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COST EFFECTIVE OPERATION OF HVAC SYSTEM UNDER THERMAL DISTURBANCE

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ABSTRACT

Varying cooling load requirements in HVAC system become a major concern to many consumers because of the additional cost of electricity. The cooling load variation of HVAC system usually occurs when the domestic house door is frequently kept open for prolonged durations, which is particularly important in hot seasons. The present study, addresses a comparison of energy consumption due to the thermal disturbance during domestic house door keep opened for various duration when the Variable Frequency Driver (VFD) and ON/OFF controllers are installed in HVAC system. The experiments are carried out in two identical houses during six warm days in a hot season where the outdoor temperatures have similar patterns throughout the days. The energy response of HVAC system is analysed incorporating the thermal and the electricity consumption data because of the change of the indoor temperature during opening of the house main door. The cost analysis is carried out and it is extended to include several repeats of door opening durations. It is the first time demonstrated that the energy consumption for HVAC system increases dramatically when the house main door is kept opened for several times in a day. The energy consumption and additional cost increase significantly for the case when the period of the main door opening is extended. In this case, VFD A/C controller unit achieves more energy savings than that of ON/OFF A/C controller unit.

Keywords: *HVAC, Energy Consumption, Variable Frequency Drives VFD, ON/OFF Cycle, Cost Analysis*

INTRODUCTION

Air conditioning (A/C) is mainly utilized for maintaining thermal comfort in indoor environments, especially for hot and humid climate. Nowadays, air conditioning has become a necessity in residential area, commercial buildings and industrial processes. It is considered to be one of the fastest growing energy sectors in Saudi Arabia. A/C system is directly participating in increasing energy consumption due to the Saudi Arabia weather which is characterized with high temperature, humidity, and dust storms. A temperature in Saudi Arabia follows the pattern of the desert climate, with the exception of the southwest. The average summer temperature is about 45° C, and the highest temperature is reaching 55° C are not unusual [1-2]. In the following years, the climate change could make temperature raise high in summer days in the Arabian Gulf [1]. As a consequence, the higher outdoor temperature increases the demand for cooling over the years and the energy consumption. Although several attempts have been made to improve thermal performance of cooling systems, such as air conditioning (A/C) units [3-7], it is the first time to consider the efficient operation of cooling systems under temporal thermal disturbance due to house main door opening for several durations.

Minimizing the energy consumption in residential areas is always the main concern and retains a lot of research attention. Energy consumptions in the Kingdom of Saudi Arabia (KSA) have grown substantially over the previous years. Electricity consumption in the KSA is considered one of the highest per capita consumption rates in the world around 8.161 kWh /capita which is approximately three times more than the world's average [8]. The energy demand in correspondence has grown at a much higher pace of approximately 5-8% per year [8]. Moreover, A/C systems are considered to be the major energy consumptions in the residential area in KSA and it is accounted for approximately 60% [9-10]. The significant focus in evaluating the performance of HVAC systems is ensuring the thermal comfort and reducing the energy consumption.

On the other hand, most of the occupants have bad energy consumption habits. They frequently kept the main door of the house open while the A/C unit is in operation; this leads the hot and moist ambient air mixing with

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the indoor cool air. Since the door opening behavior significantly affects the thermal comfort level, this may have an impact on energy consumption patterns. However, it does matter how frequent the bad habit repeats. If the main door of the house remained opened frequently and for long periods of time, large amount of energy might be wasted per a year. Therefore, the door opening/closing effect is truly a major concern to many consumers. Fabi et al. [11] discussed that the window opening behavior might have direct effects on energy consumption for cooling by varying the indoor air flow rate inside the houses. Pan et al. [12] had conducted an experimental test in an office building in Beijing, China and monitoring of occupants' window opening behavior, together with important indoor and outdoor environmental variables. They found that window opening behavior influences the performance of buildings significantly, and it was required to be improved to promote the energy efficiency of the building. Rijal et al. [13] developed an adaptive window opening algorithm to predict the thermal comfort, energy use and overheating in buildings. It was found that when the window was open the mean indoor and outdoor temperatures were higher than when closed, and they used adaptive algorithm to achieve more comfortable, lower energy buildings while avoiding overheating. Brown et al. [14] investigated a large scale energy surveys in the UK retail. They conducted the survey to examine differences in energy use behavior and the effect of open doors in retailers, between winter and summer season. The estimates of heating and cooling wastage have been made using computer simulation and empirical equations to model air flow through open doors with an inside to outside temperature difference. The results showed that the use of energy saving measures during the cooling season, such as closing external doors or using air curtains was minimal compared to the warm season.

Since the main door opening influences the energy consumption, duration of the house main door opening becomes critical for air-conditioning (A/C) unit operation. Although the effect of the door air flow on A/C energy consumption was studies previously [9-15], the temporal effects of the cooling load demand on energy consumption were not included in the studies. The temporal demands for the domestic cooling load can occur when the house door is frequently kept open in buildings. The energy consumption increases to overcome the need for the cooling load. This, in turn, influences the cooling system performance and the cost. Consequently, in investigation of outdoor air flow on energy consumption of A/C unit in hot environments becomes essential. Two experiments are conducted to investigate the energy consumption of HVAC systems, due to the warm and humid air transfer from the surroundings to the house, through the opening of the house main door for selected periods of time. In the present study, two different units of air conditioning systems are incorporated and each system is installed in two identical houses. Two cases are considered during six warm days where the outdoor temperatures have similar patterns throughout the days of the study. In the first case, the house main door is opened during the periods of 15 minutes, 30 minutes and 60 minutes for three days when A/C unit is active. The time of start for the main door opening is at 12:30 p.m. local time in Kingdom of Saudi Arabia. The second case is carried out for the other three days and the door is kept closed for all periods while A/C unit remains functional. Energy consumption and cost analyses are carried out to assess the performance of HVAC systems when the main door remained opened for selected durations. It should be noted that the duration for keeping the main door open is recorded over the period of one year in the local area where the tests are carried out. It is observed that the most frequent period of keeping the main door open is within 15, 30, and 60 minutes. The frequent door openings are mainly associated with the children in and outdoor activities. However, 60 minutes opening of is mainly related to forgetting to close the door.

EXPERIMENTAL SETUP

The performance and energy consumption of two A/C systems are assessed incorporating the weather conditions inside and outside of two identical houses considered. The monitoring and measurement hardware comprise of four major blocks: two 5-ton Al-Zamil rooftop A/C 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 thermocouple input. In measurements, four temperature sensors (three sensors for indoor and one for outdoor), two humidity sensors (indoor and outdoor), an irradiation sensor, barometric pressure sensor, and three air flow sensors are used. The host computer has the National Instrument (NI) software, which is the main communicator with DAQ-chassis. The host computer initiates the execution commands, store the data, and display them on the monitor.

Experiment Procedures

The experiments were carried out in two identical houses at the KFUPM campus, Dhahran, Saudi Arabia. The floor plan is shown in Figure 1. Each house consists of a living room, one bedroom, a kitchen and a bathroom. All details of the houses which are integrated with ON/OFF and VFD HVAC systems are described in this section and followed by details of the HVAC monitoring and measurement systems [16-17].

Houses Details

General project information for two houses, location and environment parameters are presented in Table 1.

Table 1. Houses details and environment parameters for project

Weather reference city	Dhahran, Saudi Arabia
Project location	KFUPM, Guest-Houses #3305 and # 3307
House # 3305	ON/OFF HVAC unit
House # 3307	VFD HVAC unit
Barometric pressure	1007.652
Altitude	22.86 meters
Latitude and longitude	26.288768 and 50.114103

Sensors Location in the Houses

The measurement system and sensors are placed in both houses to monitor the required data for the performance assessment of the A/C units. Figure 2, shows the location of each sensor in the house. Three thermocouples are located in the bedroom wall (close to the door), one in the corridor wall (close to the house main door) and one in the living room wall. Temperatures are measured from three positions and later average temperature is estimated for the house. Airflow sensors are located in the middle of each duct exit to measure the A/C unit air mass flow rate. The pressure sensors are located inside the house to monitor indoor pressure variation. Thermocouples, outdoor humidity sensors, wind speed sensors, and the solar irradiation sensor are placed on the roof of the house to measure the ambient temperature, wind speed, and daily solar radiation.

Monitoring and Measurement Systems

The monitoring and measurement systems for both units are developed to achieve different tasks such as displaying several physical and electrical characteristics, and environmental conditions. Furthermore, the data acquisition systems incorporate signals, sensors, actuators, signal conditioning, data acquisition devices, and application software. The data acquisition system enables to measure electrical or physical parameters such as voltage, current, temperature, irradiation, humidity, pressure, and wind speed. In addition, the PC-based data acquisition system uses a combination of modular hardware, and application software (Lab-View). Figure 3 shows the chart of the monitoring and measurement system [18].

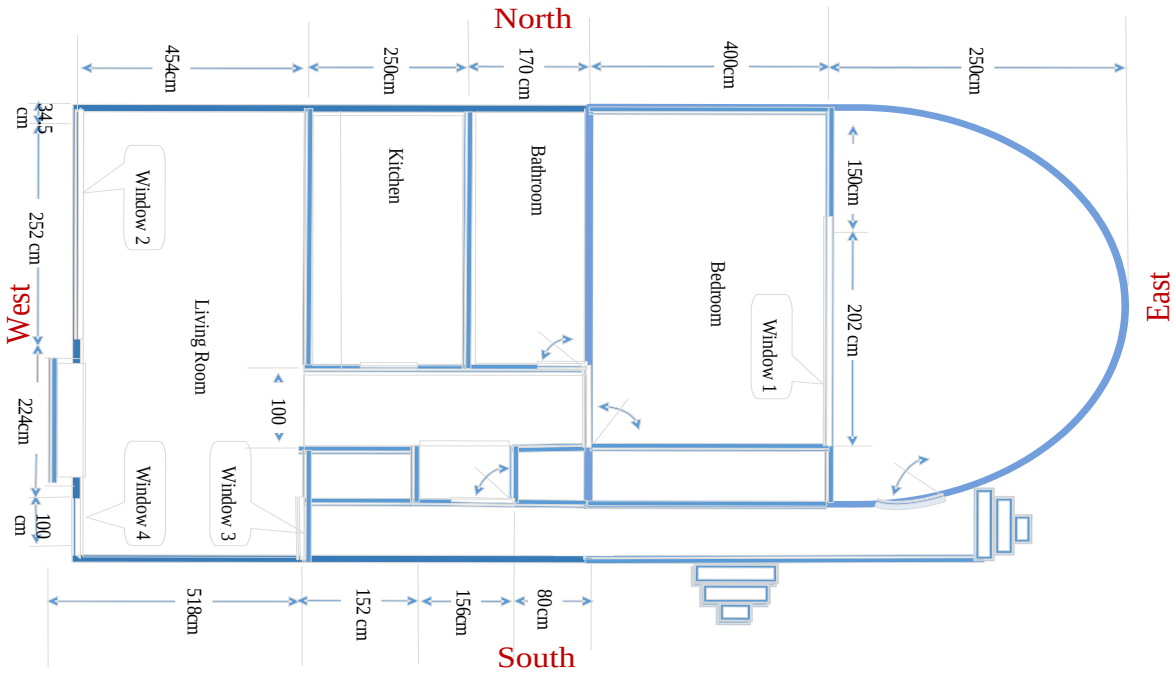

Figure 1. Floor plan for houses #3305& #3307

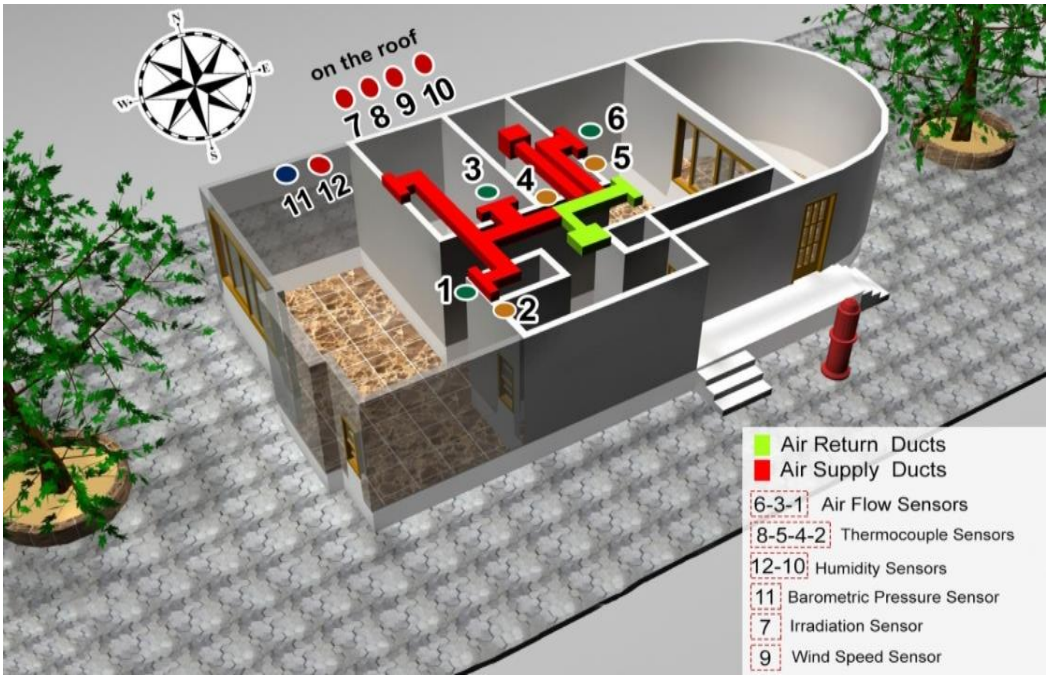

Figure 2. Ducts plan and sensor's locations in the houses

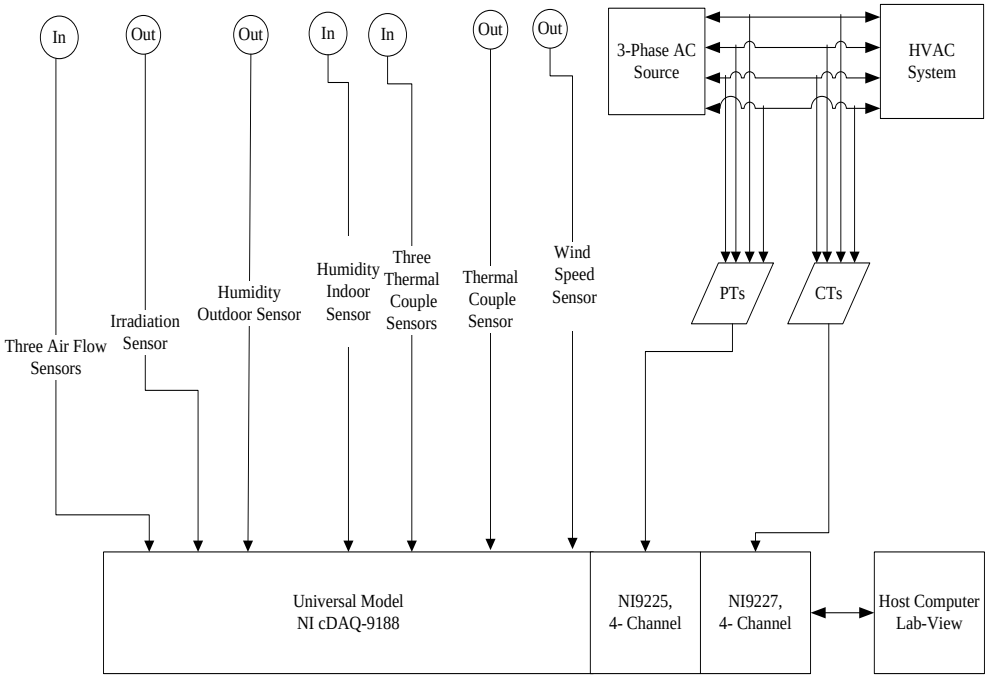

Figure 3. HVAC monitoring and measurement system

All the equipment and measuring devices are calibrated prior to the experiments. Table 2 gives the calibration data.

Table 2. The extra experimental tools for calibration and measurements

Instrument	Multi-Function Ventilation Meter VELOCICALC (9565)	Digital Handheld Multi-meter (PeakTech-3315)	Power Quality Analysis (PQA-HIOKI 3197)
Measurements	Temperature, humidity, pressure, air velocity, and wind speed	Current, frequency, and voltage, etc.	Validate the measured power by Lab-View platform
Accuracies	±3% of reading or ± 0.015 m/s, ± 0.3°C and ± 3% RH	± 0.1% reading + 0.2% range	±0.3 % rdg . ±0.01% f.s within ±0.5°C, ±3% at 40Hz to 5kHz

RESULTS AND DISCUSSION

The experiments are conducted to investigate the effect of opening the main doors of two identical houses on the cooling performance of A/C units for selected time periods. The study is performed during six warm days (8^{th} to 13^{th} of October, 2016) when the outdoor temperatures have similar patterns throughout the days.

Opening Main Door for House Equipped With VFD HVAC Unit

Figure 4 shows the outdoor air temperatures for the house equipped with VFD HVAC unit during the selected three days from 12:00 p.m. to 15:00 p.m. The indoor air temperature is taken as an average of three thermocouple readings placed at three different locations in the house. The indoor and outdoor temperatures are listed in Table 3 during the starting and ending of door opening operation.

Table 3. Outdoor and indoor temperature for both units on 11th, 12th and 13th of October, 2016

Date	Start of Opening (Main Door) ON/OFF& VFD	End of Closing (Main Door) ON/OFF &VFD	Outdoor Temp During Opening Time	Outdoor Temp During Closing Time	Indoor Temp During Opening Time		Indoor Temp During Closing Time	
					ON/OFF	VFD	ON/OFF	VFD
11/10/2016	12:30 p.m.	12:45 p.m.	42.23 °C	43.22 °C	22.74 °C	23.31 °C	26.17 °C	26.17 °C
12/10/2016	12:30 p.m.	13:00 p.m.	41.96 °C	40.98 °C	23.37 °C	22.14 °C	26.49 °C	26.49 °C
13/10/2016	12:30 p.m.	13:30 p.m.	40.54 °C	39.03 °C	24.06 °C	23.07 °C	25.41 °C	25.41 °C

On 11th of October, 2016 the main door is opened at 12:30 p.m. and it kept open for 15 minutes. The indoor temperature increases after one minute from the start of the main door opening period, which is associated with the hot air, which enters into the house. In this case, indoor temperature increases to reach 28 °C. However, it causes increasing of cooling air temperature, and gives rise to the operation of the A/C to supply low temperature cool air in the house. The increased temperature is recovered by the cool air flow until it reaches the desired set point temperature (23.5 °C). The main house door is closed after 15 min and the power reading for A/C unit and temperature recovery time are recorded via Data accusation system.

On the following day, the main door is kept open for 30 minutes on 12th of October, 2016, from 12:30 p.m. to 13:00 p.m. Indoor temperature variation is recorded staring at the time of the main door opening and the maximum temperature increases to reach 28 °C at the end of door opening period. However, temperature fluctuates in between 24.5 °C and 28 °C during the test because of non-uniform cooling. Once the main door is closed, the minimum indoor temperature becomes less than the set point temperature and it reduces around 21.5 °C. This variation occurs to recover the heat loss for the whole house to reach the set point temperature. On the last day, the main door is kept open for 60 minutes from 12:30 p.m. to 13:30 p.m.; similar changes takes place for the indoor temperature and some small temperature variation occur after the time of main door opening. It is noticed that the response of the VFD HVAC unit on the indoor temperature during the experiment is faster than the ON/OFF HVAC system. However, VFD unit has the ability to recover and match the desired temperature in a short time period.

Opening Main Door for House Equipped With On/Off HVAC Unit

The similar test of variable frequency HVAC unit is conducted for the house equipped with ON/OFF HVAC unit. The door is opened for three different periods 15 minutes, 30 minutes and 60 minutes on 11th, 12th and 13th of October, 2016. Figure 5 shows the outdoor temperature pattern and the indoor air temperature variation for each day. The switching ON/OFF band of the air conditioner is set as –1.5 °C and +1.5 °C. On the first day the main door is kept open for 15 minutes starting from 12:30 p.m. to 12:45 p.m. The variation on the indoor air temperature indicating that during the operation of opening the main door, the indoor temperature is lower than the set point and it takes approximately 4 minutes to pass the set point temperature and reaches 27 °C, then it continue fluctuating between 26 °C and 28 °C. The indoor temperature drops to 22 °C after 5 minutes from the door closing moment, and then it increases again to reach the desired set point. In the following day the door is opened for 30 minutes. According to Figure 6 the indoor temperature is varied from 24 °C to 28 °C during main door opening period, and due to the higher indoor temperature, the air conditioning system has run for a bit longer period of time, after the door closing to match the indoor temperature with the set point temperature.

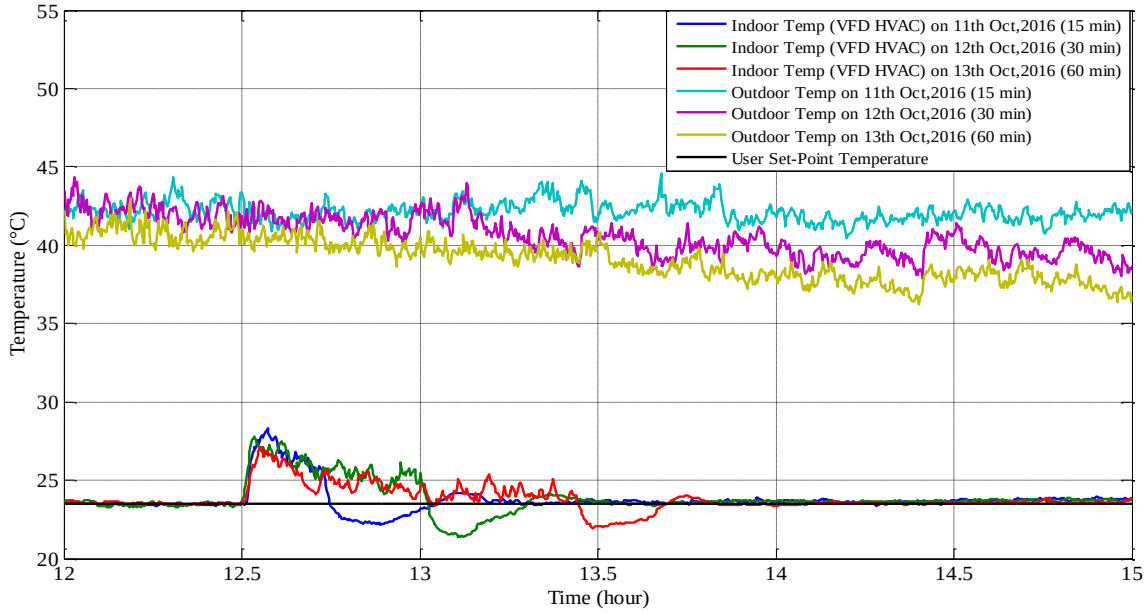

Figure 4. The outdoor air temperatures and indoor air temperatures responses during the door opening experiment in house #3307 VFD HVAC

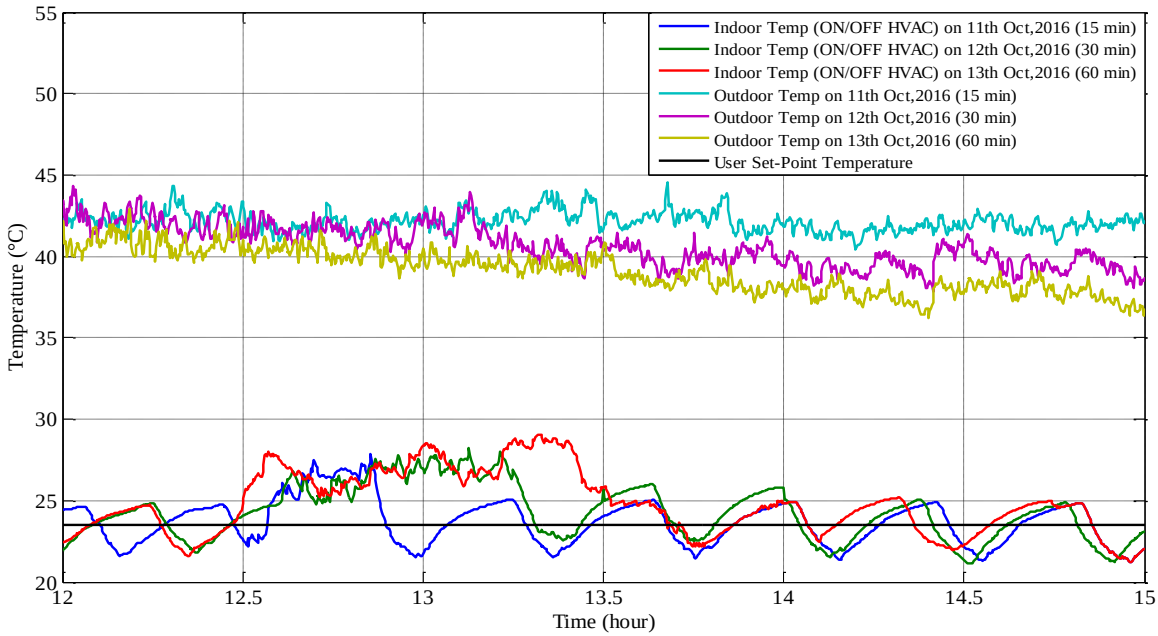

Figure 5. The outdoor air temperatures and indoor air temperatures responses during the door opening experiment in house #3305 ON/OFF HVAC

Finally, on the 13th of October, 2016, the door is kept open for 60 minutes starting at 12:30 p.m. and closed at 13:30 p.m. It can be observed From Figure 5 that the indoor temperature is nearly matching the set point temperature during the test of the main door opening and it is directly increases to 28 ºC, which means there are some factors can contribute to increase the house indoor temperature in a short period of time, such as the wind speed and outdoor humidity. Moreover, at the time of door opening, the measured temperature is 24.07 ºC, and after few second it increases to 25.5 ºC. This behavior occurs because the A/C unit was OFF before and during the action

of the door opening. The ON/OFF A/C is cycling based on the operation range or the threshold of the thermostat which set between –1.5 ºC to +1.5 ºC. The starting temperature is 25 ºC and the stopping temperature is 22 ºC. The variation of the indoor temperature is actually associated with the outdoor temperature and the internal houses activities. The indoor temperature fluctuates during one hour between 25 ºC to 28 ºC and until the closing time. It starts to decrease to match the set point temperature. In addition, opening the main door of the house during the operation of the air conditioning can vary the indoor temperature greatly and it is reflected into the amount of the energy consumption over the day.

Power Consumption of VFD HVAC

Figure 6 shows the responses of power consumption at various variation of the compressor motor speed of VFD HVAC unit, for three hours of each day 11th, 12th and 13th of October,2016, respectively, staring at 12:00 p.m. to 15:00 p.m. On the first day experiment, the door is kept open for 15 minutes from 12:30 p.m. until 12:45 p.m. During the test of opening the main door the controller is maximized the error between the set point temperature and actual indoor air temperature by varying the speed of the compressor motor, due to the sudden change of indoor air temperature. It is noticeable from Figure 6 that the compressor varies its speed directly when the door opened, and it run with high speed to match the indoor temperature to the set point (23.5 ºC). The compressor motor speed drops abruptly after 3 minutes from the door closing time. The speed compressor motor is manipulating by the controller based on the return air temperature from the house until the indoor air temperature is at or close to its set point temperature. Table 4 gives the energy consumption by VFD HVAC unit for the first day when the door is kept open for 15 minutes. 5.9153 kWh is energy consumptions for three hours from 12:00 p.m. to 15:00 p.m. for the first day test. On second day, the power response of the VFD follows the pattern of the previous day as the starting time of main door opening is also the same. Furthermore, it continues with high speed until the main door is closed at 13:00 p.m. The compressor motor reduces its speed and it drops with some fluctuation in the speed attempt to adjust the indoor temperature with set point. Table 4 depicts that 6.7069 kWh is energy consumption of VFD HVAC unit during three hours. On the last day, as the door is kept open for long period (60 minutes) the compressor motor follows the same pattern of the previous two days as the starting time is the same, and during 60 minutes the speed of the compressor is varied with high speed. However, after the closing time, it drops quickly and the fluctuation is relatively quite small until it reaches the desired temperature, and the energy consumption is 8.8365 kWh per three hours.

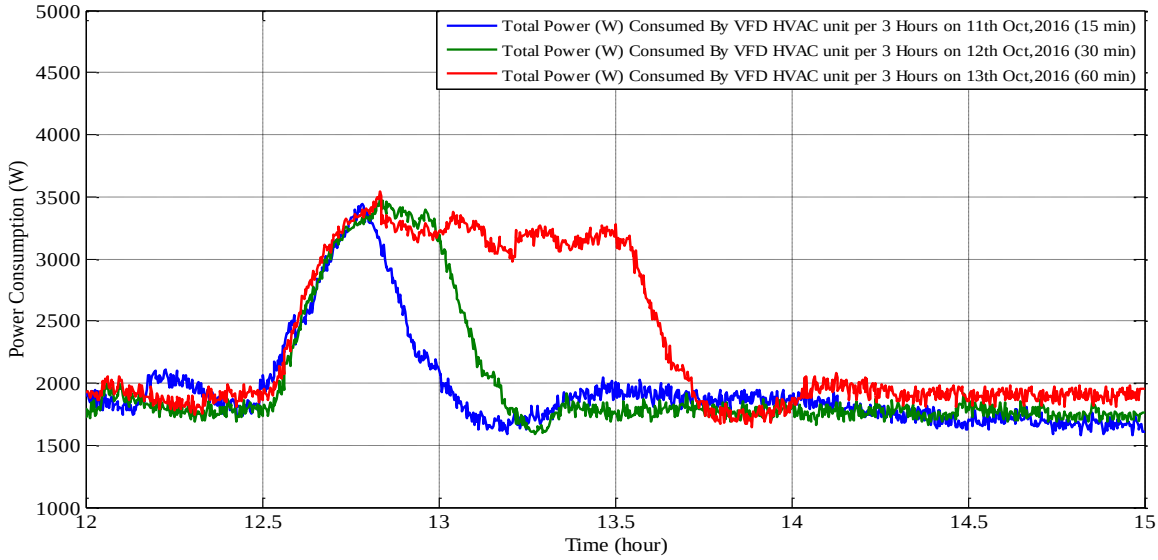

Figure 6. Power consumptions for 3 hours by VFD unit on 11th, 12th and 13th of Oct .2016

As can be concluded at the end of this section, the VFD HVAC responds faster once the door is opened. This leads to the level of user comfort can be matched shortly. In addition, as the door is kept open for three different periods of time. It can be noticed, that after the door closing time of each period the curves looks similar to each other and the power consumption has its steady state value around 1.65 kWh, beyond which, the power becomes nearly constant or just fluctuating in the narrow range.

Table 4: Energy consumption by VFD & ON/OFF unites on 11th, 12th and 13th of Oct. 2016

Date	Time of the Experiment (Door Opened)	Energy Consumption Time (Hours)	Time (3 hours)	VFD Unit Energy Consumption	ON/OFF Unit Energy Consumption	Difference in Energy Consumption VFD &ON/OFF
11/10/2016	15 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	5.9153 kWh	9.393 kWh	3.478 kWh
12/10/2016	30 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	6.7069 kWh	10.884 kWh	4.1772 kWh
13/10/2016	60 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	8.8365 kWh	12.923 kWh	4.0868 kWh

Power Consumption of On/Off HVAC

ON/OFF control is one of the oldest techniques that is practiced in buildings for the purpose of energy saving and occupant thermal comfort level. Figure 7 shows the power consumptions of ON/OFF HVAC system for three hours of each day 11th, 12th and 13th of October, 2016, respectively; staring at 12:00 p.m. to 15:00 p.m. On the first day, the main door is kept open for 15 minutes from 12:30 p.m. to 12:45 p.m. The compressor motor is OFF during the staring time of the main door opening test. The thermostat ON/OFF controller takes around 2 minutes to minimize the error between the set point temperature and the indoor air temperature by turning ON the compressor motor. It is clearly observed from Figure 7 that the controller turns OFF after 13 minutes from the door closing time. This action is taken to allow a faster heat loss recovery to the house until the indoor air temperature reaches the lower limit of the set point temperature. Under the ON/OFF condition, the compressor motor speed fluctuates from equivalent 635 Watt to full speed and stops several times as the blower motor is set on the fixed mode and it is working continuously during the whole day. From Table 4, 9.3933 kWh is the energy consumption of ON/OFF HVAC unit for three hours of the first test.

Based on the experiment on the second day, the main door of the house is kept open for 30 minutes from 12:30 p.m. to 13:00 p.m. Figure 8 shows the compressor motor is already ON during the main door opening operation. After 12:30 p.m. the compressor motor is running continuously and turns OFF after 12 minutes from the door closing moment. Moreover, the compressor motor resumes its ON/OFF cycling until the end of the day. Table 4 gives the energy consumption 10.8841 kWh during the three hours, and compares to the three hours of the first day the energy consumption is higher by 1.491 kWh. On the other hand, the main door of the house is kept open for 60 minutes in the third day of test, and Figure 8 shows that after 2 minutes from the main door opened the compressor motor turns ON. The compressor motor runs continuously and exceeds the door closing time by 18 minutes, before resuming its ON/OFF cycling. The reason that the compressor runs continuously for a longer period of time is that main door is kept open for one hour, much of the surrounding warm and moist air mixes with house cool indoor air temperature which increases the indoor air temperature above the desired temperature rapidly. According to Table 4, 12.9233 kWh is the energy consumption of the three hours when the door kept opened for 60 minutes.

Frequently opening the main door causes the increase of energy consumption. The performance of the ON/OFF system is running under one fixed compressor speed without any capacity control. In addition, the ON/OFF is using the full speed of the electric compressor that is equivalent to 6200 Watt. It can be claimed that energy consumption for the ON/OFF unit is higher than the VFD unit. The main reason for this is the difference between the

operation modes as the ON/OFF unit is running under constant speed, and the VFD unit has the ability to vary its speed.

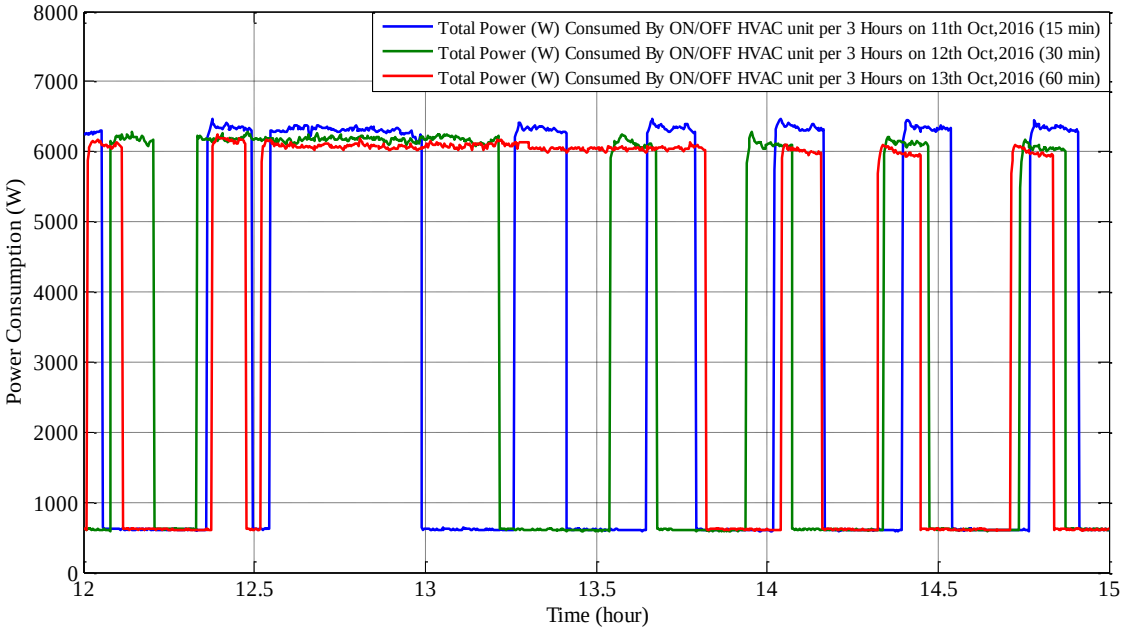

Figure 7. Power consumptions for 3 hours by ON/OFF unit on 11th, 12th and 13th of Oct. 2016

From the technical side of both HVAC units, the ON/OFF unit is controlling by the thermostat device and the VFD unit is controlling by using two types of Proportional, Integral and Derivative (PID) control integrated with variable frequency drive. However, one PID controller use to control on the startup of the unit and the second PID use to control during unit operation. The startup control must prevent an excess of requested power. Since at startup the status of the load is not known but only the temperature is, the power must be entered little by little, waiting for the reaction of the system. It can regulate on the value of the return temperature using a wide proportional band (2-3 times the nominal thermal gradient) and a large enough integral time that is greater than the system time constant. The control during operation must be quick in order to follow any load variations and maintain the supply temperature as close to the set point value as possible. In this case, the time constant is given by the reaction of the compressor - evaporator system and is in the order of a few tens of seconds (slower with shell and tube evaporators, faster with plate evaporators). The PID controllers integrate the "anti-windup" function that limits the integral action when the request has reached the maximum and minimum limits.

It can be concluded that VFD A/C unit has the ability to control the cooling load by varying its speed (compressor speed) according to the temperature of the air return from the house. The response of speed controlling of the compressor is fast which has an influence in the amount of the energy variation and energy consumption. The VFD A/C unit can achieve the desired temperature to the house without costing significant energy consumption. ON/OFF A/C unit is cycling based on the temperature obtained by the thermostat. The time response of ON/OFF unit to reach the desired temperature is very long comparing to the time response of VFD unit. The longer time taking for response and achieve the set point temperature is the huge energy consumption. In addition, the condenser motor of the VFD A/C unit is running on the same mode of the compressor motor (Auto Mode), and the condenser motor of the ON/OFF unit has different mode comparing to the compressor motor mode (Fixed Mode). The condenser motor is running continuously without any stop throughout day. The motors of ON/OFF unit are running under full power load about (6000 W) and the motors of VFD A/C unit are running under different power load based on the required air return.

Closing of House Main Door Equipped With VFD HVAC Unit

Figure 8 shows the indoor and outdoor temperatures for three days from 12:00 p.m. to 15:00 p.m. on 8th, 9th and 10th of October, 2016, while the main door of the house is kept closed. The outdoor temperatures vary between 37 ºC to 45 ºC, and the indoor air temperature is taken as an average of three thermocouple sensors located at three different places in the house #3307. It is clearly shown that the indoor air temperatures have similar patterns throughout the days, and it is almost similar to the set point temperature. A variable frequency compressor could distribute conditioned air at different temperature. Consequently, closing the door during the operation of air conditioning gives the occupants a very comfortable level of satisfaction, with minimum energy consumption.

The indoor and outdoor temperatures during the starting and ending of door closing tests are given in Table 5.

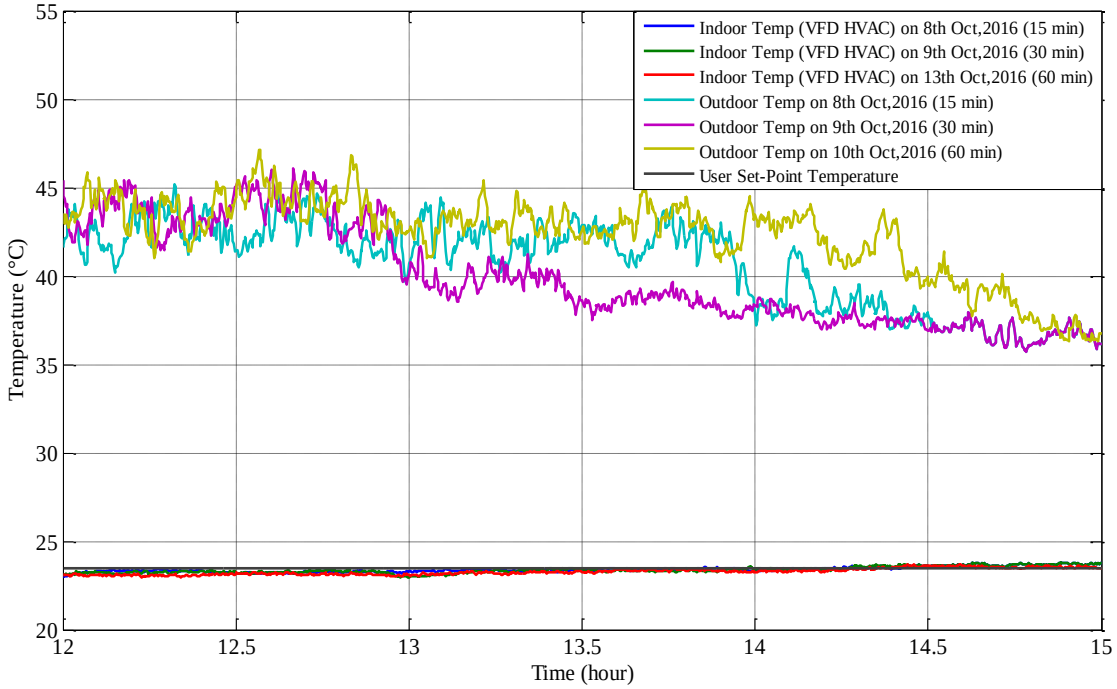

Figure 8. Indoor and Outdoor temperature for 3 hours for house #3307 on 11th, 12th and 13th of Oct. 2016

Table 5: Outdoor and indoor temperature for both unites on 11th, 12th and 13th of Oct. 2016

Date	Start of Closing (Main Door) ON/OFF &VFD	End of Closing (Main Door) ON/OFF &VFD	Outdoor Temp During the Start of Closing Time	Outdoor Temp During the End of Closing Time	Indoor Temp During the Start of Closing Time		Indoor Temp During the Closing Time	
					ON/OFF	VFD	ON/OFF	VFD
08/10/ 2016	12:30 p.m.	12:45 p.m.	41.36 ºC	43.11 ºC	24.46 ºC	22.80 ºC	24.87 ºC	21.85 ºC
09/10/ 2016	12:30 p.m.	13:00 p.m.	42.37 ºC	42.10 ºC	24.63 ºC	22.79 ºC	22.17 ºC	22.6 ºC
10/10/ 2016	12:30 p.m.	13:30 p.m.	41.85 ºC	41.12 ºC	23.98 ºC	22.9 ºC	23.65 ºC	22.87 ºC

Closing of House Main Door Equipped With On/Off HVAC Unit

Figure 9 shows indoor and outdoor temperatures for three days from 12:00 p.m. to 15:00 p.m. on 8th, 9th and 10th of October, 2016, as the door is closed of house #3305. It is clearly shown that the ON/OFF HVAC system turns on when indoor air temperature is greater than that of the set point temperature 23.5 ºC plus a band range +1.5 ºC, and then it turns off at the lower limit –1.5 ºC of set point temperature. It is noticeable that keeping the door closed maintains the air conditioning system cycling during the day and the indoor temperature fluctuates in the range of ±1.5 ºC without any extra variation.

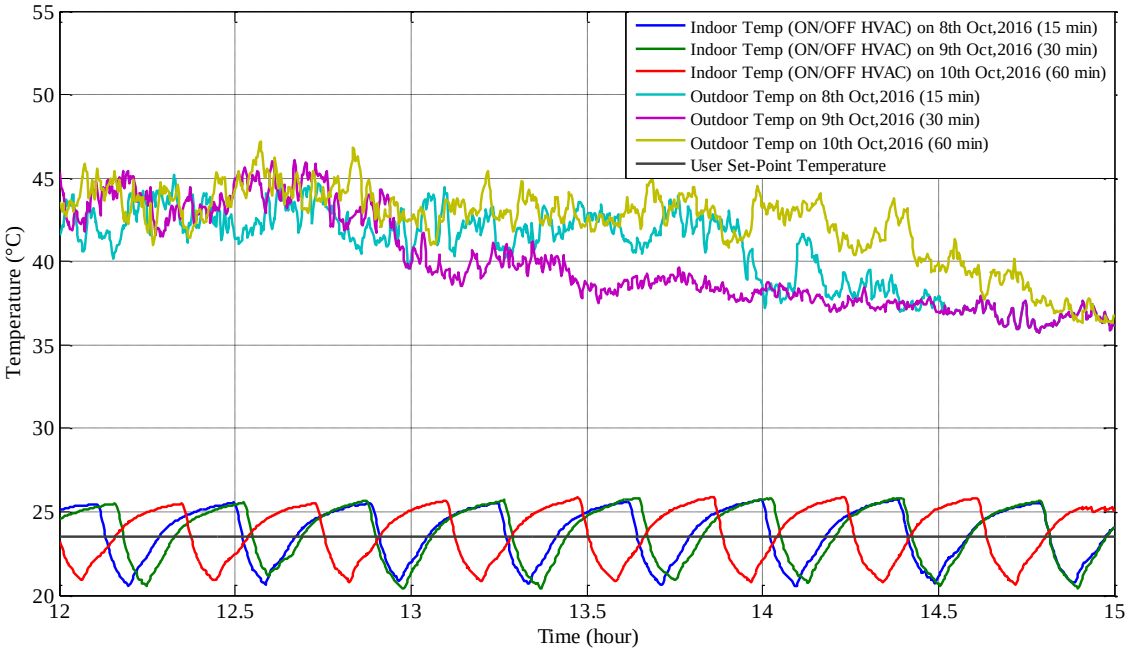

Figure 9. Indoor and outdoor temperatures for 3 hours for house #3305 on 8th, 9th and 10th of Oct .2016

Keeping the main door of the house closed during the operation of the air conditioning systems maintains the indoor air temperature on the range of the set point temperature, and provides the desired thermal comfort throughout the day with minimum energy consumption.

Power Consumption of VFD HVAC Unit

Figure 10 shows the power consumptions of VFD HAVC unit for three days without main door opening from 12:00 p.m. to 15:00 p.m. The compressor capacity of the air conditioning system is matched to the load by regulating the speed of the compressor motor, for example with low load, the compressor runs at low speed, and hence consumed less energy. It is shown in Figure 10 that a considerable amount of power consumptions vary between 1500 watts to 2000 watts. There is a small difference in the energy consumptions of VFD HVAC during the three days, and that is due to the changes in the house activities and the outdoor temperature. The difference is approximately 0.5 kWh. As the compressor motor is reduced, a significant reduction in power requirement is achieved. Consequently, power consumptions could be reduced by closing the main door of the house during the operation of the air conditioning system. Without a huge variation in the power consumptions, Table 6 gives the energy consumptions by the VFD HVAC unit within three hours on 8th, 9th and 10th of October, 2016.

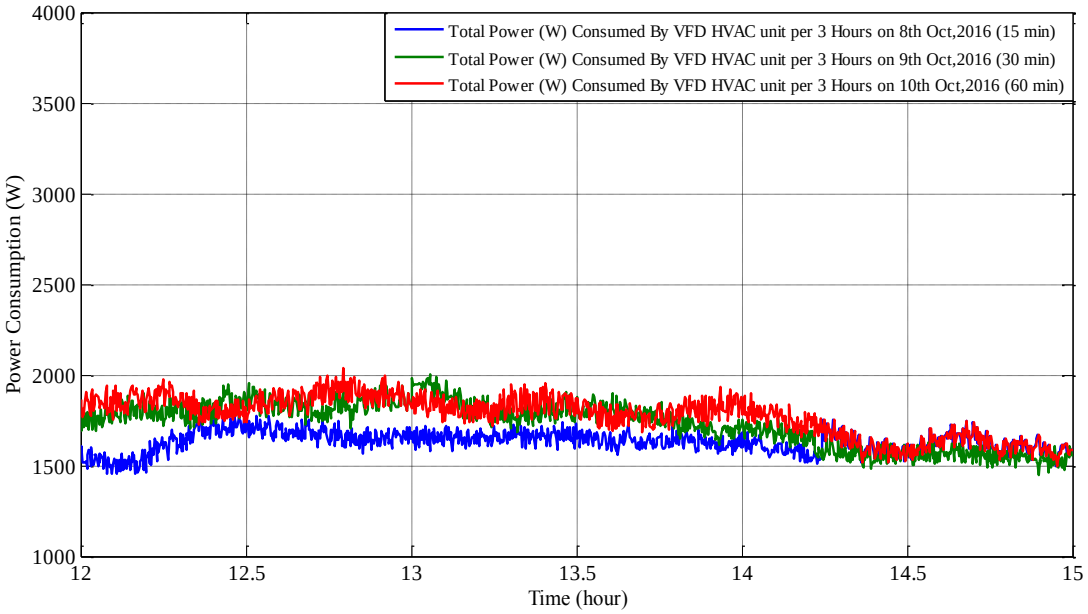

Figure 10. Power consumptions for 3 hours by VFD unit on 8th, 9th and 10th of Oct. 2016

Table 6. Energy consumed by ON/OFF & VFD unite on 8th, 9th and 10th of Oct.2016 (Door Closed)

Date	Time of the Experiment (Door Closing)	Energy Consumption Time (Hours)	Time (3 hours)	VFD Unit Energy Consumption	ON/OFF Unit Energy Consumption	Difference in Energy Consumption VFD&ON/OFF
08/10/2016	15 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	4.8976 kWh	5.8708 kWh	0.9732 kWh
09/10/2016	30 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	5.2179 kWh	6.1616 kWh	0.9437 kWh
10/10/2016	60 Min	3 hours	From 12:00 p.m. To 15:00 p.m.	5.3268 kWh	6.3131 kWh	0.9863 kWh

Power Consumption of On/Off HVAC Unit

Figure 11 shows the power consumptions for 3 hours from 12:00 p.m. to 15:00 p.m. by ON/OFF unit on 8th, 9th and 10th of October, 2016. In addition, Table 6 lists the energy consumption by the ON/OFF HVAC system when the main door is closed within three hours. Closing the main door of the house during the operation of A/C system has great effect on the power consumption. If the door is closed for a long period of time, energy consumption decreased obviously. The ON/OFF HVAC unit mode is triggered by the thermostat at a specific set point temperature. As a result the thermostat triggers the compressor in OFF mode quickly which ultimately increases the compressor ON/OFF cycling. The power consumption of the compressor motor varies between equivalent 640 Watt to the full speed of the compressor which to 6200 Watt and stops several times. In addition, the blower motor consumes 635 Watt and it sets on a fixed mode. Due to the main door closing condition, the indoor temperature drops below the set point, and the ON/OFF HVAC turns OFF and it repeatedly turns itself ON and OFF throughout the day.

On the other hand, it is well established from experimental study in [9], that the compressor ON/OFF cycle causes significant amount of efficiency and capacity loss. In addition, it is experimentally found that efficiency loss of the system is 9% and the capacity loss is 11% due to compressor motor ON/OFF cycling. The frequent sharp pulse for compressor always generates noisiness and affects the lifetime of the motor seriously. Based on the experiments,

it is found that keeping the main door closed during the operation of the A/C system helps to reduce the energy consumption either by using the VFD HVAC unit or ON/OFF HVAC unit.

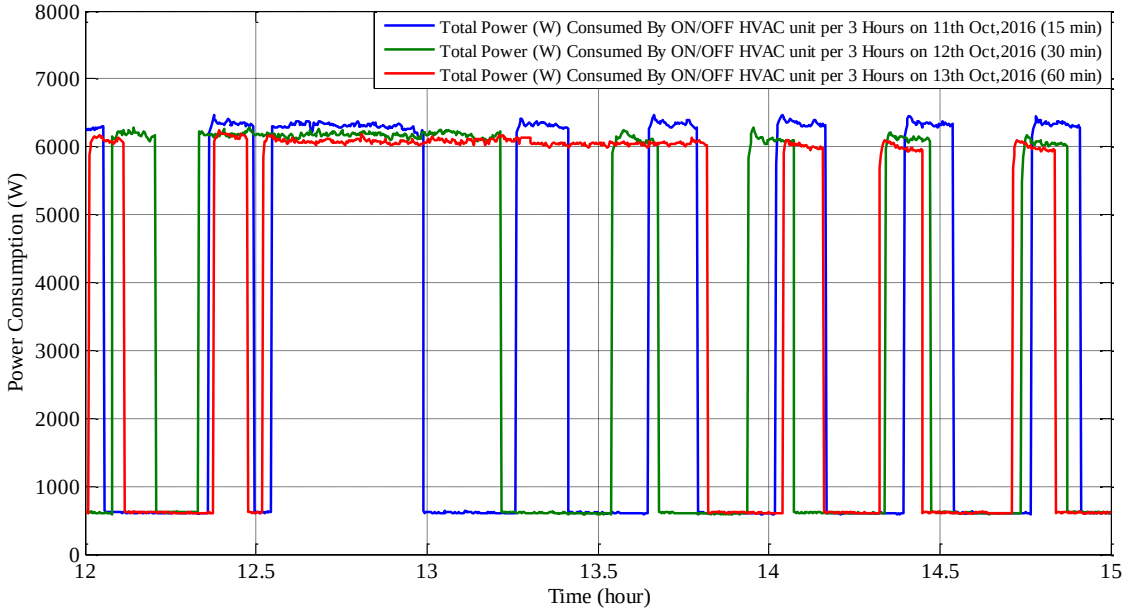

Figure 11. Power consumptions for 3 hours by ON/OFF unit on 8th, 9th and 10th of Oct. 2016

Difference of Door Opening/Closing Energy Consumptions

Table 7 gives the energy consumptions of the VFD HVAC unit during the main door opening /closing conditions. Form the experiment results, energy consumption of VFD HVAC unit when the main door kept open for 15 minutes increases by 1.0177 kWh compared to the same unit without door opening. The energy consumption when the main door kept open for 30 minutes is greater by 1.489 kWh compared to the energy consumption of the closing door test. In addition, when the main door opening for 60 minutes, the VFD HAVC unit consumes 3.5097 kWh compared to closing door condition for the same unit.

Table 7: Difference in energy consumption VFD door opened and VDF door closed

Date (Door Opened)	Date (Door Closed)	(Door Opening Time& Door Closing Time	Energy Consumption Time (3 hours)	VFD Unit Energy Consumption (Door Opened)	VFD Unit Energy Consumption (Door Closed)	Difference in Energy Consumption for VFD unit
08/10/2016	08/10/2016	15 Min	From 12:00 p.m. To 15:00 p.m.	5.9153 kWh	4.8976 kWh	1.0177 kWh
09/10/2016	09/10/2016	30 Min	From 12:00 p.m. To 15:00 p.m.	6.7069 kWh	5.2179 kWh	1.489 kWh
10/10/2016	10/10/2016	60 Min	From 12:00 p.m. To 15:00 p.m.	8.8365 kWh	5.3268 kWh	3.5097 kWh

Table 8 gives the energy consumptions of the ON/OFF HVAC unit during the main door opening/ closing tests. From the test result of door opening condition for 15 minutes, the energy consumptions increases by 3.5225 kWh compared to the closed door condition. When the duration of opening the main door increases to 30 minutes, the differences of energy consumption of opening and closing the main door increases to 4.7225 kWh. Furthermore, opening the main door for 60 minutes has a strong influence on the energy consumption for the ON/OFF HVAC unit. It increases by about 6.6102 kWh compared to the door closing condition. Consequently, it is noticeable from the experiment results that a significant amount of energy consumption increases with increasing of the duration of the

door opening test. Moreover, the energy consumption difference between the door opening/closing tests for the ON/OFF HVAC unit is greater than the difference of the energy consumption by the VFDHVAC unit. The reason behind that is the ON/OFF HVAC is cycling during the air conditioning operation which reflected to consume more energy.

Table 8: The energy consumptions of the ON/OFF HVAC unit during the door opening/closing conditions

Date (Door Opened)	Date (Door Closed)	(Door Opening Time& Door Closing Time)	Energy Consumption Time (3 hours)	ON/OFF Unit Energy Consumption (Door Opened)	ON/OFF Unit Energy Consumption (Door Closed)	Difference in Energy Consumption for ON/OFF unit
11.10.2016	08.10.2016	15 Min	From 12:00 p.m. To 15:00 p.m.	9.3933 kWh	5.8708 kWh	3.5225 kWh
12.10.2016	09.10.2016	30 Min	From 12:00 p.m. To 15:00 p.m.	10.8841 kWh	6.1616 kWh	4.7225 kWh
13.10.2016	10.10.2016	60 Min	From 12:00 p.m. To 15:00 p.m.	12.9233 kWh	6.3131 kWh	6.6102 kWh

Cost Analysis

Table 9 gives the cost analysis of electric energy consumption for both VFD & ON/OFF HVAC units. The energy consumption by ON/OFF HVAC is greater than the energy consumption by the VFD HVAC. Therefore, opening the house main door, which is equipped with a conventional ON/OFF unit, causes the additional cost to the occupants due to the increasing of the electricity bill. When comparing to VFD and ON/OFF HVAC units in terms of energy consumptions, there appears to be small difference in energy consumptions. In addition, if the occupants are conservative and aware of the result for opening/closing the main door during the operation of air conditioning units, a significant amount of energy could be saved. This can be observed in Table 9. The additional cost due to energy consumption is presented by US Dollars. It should be noted that the average cost of electric energy in the world is $ 0.11683 per kWh. [19].

The cost analysis is carried out for a several repeating days of main door opening conditions. 10, 30, and 60 days are selected in one year period to conduct the overall cost analysis and forecasting the cost of energy consumption due to the main door opening. The difference of the energy consumption of each time duration of door opening 15 min, 30 min, and 60 min is calculated with all durations of the selected days in a year. Table 9 illustrates the difference in energy consumption, energy increases per day, and additional cost in US Dollars.

Based on the calculation performed in Table 9, in the first case, when the main door is kept open for 15 minute within 10, 30 or 60 days, the additional cost difference between the ON/OFF and the VFD units in the period of these days are $ 2.8091, $ 8.4695, and $ 16.9606, respectively. It is observed that the conventional ON/OFF unit costs more than the VFD unit for the same conditions. On the other hand, the cost different due to frequent keeping the main door opened for 30 minutes of 10, 30, or 60 days, is having $ 3.7774, $ 11.3316, and $ 22.665 addition to the regular cost of electricity bill. In this case ON/OFF unit consumed more energy and cost the occupants some extra money than that of the VFD unit. In the third case, if the main door opened for one hour throughout 10, 30 or 60 days, ON/OFF unit charges about $ 3.6223, $ 10.867, and $ 21.736 more than VFD unit from the additional cost. Overall, it can be noticed that both unites are cost the occupants some extra money, when they open the main door for period of time during the operation of A/C systems. If the duration of door opening increases, the additional cost increases, however, the ON/OFF unit charges more money than the VFD unit.

Table 9: Cost analysis of energy consumptions during the door opening/closing conditions

Door Opening Time	Repeating of Door Opening/Day	Difference in Energy Consumption		Energy Increased Per Day		Additional Cost kWh = $ 0.11683 U.S. Dollar	
		VFD (kWh)	ON/OFF (kWh)	VFD (kWh)	ON/OFF (kWh)	VFD ($)	ON/OFF ($)
15 Minutes	10 days	1.017	3.422	10.177	34.225	1.1889	3.998
	30 days			30.177	102.67	3.5255	11.995
	60 days			60.177	205.35	7.0304	23.991
30 Minutes	10 days	1.489	4.722	14.892	47.225	1.7398	5.5172
	30 days			44.676	141.67	5.2194	16.551
	60 days			89.352	283.35	10.438	33.103
60 Minutes	10 days	3.509	6.610	35.097	66.102	4.1003	7.7226
	30 days			105.29	198.30	12.301	23.168
	60 days			210.58	396.61	24.60	46.336

CONCLUSIONS

The energy consumption and corresponding cost analysis of HVAC systems due to opening/closing of the main door of the house are investigated, for the first time, for the selective periods in hot season of Saudi Arabia. The tests are carried out in two identical houses during three warm days where the outdoor temperatures have similar patterns. However the main door is kept open for 15 min, 30 min and 60 min respectively for the tests and analysis in line with regular practices of hot house of local area in Saudi Arabia. The tests due to door closing are carried out on the other three days. In addition, experimental set up is developed incorporating the Lab-View based data acquisition monitoring and measurement system for each house. House #3305 is equipped with a conventional ON/OFF A/C controller while house #3307 is equipped with VFD A/C controller. The findings revealed that keeping the house main door opened for considerably prolonged time, electrical energy consumption increases significantly to maintain the thermal comfort level in the house in terms of the desired temperature.

The specific conclusions derived from the present work are as follows:

- In the case of VFD A/C controller, it is found that energy consumption increases by 1.10 kWh, 1.4 kWh and 3.5 kWh when the door is kept open for 15 minutes, 30 minutes, and 60 minutes, respectively. In the case of the conventional ON/OFF A/C controller, the energy consumption increases by 3.52 kWh, 4.72 kWh, and 6.61 kWh when the house door is kept opened for 15 minutes, 30 minutes, and 60 minutes, respectively. `
- Indoor temperature fluctuation increases with increasing door opening duration, which makes indoor air temperature level uncomfortable. The energy consumption increases for both HVAC controllers used because of the excessive operation of the A/C compressors to meet and recover the desired indoor temperature.
- The additional cost difference between the ON/OFF and the VFD controller unit is found to be about $9.41, when the main door is kept open for 15 minutes. On the other hand, when the main door is kept open for 30 minutes, this cost increases to approximately $12.6. The additional cost difference becomes about $12, when the main door is kept open for 60 minutes. Therefore, increasing the duration of the door opening results in is excessive additional to the cost to the electricity bill.

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