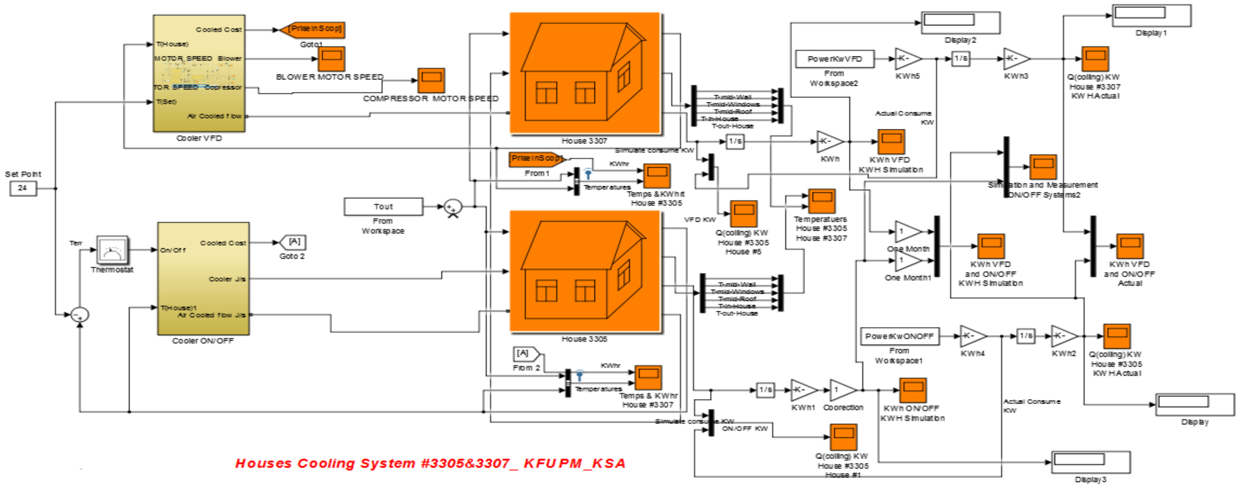


Figure 3. House thermal model integrated with the VFD & ON/OFF HVAC system using simscape physical components

Conventional A/C System (On/Off Cycle)

The air conditioning unit attains the desired temperature based on the temperature set by its thermostat. When the compressor of the air conditioner is turned ON, it remains on until the room temperature decreases to the desired temperature on the thermostat. Once the desired temperature is reached, the compressor turns OFF until the room temperature increases again.

The cooling unit is a subsystem that has a constant air flow rate, " $\dot{M}$ ". The thermostat signal turns the cooler ON or OFF. When the cooler is ON, it absorbs hot air at a temperature (for example 10 degrees Celsius = 50 degrees Fahrenheit by default) at a constant flow rate (for example 1kg/sec = 3600kg/hr by default). The cool airflow is expressed by the equation (15).

$$\frac{dQ_{Cooler}}{dt} = C_p \left(T_{HVAC} - T_{House} \right) \dot{M}_{HVAC} \quad (15)$$

Variable Frequency Drive A/C Systems

The Variable Frequency Drive (VFD) has been widely used in the HVAC application, including fans, pumps, compressors, etc. A better understanding of the VFD will lead to improved application and selection of both equipment and HVAC systems. A Variable Frequency Drive (VFD) is a type of adjustable speed drive used to control the speed of the motor based on the system load requirements and operation schedule, resulting in a dramatic cut in energy consumption [20]. VFD technology allows the air conditioner to automatically vary its power output to specifically maintain room temperature at a desired or comfortable level. A non-inverter appliance maintains the temperature by repeatedly switching the power ON and OFF, which consumes much more electrical energy upon starting.

The VFD cooler has two options; constant value and variable air flow rate, " $\dot{M}_{HVAC}(t)$ ". Based on equation 16, the variable airflow rate is delivered from the cooler system using a PI system. The air specific heat is multiplied with airflow rate to produce cooler gain by equation 17. The HVAC coil temperature (T_{HVAC}) uses variable values that are controlled by the PI system. Equation 18 is used to calculate the absorbed heat by the air in the house. In the second subsystem equation 19, T_{House} and $T_{Setting}$ are the inputs signal for the HVAC coil temperature subsystem and the cooling air flow subsystem. The cooling airflows (Q_{Cooler}) into the house are produced from the difference between indoor temperature (T_{House}) and the HVAC coil temperature (T_{HVAC}) and then multiplied by cooling gain.

$$\dot{M}_{HVAC} = K_0 \frac{d(T_{setting} - T_{House}(t))}{dt} + K_1 T_{House}(t) \tag{16}$$

$$\text{Cooler Gain}(t) = \dot{M}_{HVAC}(t) \times C_P \tag{17}$$

$$T_{HVAC} = K_2 \frac{d(T_{setting} - T_{House}(t))}{dt} + K_3 T_{House}(t) \tag{18}$$

$$\frac{dQ_{Cooler}}{T} = (T_{House} - T_{HVAC}) \times \text{Cooler Gain}(t) \tag{19}$$

dt House HVAC

EXPERIMENTAL ANALYSIS

Experimental Setup

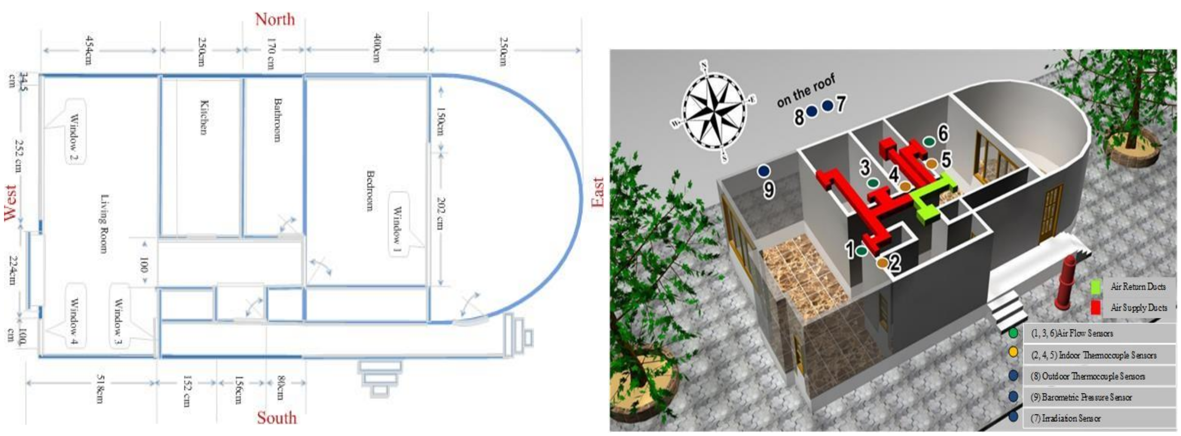
The major role of the experimental work in this study is to confirm the validly of the simulation work, and to evaluate the performance and energy consumption of the A/C systems. The monitoring and measurement hardware system is comprised of four major blocks: two 5-ton Al-Zamil rooftop units, a Data Acquisition (DAQ) chassis with National Instrument modules (Lab-View), sensors, and a host computer. The National Instrument DAQ-chassis monitoring system has several modules such as voltage measurements, current measurements, and thermocouples. There are four thermocouple sensors (three sensors for indoor and one for outdoor temperature), two humidity sensors (indoor and outdoor), an irradiation sensor, barometric pressure sensor, and three air flow sensors. The host computer has the National Instrument (NI) software, which is the main communicator with DAQ-chassis. The host computer will initiate the execution commands, store the data and display them on the monitor.

Experiment Procedures

The experiments were conducted in the Guest Houses in KFUPM campus, Dhahran, Saudi Arabia. The floor plan and the duct plan are shown in Figure 5.a. Each house consists of two rooms (one living room and one bedroom), kitchen and bathroom. Moreover, all details of the houses which are integrated with ON/OFF and VFD HVAC systems are described in this section and followed by a HVAC monitoring and measurement system.

Sensors Location in the Houses

Different types of sensors have been chosen and placed in both houses to read and measure the required data for the experiment, Figure 4.b, and provide the location of each sensor in the house. Three thermocouple sensors are fixed in the bedroom, corridor and living room. The temperatures are measured from three positions and then we take the average temperature for a house. Airflow sensors are located near inlet air ducts to measure A/C unit flow in kilogram per second. A pressure sensor is also placed inside the house to measure in-house pressure. A thermocouple sensor and an irradiation sensor are placed on the roof of the house to measure the ambient temperature in degree and daily irradiation in watt per meter square.



(a) (b)

Figure 4. (a) Floor plan for both houses, (b) Ducts plan and sensor's locations in the houses

Monitoring and Measurement Systems

The monitoring and measurement systems for both units have been developed to achieve different tasks such as displaying several physical and electrical characteristics, as well as environmental conditions. Furthermore, the data acquisition systems incorporate signals, sensors, actuators, signal conditioning, data acquisition devices, and application software. The purpose of data acquisition system is to measure the electrical or physical parameters such as voltage, current, temperature irradiation, humidity, pressure, and wind speed. The PC-based data acquisition system uses a combination of modular hardware, application software (Lab-View), and a computer to take measurements [21]. Figure 5 shows the drawing map of the monitoring and measurement system.

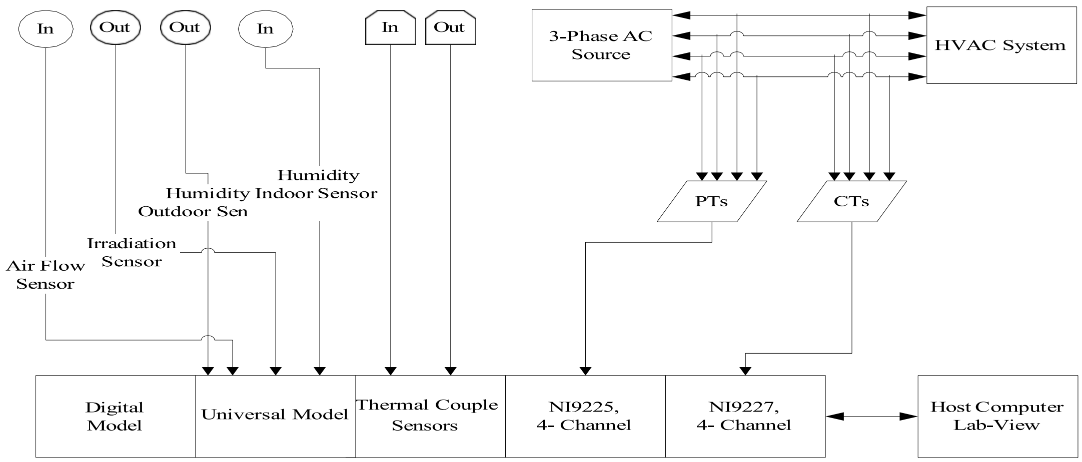
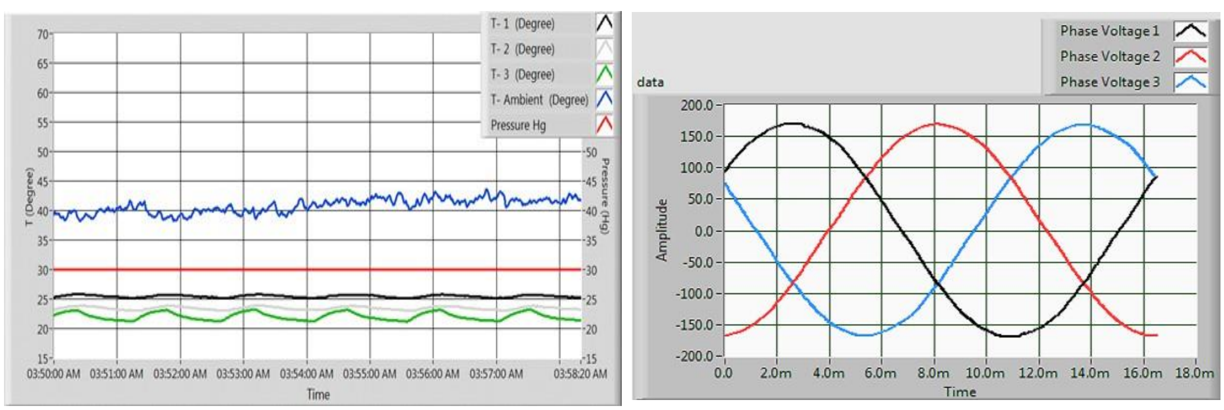


Figure 5. HVAC monitoring and measurement system

The superimposed graph displayed in Figure 6.a shows the instantaneous values of four temperatures and pressure with time and Figure 6.b displays the instantaneous values (peak to peak) of line voltage with corresponding RMS values.



(a) (b)

Figure 6. (a), (b), Monitoring and measurement system (Lab-View Platform)

RESULTS AND DISCUSSION

With validation against the measurement data, this part presents the findings of the simulation model. Monthly results for fluctuations of energy consumption, energy savings, and COP are also provided. The payback time for each unit has also been computed in the cost analysis of the ON/OFF and VFD HVAC systems.

Validation of the Simulation Results with Measurement Data for Both HVAC Systems

Simulation results for in-house air temperature and power consumption for one typical day, with normal activities, (9th of April 2016) have been presented using Simulink/Matlab. The normal internal activities of the house are shown in the Figure 2. The simulation results are produced for ON/OFF and VFD air conditioning units. Measurement data are collected by Lab-View program for both residential houses. These data are validated with the simulation results for both in-house air temperature and power consumption. Set point temperature is 24 ^{o}C with a threshold (+1 ºC & -1.5 ºC) and the initial house air temperature is 24.1 ºC.

Typical Day Activities (April 9, 2016) for the On/Off Cycle A/C Unit

Typical day activities validation for indoor temperature is shown in Figure 7. Simulated results are closely following the measurement results where the number of pulses is also equal to 53. The average cycle period is also identical, and the ON-time operation obtained by simulation and measurement are the same (451.05 min = 7.5175 h). The outdoor air temperature affects directly the ON/OFF A/C unit as well as the ON pulse numbers. The outdoor temperature as shown in Figure 7 is still constant and equal to 23 ºC from midnight to 6:00 AM and then it increases dramatically to 42.5 ºC at 12:30 PM. The temperature decreases again slowly to reach 27.5 ºC at 7:30 PM. The house has permanent activities (fridge, computer, monitor, Wi-Fi, lights, and printer) and variable activities (cooking, washing machine, open/close door and windows, etc.).

The activities of heat losses begin at 1.087 kW and goes up to reach 1.27 kW. Then it goes down to 0.87kW as the outdoor temperature stays at 23 ºC. From 2:30 AM to 4:00 AM, a decrease is observed in duty cycle that is affected by outdoor temperature reduction to 21ºC as well as a reduction in in-house activities. While the outdoor temperature increases from 05:30 AM to 10:00 AM, the duty cycle is still low, and it is affected directly by the tree's shadow that is close to the east window of the house. From 10:00 AM to 6:00 PM, the ON/OFF frequency increases due to the increase in the outdoor temperature that reaches 42.5 ºC at midday. The social activities (lunch, dinner, washing machine, open/close windows and door, etc.), increase the duty cycle. The ON/OFF frequency again decreases slowly as a result of the outdoor temperature reduction to 26 ºC and some of the social activities (cooking dinner, boiling tea water, etc.), so the duty cycle decreases slowly again.

The simulation and the measurement of the power consumption for the ON/OFF cycle unit on April 9, 2016 are presented in Figure 8. The simulated results are similar to the measurement results (4.95 kW rated value), where the number of the ON/OFF pulses are also equal (53 pulses). The OFF time is (989.112 min = 16.4852 h). The outdoor temperature shown in Figure 7 went up at 10:00 AM to 32 ºC and reached 42.5 ºC at 12:30 PM. This causes the condenser of the A/C unit to start increasing the power consumption. The total power reached to 5.4 kW when the condenser of the A/C unit is connected directly with the compressor supply. On the other hand, when the outdoor temperature reaches 27.5 ºC, the compressor A/C unit temperature decreases so the condenser power consumption also decreases. In this case, the total power reaches the nominal power of 4.95 kW.

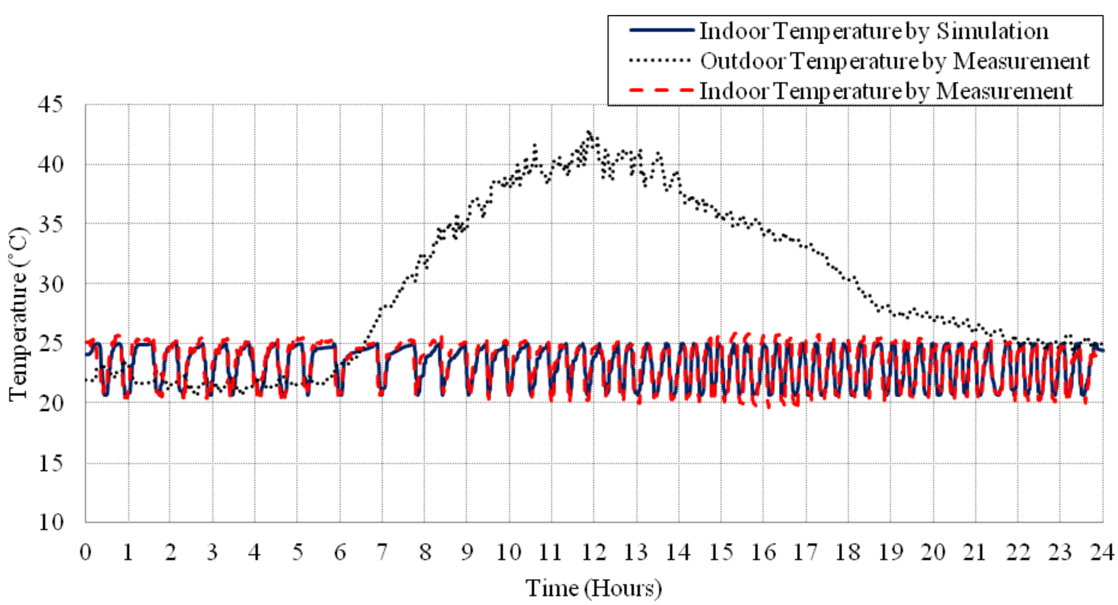


Figure 7. Measured and simulated indoor temperature and the outdoor temperature on 9th of April 2016

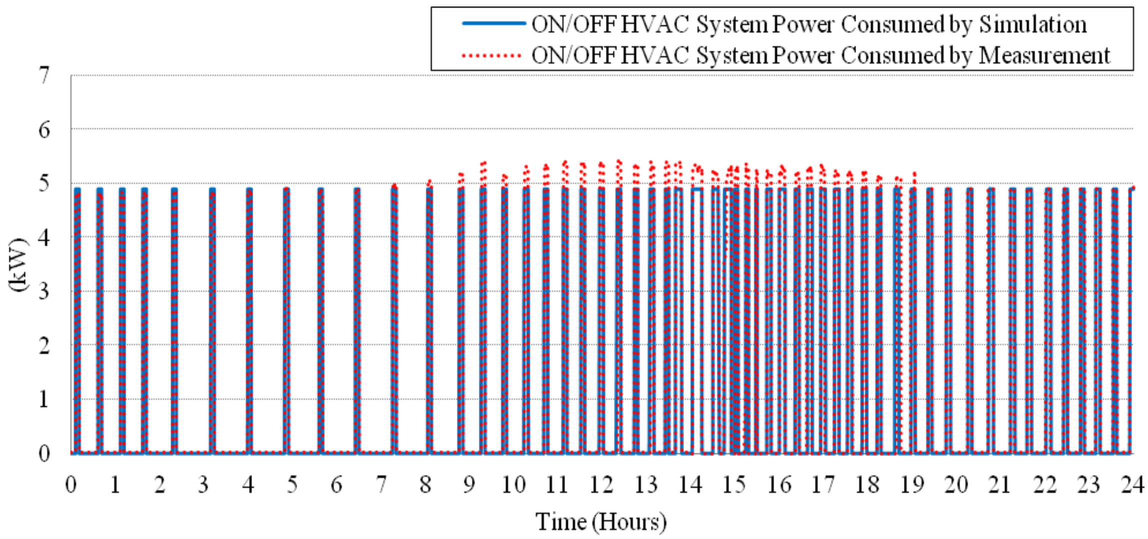


Figure 8. Measured and simulated consuming power for the ON/OFF cycle A/C unit on the 9th of April 2016

Typical Activities (April 9, 2016) for the VFD A/C Unit

Similarly, the typical activities validation for the indoor temperature is displayed in Figure 9. The simulated results are similar to those of the measurement, where the temperature for both values is in the same level (24.5 °C to 23 °C). The outdoor temperature and typical activities (permanent and social heat load) have a direct effect on the VFD A/C unit performance, where the amount of flow rate is increased or decreased to match closely the set point temperature (24 °C).

The simulation and measurement of the power consumption for the VFD A/C unit on the 9th of April, 2016 are shown in Figure 10. The power consumption starts to rise at 05:30 AM and reaches a maximum value (1.7 kW) at 10:00 AM until 12:00 PM because of the in-house activities (cooking breakfast/lunch, washing machine, open/close windows and door, etc.), and rise in the outdoor temperature. The power consumption decreases gradually until it reaches 0.9 kW at 3:00 PM and increases again to 1.3 kW because of the increase in the in-house activities (cooking dinner, washing machine, open/close door, boiling tea water, etc.). It then goes down to 0.4 kW till 09:00 PM and finally goes up to 0.9 kW at midnight.

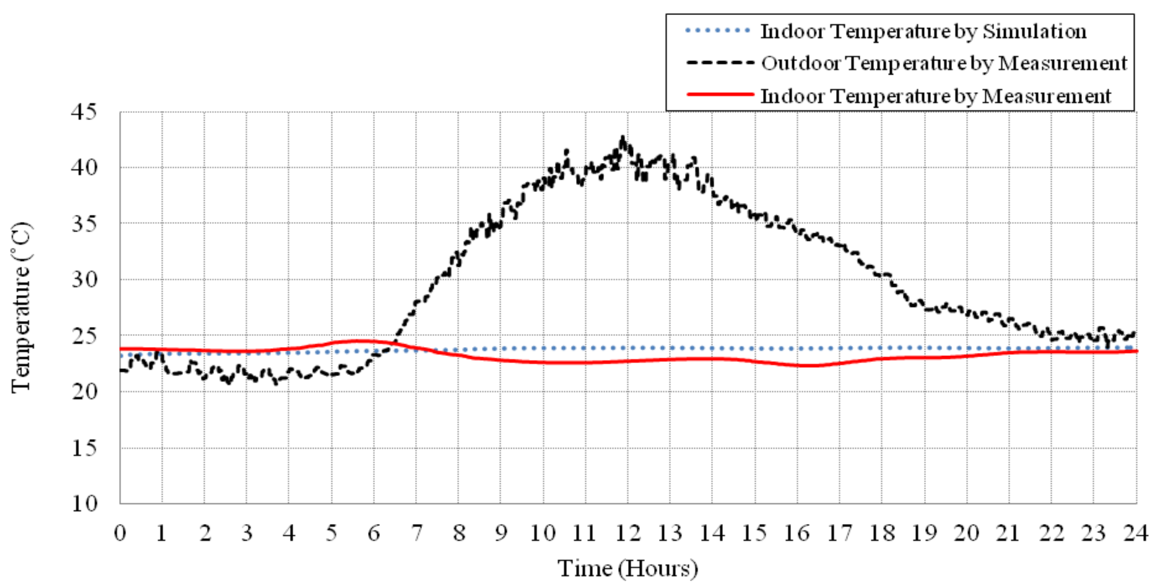


Figure 9. Outdoor measured temperature and indoor measured temperature and indoor simulated temperatures by the VFD HVAC unit on the 9th of April, 2016

ISSN: 2456-5660 Volume 7, Issue 10 (Oct -2022)
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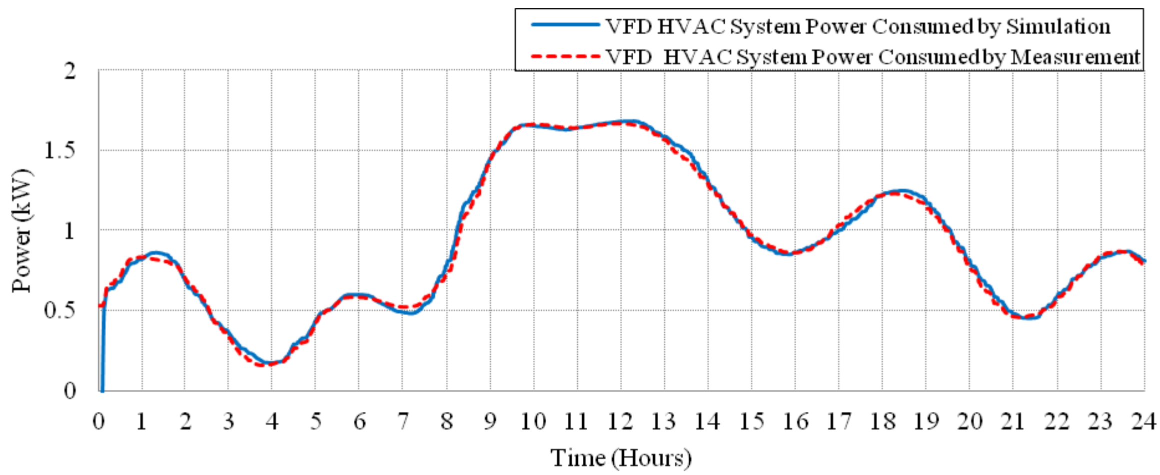

Figure 10. Measured and simulated power consumption for the VFD A/C unit on the 9th of April, 2016

Energy Analysis for Both On/Off Cycle and VFD HVACSystems

The energy consumption for the ON/OFF cycle and the VFD HVAC units is calculated by integrating the area under power consumption curve as shown in Figures 8 & 10 for typical activities (9^{th} of April, 2016) for both simulation results and data measurement. Table 1 shows the energy consumption of both ON/OFF and VFD HAVC for one typical day.

Table 1. Energy analysis for the ON/OFF cycle and the VFD HVAC systems for one day

Day	Simulated Results			Measurement Data		
	ON/OFF Cycle Unit (kWh)	VFD Unit (kWh)	Saving %	ON/OFF Cycle Unit (kWh)	VFD Unit (kWh)	Saving %
Typical activities (April 9, 2016)	37.212	22.4	39.53	38.44	23.71	38.31

A summary of measured energy consumption for two months (April 2016 and May 2016) that is used for the validation of the simulation results is presented in Table 2. The comparison of the energy consumption for the ON/OFF cycle and the VFD HVAC units and energy savings are also presented in the Table.

Table 2. Comparison energy consumption for the ON/OFF cycle and the VFD HVAC systems for two months, 2016

Months	Simulated Results			Measurement Data		
	ON/OFF Cycle Unit (kWh)	VFD Unit (kWh)	Saving (%)	ON/OFF Cycle Unit (kWh)	VFD Unit (kWh)	Saving %
April	1042.058	571.0345	45.2012	1098.3	519.3	52.7184
May	1763.567	1038.548	41.1109	1606.11	1130.88	29.589

Monthly Variation of Energy Consumption

Table 3 presents a summary of the results of energy consumption for seven months of study. Both the ON/OFF cycle HVAC and the VFD HVAC systems are used with the same conditions. The average operation period of the ON/OFF cycle and the number of ON pulse also are displayed in the table. The energy consumption in kW is presented for both the ON/OFF cycle and the VFD HVAC systems. The hottest months, June and July, show the higher duty cycle per month. The comparison of the energy consumption for both systems is shown in Figure 11 and the energy savings per month is presented in Figure 12. Table 3 shows that a considerable amount of savings of energy occur from April 2016 to Oct. 2016.

Table 3. Comparison energy used for the ON/OFF and the VFD HVAC systems for several months

Months	ON/OFF Cycle HVAC System					VFD HVAC System	
	Numbers of (ON) Pulses	The average of ON Time (mins)	The average of OFF Time (mins)	The average ON Duty Cycle (%)	Energy used per Month (kWh)	Energy used per Month (kWh)	Energy Saving (%)
April 2016	1450	7.0172	16.982	50.342	1042.058	571.0345	45.2012
May 2016	1906	11.492	12.507	53.072	1763.567	1038.548	41.1109
June 2016	2190	13.500	10.499	54.15	2004.897	1329.972	33.6638
July 2016	2309	13.796	10.203	54.380	2117.09	1419.172	32.9659
Aug. 2016	2208	13.046	10.953	53.166	2002.028	1326.967	33.7188

Table 3. (Cont.) Comparison energy used for the ON/OFF and the VFD HVAC systems for several months

Months	ON/OFF Cycle HVAC System					VFD HVAC System	
	Numbers of (ON) Pulses	The average of ON Time (mins)	The average of OFF Time (mins)	The average ON Duty Cycle (%)	Energy used per Month (kWh)	Energy used per Month (kWh)	Energy Saving (%)
Sep. 2016	2150	11.732	12.267	53.333	1742.216	1142.922	34.3983
Oct. 2016	1540	7.9502	16.049	51.633	1219.962	756.8483	37.9613

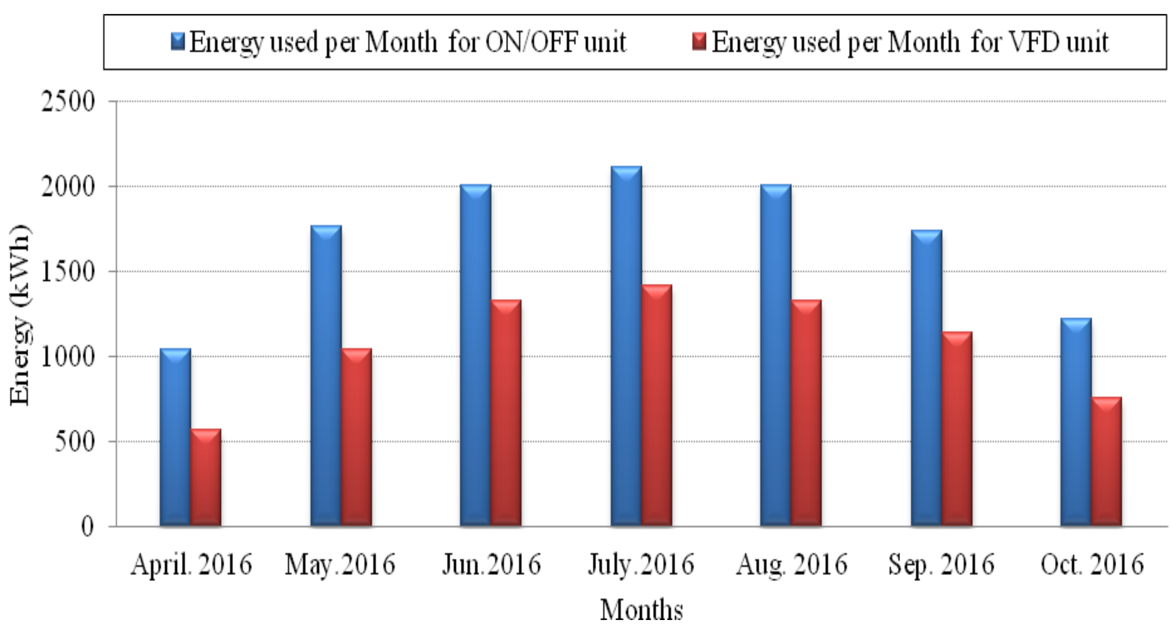

Figure 11. Energy consumption for the ON/OFF cycle and the VFD HVAC system

Monthly Energy Savings

The energy consumption is the power (*P*) multiplied with the time of operation (*t*) of the AC system [22], whereas the percentage of energy savings is calculated based on the difference between energy consumed using the ON/OFF control and energy consumed using the VFD control.

$$\text{Power} = \frac{V \times I \times PF}{1000} \text{(kW)} \tag{20}$$

where I is the current (Ampere), V is voltage (Volts), and PF is the power factor.

$$\text{Energy} = \text{Power} \times t \quad \text{(kWh)} \tag{21}$$

$$\text{Energy Savings} = \frac{[\text{ON/OFF HVAC Energy}] - [\text{VFD HVAC Energy}]}{[\text{ON/OFF HVAC Energy}]} \times 100 \tag{22}$$

The energy savings per month is shown in Figure 12.

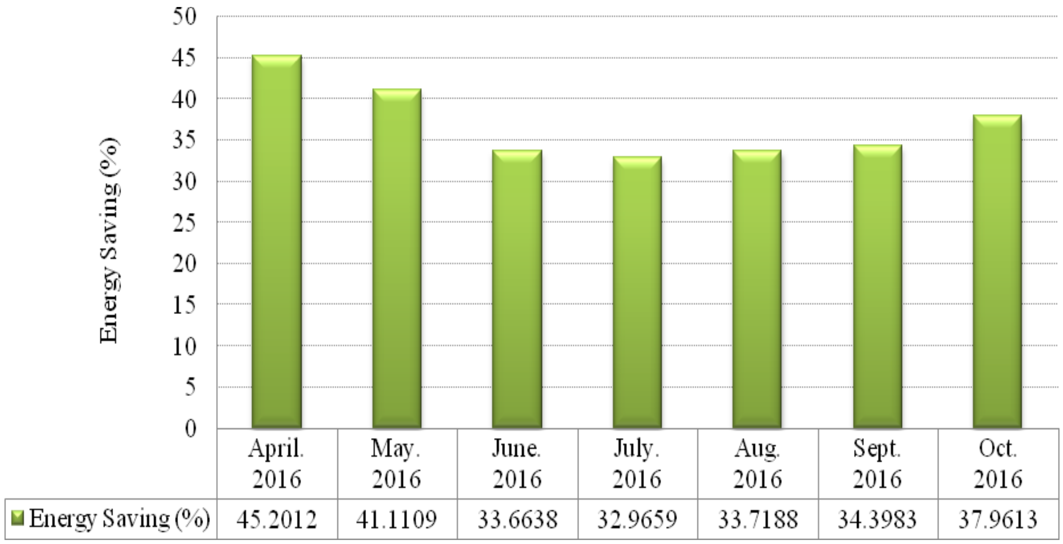

Figure 12. Energy saving rate per month

Average Monthly COP Variations

The coefficient of performance (COP) is commonly used to express the efficiency of an air-conditioning system [22]. The main purpose of the A/C system is to remove heat or to process load from the evaporator (Q_L). The energy required at the compressor (W_{com}) is to accomplish the refrigeration effect. Thus, the COP is expressed as:

$$COP = \frac{(h_1 - h_4)}{(h_2 - h_1)} = \frac{Q_L}{W_{com}} = \frac{\text{Internal Heat Gain (Energy Input) (kWh)}}{\text{Total Energy Consumption (kWh)}} \quad (23)$$

where, h_1 and h_2 (kJ/kg) are the enthalpy at the compressor inlet and that of the compressor outlet, respectively, h_4 (kJ/kg) is the enthalpy at the evaporator inlet, Q_L (kWh) is the refrigerating effect, and W_{com} (kWh) is the compression work.

The maximum theoretical COP for the air conditioning system is expressed by Carnot's theorem given by the following equation:

$$COP_{Maximum} = \frac{T_C}{(T_H - T_C)} \quad (24)$$

where T_C is the cold temperature and T_H is the hot temperature. The air conditioning system cools the house to 22.5 °C for (ON/OFF) and 24 °C for (VFD). If the average outdoor temperature is 35.55 °C the theoretical maximum COP is:

$$COP_{Max(ON/OFF)} = \frac{T_C}{T_H - T_C} = 1.72 \qquad COP_{Max(VFD)} = \frac{T_C}{T_H - T_C} = 2.10 \tag{26}$$

The total internal heat gain for the 9th of April 2016 is calculated based on the solar heat gain, mass heat gain, and the internal house activities in both houses. On the other hand, the monthly average COP variation is calculated based in the measured energy and the internal Heat Gain (April 2016).

The daily average of internal Heat Gain for the month of April for both houses = 42.922 kWh

The daily average of energy used for the month of April by the ON/OFF HVAC unit = 36.61 kWh

The daily average of energy used for the month of April by the VFD HVAC unit = 20.82 kWh

$$COP_{(ON/OFF)} = \frac{Q_L}{W_{com}} = \frac{42.922kWh}{36.61kWh} = 1.172 \tag{27}$$

$$COP_{(VFD)} = \frac{Q_L}{W_{com}} = \frac{42.922kWh}{20.82\,kWh} = 2.062 \tag{28}$$

Cost Analysis of Both the On/Off and the VFD HVAC System

The payback period is calculated by counting the number of years it will take to recover the cash invested in installing the VFD HVAC unit instead of the conventional ON/OF HVAC unit. The payback period for setting the temperature to 24 ºC can be calculated by the following formula.

$$\text{Payback Period} = \frac{\text{Additional Cost}}{\text{Annual Saving}} \tag{29}$$

The cost difference between the ON/OFF unit and the VFD unit is about 40% (8750SR) in which the VFD unit is higher cost than the conventional ON/OFF unit.

Based on the calculation performed in Table 4, the payback period is six years and 6 months, so if the user installs a VFD HVAC system, he can recover the extra paid money within 6 years and 6 months. During the time after the payback period, the user will start to get the benefit of having the VFD HVAC in the house as the energy consumption is going to be less than that of having an ON/OFF unit.

Table 4. Payback period for a residential HVAC

Electrical Energy Cost [23]		Annual Consumption				
Residential Sector		ON/OFF	VFD	Annual Energy Savings	Annual Cost Saving	Payback Years
kWh	Halalah					
1-2000 2001-4000 4001-6000 6001- 8000	5 10 20 30	4	8734.92 kWh	34% 4481.484 kWh	4481.484 kWh* 0.3 Hala=1325.54SR	6 years & 6 months
8000 <	30					

CONCLUSIONS

To find out how much power the HVAC compressor needs in residential areas on the Saudi Arabian campus of King Fahd University of Petroleum and Minerals, we looked at HVAC systems that used an ON/OFF controller and a variable frequency drive (VFD). When doing thermal analysis, it is done in

in keeping with the experimental settings used to measure the HVAC system's power usage. A data gathering, monitoring, and measuring system based on LabVIEW is integrated into the experimental setup. Various AC system controllers (ON/OFF, VFD) are taken into account by the thermal model. An analysis was conducted to compare the predicted and actual HVAC power consumptions. An on/off cycle cooling source model and variable frequency drive (VFD) air conditioning systems are included into the mathematical thermal home model that has been constructed. In the Matlab/Simulink environment, the created thermal models are rendered via the use of Simscape physical components. Furthermore, all relevant analyses regarding energy consumption, energy savings, and payback time cost have been assessed. As a rule, an air conditioning system with a variable frequency drive controller will be more efficient and cheaper. On top of that, below are the exact findings from the current study: Over the course of many months, the energy consumptions were studied, and the results showed that energy savings ranged from 32% to 45% from April 2016 to October 2016. The performance system simulation has been shown to be impacted by both the outside temperature and the inside activities that take place during the day. In a moderate outdoor environment, the energy savings achieved by using a VFD were 45 percent. There was a 3% discrepancy between the experimental data measurement and the modeling findings. The results showed that the VFD unit had a greater COP than the ON/OFF cycle, based on the daily and monthly average COP changes of the real and ideal systems.

We have computed the payback time and the cost analysis. It takes the consumer little over seven years to recoup the extra expense. A further reduction in the price of the VFD unit in the near future will serve as a spur for the development of energy conversion via its usage. The research demonstrated that a home HVAC system may achieve significant energy savings throughout the ON/OFF cycle by using a variable frequency drive (VFD).

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