Investigation of Energy Saving in HVAC Systems: *Modeling, Simulation, and Measurement Using Fuzzy Logic Controller*

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***Abstract*—Achieving thermal comfort with minimum energy consumption is the main requirement in designing the air conditioning system. The aim of this work is to investigate energy saving in two different types of air conditioning systems installed in two identical houses located at a university campus in Dhahran, Saudi Arabia. The conventional A/C system is equipped with an ON/OFF cycle and new the technology A/C system is equipped with variable frequency drive (VFD) both of which have been modeled by two different control strategies. The controllers are Fuzzy Logic Controllers (FLC) and Proportional- Integral-Derivative (PID). The thermal model for both houses has been developed with two different types of air-conditioning systems. LabVIEW platform is utilized for measuring the environment parameters and power consumption. It is found that the thermal comfort level of the house along with significant energy saving can be obtained through a proper selection of controller parameters. This paper shows that through utilizing a variable speed compressor and selecting the suitable control technique, the indoor environment of the house is able to be controlled with a great amount of energy saving.**

Keywords—Air-Conditioning, Energy Consumption, Energy Savings, Variable Frequency Drives VFD, Fuzzy Logic Controller, PID Controller, ON/OFF Cycle

I. Introduction

Nowadays, the world demand for HVAC equipment is going up by 6.2% per year, reaching a total of $93.2 billion in 2014 [1]. Space-conditioning equipment will continue to overtake heating equipment globally with increasingly hot weather conditions. The increasing demand for cooling equipment is leading to the increased demand of energy consumption. Minimizing energy consumption has become one of the most important aspects in HVAC control system design due to the fact that 50% of the world energy is consumed by HVAC equipment in residential & commercial buildings [2-3]. Therefore, modeling of HVAC systems is gaining more interest for system performance assessment as well as energy saving. Controlling air conditioning can be achieved by utilizing a number of advanced control techniques such as Proportional–Integral–Derivative controller (PID controller) and Fuzzy Logic Controller (FL controller). Most of the control systems over the entire world are operated by utilizing a PID controller. PI control implementation for building air conditioning system has been proposed in [4]. They have used the PI controller to control the speed of the air conditioning compressor to match the cooling load inside the building as well as to have a higher energy efficiency to obtain the desired thermal comfort level. The experimental part has been conducted and found that the PI technique provides better temperature control with more energy efficiency compared to the conventional ON/OFF controller. A study of potential electricity savings by using "Variable Speed Compressor" (VSC) for HVAC system is presented in [5]. They used a PID controller for the air conditioning system. The simulation results show that using a PID controller with VSC gives the highest energy saving while having variable load condition, a PD controller offers the best option. On the other hand, fuzzy logic control application to buildings is effective and suitable for non-linear system control [6]. If the fuzzy rules are designed to be more robust, fuzzy controllers can enhance the disturbance response by reducing undershoot and overshoot present in the controlling variable. In addition, in [7] the researchers utilized this technique to control discontinuously occupied buildings. Many other researchers have been working on the application of only fuzzy logic to control the thermal comfort of buildings [8]. They presented fuzzy logic based energy saving technique for a central air conditioning system.

In [9] the fuzzy-logic-based current controller is proposed to minimize the dominant torque harmonics, and the results have been evaluated on a laboratory PMSM drive system under different load conditions and operation speeds. The PI and FLC controllers are used for the shunt series and they are designed in MATLAB/Simulink. The results show that unified power flow controllers prototype had successfully controlled the power flow dynamically in the transmission line with enhanced accuracy [10]. In [11], a PID fuzzy controller is developed for indoor temperature control consent to energy resources management in buildings. Moreover, the use of fuzzy PID, fuzzy PD and adaptive fuzzy PD for controlling thermal visual comfort and indoor air quality are presented in. One of their main objectives was to reduce the energy consumption. Furthermore, fuzzy logic control of air-conditioning systems in residential buildings or efficient energy operation and comfortable environment are investigated in [12]. The simulation has been done and fuzzy controller results are compared with the conventional PID controller. The results indicate that the proposed control strategy satisfies the load and at the same time achieves the comfort zone, as defined by the ASHRAE code. It has been demonstrated that fuzzy logic controller makes the HVAC system more efficient and consumes less energy than the HVAC controller by a PID controller.

Most of the achieved studies have been conducted without validation of their work. In this study the modeling, simulation and measurement work have been developed to investigate the performance of each HVAC unit and evaluate the energy consumption with energy saving for different control techniques (FLC, PID and ON/OFF) controllers.

II. Design Methodology and Simulation

A. House Thermal Model

The thermal model of both identical houses is built by applied Simscape Physical components in Simulink/Matlab. 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 and tested with two different units of an air conditioning system; the 1st house has been equipped with a VFD HVAC (FLC and PID controllers) unit and the second house has been equipped with an ON/OFF HVAC unit. The following equations (1), (2), (3) and (4) are expressed the model of the house.

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

$$\dot{T}_2(t) = \frac{1}{C_{Wall}}\left(U_{22}\left(T_{out}(t) - T_2(t)\right) - U_{11}\left(T_1(t) - T_H(t)\right)\right) \quad (2)$$

$$\dot{T}_3(t) = \frac{1}{C_{Window}}\left(U_{32}\left(T_{out}(t) - T_3(t)\right) - U_{31}\left(T_3(t) - T_H(t)\right)\right) \quad (3)$$

$$\dot{T}_H(t) = \frac{1}{C_{Air}}\left(\begin{matrix}(U_{11}\times T_1(t)) + (U_{21}\times T_2(t)) + (U_{31}\times T_3(t)) - T_H(t) \\ (U_{11}+U_{21}+U_{31}) + Q_{Heat}(t) - Q_{Cooler}\end{matrix}\right) \quad (4)$$

B. Model of HVAC VFD unit by FLC

Fuzzy logic control is the one of the most powerful controller which can control non-linear system because of its non-linearity characteristic behavior. Figure 1 presets the basic configuration of Fuzzy logic controller.

Matlab/Simulink Fuzzy Logic Toolbox is used to develop and design the fuzzy logic controller. Basically, the fuzzy logic controller is comprised of four basic components: fuzzification, a knowledge base, inference engine, and a defuzzification interface as shown in Figure 1, Each component affects the effectiveness of the fuzzy controller and the behavior of the controlled system. In the fuzzification interface, a measurement of inputs and a transformation, which converts input data into suitable linguistic variables, is performed which mimics human decision making. The results obtained by fuzzy logic depend on fuzzy inference rules and fuzzy implication operators. The knowledge base provides necessary information for linguistic control rules and the information for fuzzification and defuzzification. In the defuzzification interface, an actual control action is obtained from the results of fuzzy inference engine.

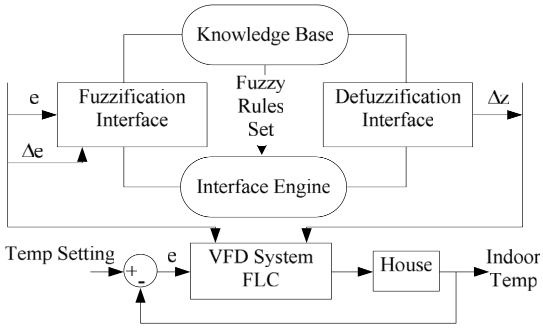

Fig.1. Proposed HVAC-VFD using FLC controller diagram.

The Mamdani techniques will be used in this system which consists of two control inputs and one control output as shown in Figure 2. The two inputs are the error (e) and the change rate of error (Δe). The output of the fuzzy control is variable speed compressor (Δz) and "centriod" de-fuzzification method has been chosen for controller design with the min and max inference method. The performance measurement is presented by the following equations.

$$e(t) = \text{Setpoint Temp}(t) - \text{Actual Indoor Temp}(t) \quad (5)$$

$$\Delta e(t) = e(t) - e(t-1) \quad (6)$$

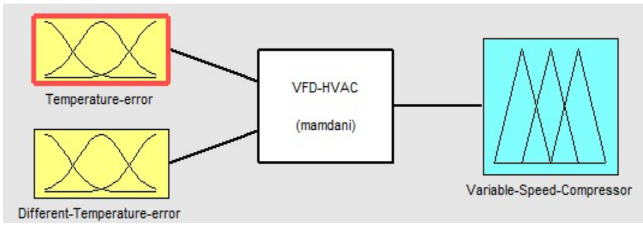

Fig. 2. VFD-HVAC controller for house thermal model.

1. First Input (Temperature Error)

Fuzzification of temperature error (e) which is the set of the user decides temperature, as the most fluctuation bound of the temperature in the residential area is approximately ±2ºC. In this system (-2ºC, +2ºC) is the range of the temperature error.

Table 1 gives the types of the membership function and their values.

TABLE 1. MEMBERSHIP FUNCTION FOR THE FIRST INPUT (TEMP ERROR)

No of MF	MF (e)	Type of MF
MF1	Very Hot (VH)	zmf
MF2	Hot (HT)	trimf
MF3	Less Hot (LH)	trimf
MF4	Normal (NR)	trimf
MF5	Cool (CL)	trimf
MF6	Cold (CD)	trimf
MF7	Very Cold (VC)	smf

2. Second Input (Difference of the Temperature Error)

Fuzzification of the change rate of the temperature error (Δe) is the different sampling period. Temperature difference gives information on the difference among actual indoor air temperature of the house and the set-point (24^{o}C). The change rate of the temperature is range ±2^{o}C. Table 2 gives the information of membership function of the second input.

TABLE 2. MEMBERSHIP FUNCTION FOR THE SECOND INPUT

No of MF	MF (Δe)	Type of MF
MF1	Negative (NL)	zmf
MF2	Negative Medium (NM)	trimf
MF3	Negative Small (NS)	trimf
MF4	Neutral (NU)	trimf
MF5	Positive Small (PS)	trimf
MF6	Positive Medium (PM)	trimf
MF7	Positive Large (PL)	smf

3. Output (Variable Speed Compressor)

Fuzzification of the output is the variable speed compressor which is divided into seven membership functions and gives the required speed level of the variable speed compressor. In general, if the indoor temperature of the house is above the set-point then the compressor automatically changes the speed according to the temperature difference. Tables 3 gives the details of membership function of output. The Δz is the output variable which is in this case is considered as voltage signal to the compressor.

TABLE 3. MEMBERSHIP FUNCTION FOR THE OUTPUT (VSC)

No of MF	MF(Δz)	Type of MF
MF1	Very Slow (VS)	zmf
MF2	Slow (SL)	trimf
MF3	Less Speed (LS)	trimf
MF4	Normal Speed (NO)	trimf
MF5	Less Fast (LF)	trimf
MF6	Fast (FT)	trimf
MF7	Very Fast (VF)	smf

Table 4 shows 49 rules that cover the two inputs and one output membership functions.

TABLE 4.RULES OF FUZZY CONTROL OF VFD-HVAC

(Δz)		(e)						
		VC	CD	CL	NR	LH	HT	VH
(Δe)	NL	VS	VS	SL	LS	LS	NO	LF
	NM	SL	SL	LS	LS	NO	LF	LF
	NS	SL	LS	LS	NO	NO	LF	LF
	NU	LS	LS	NO	NO	LF	LF	FT
	PS	LS	NO	LF	LF	LF	FT	FT
	PM	NO	LF	LF	LF	LF	FT	VF
	PL	LF	LF	LF	LF	FT	VF	VF

C. Model of HVAC VFD System by PID

One of the methods that is suggested and investigated to minimize the energy consumption from the HVAC unit is through the utilizing of the proportional-integral-derivative (PID) controller. In this study, the cooler subsystem has been molded based on equation (7) and it is integrated with a PID controller using Matlab/Simulink. In addition, the PID controller has a feedback control mechanism the error. It determines the control signal according to the error value which makes it function as a variable speed compressor that can vary the speed of the air flow.

$$\frac{dQ_{Cooler}}{dt} = \left((T_{HVAC} - T_{House}) \times \dot{M}_{HVAC} \times C_P \right) \qquad (7)$$

For the PID controller three variables had to be selected which are K_p, K_i, and K_d. The value of each gain has been obtained by using trial and error method.

III. Experimental Procedure

The experiments were conducted in the Guest Houses at the KFUPM campus, Dhahran, Saudi Arabia. 3D Floor Plan and Ducts plan are shown in Figure 3. Each house has a living room, one bedroom, a kitchen and a bathroom. The major role of the experimental work in this study is to measure and monitor the performance of the energy consumption of two A/C systems along with environmental parameters inside and outside the houses. The system hardware's are comprised 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 voltages, currents, pressures, airflows, irradiation, humidity, and thermocouples. There are four thermocouple sensors (three sensors for indoor and one for outdoor temperatures), 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 [13].

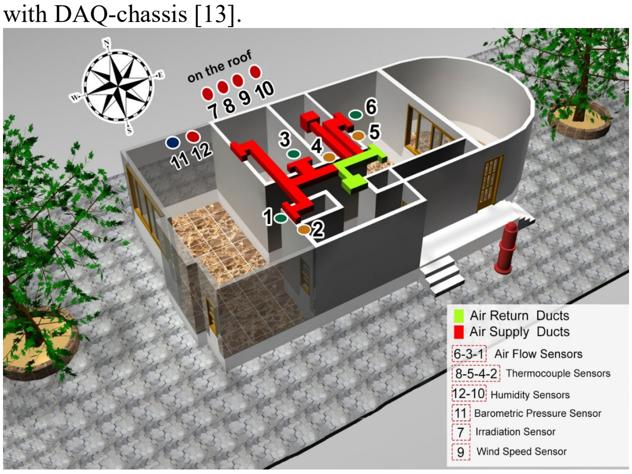

Fig.3. 3D ducts plan and sensor's location in the houses.

IV. Results and Discussion

The experiment and the simulation have been conducted to investigate the performance of the HVAC systems and their energy consumptions by using several kinds of intelligent and conventional controllers. However, the validation of the simulation work with the experimental study is provided in this section. Moreover, the experiment investigation is performed during one hot day (5th of September, 2016).

Figure 4 shows the validation of the house indoor air temperature on the 5th of September, 2016. It is clearly shown that the simulated indoor air temperature follows the pattern of the actual measured indoor air temperature throughout the day.

A. Conventional ON/OFF HVAC System: Temperature Distribution and Power Consumption Validation

The ON/OFF HVAC system turns on when the thermostat indicates that the indoor air temperature is greater than the set point temperature 24^{o}C, and then it turns off when the indoor air temperature is lower than the set point temperature. It is noticeable that the air conditioning systems cycling during the day and both temperatures have an identical cycle period without any extra variation. Consequently, the simulation approach of ON/OFF HVAC study is achieved with a typical result compared to the actual measured data.

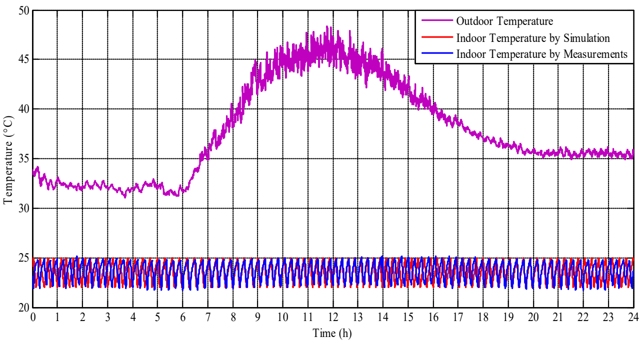

Fig. 4. Validation of simulated and actual indoor temperature of ON/OFF HVAC system on 5th of Sept, 2016.

The simulation and the measurement results of the power consumption for the ON/OFF HVAC unit are presented in Figure 5. There are three motors connected to the system: motor compressor, motor condenser, and motor blower. The motor compressor and motor condenser turn on and off together during the operation of HVAC system. The blower motor fan works continuously. The ON/OFF is using the full speed of the electric compressor that is equivalent to 5600 W.
It is clearly observed from Figure 5, under the ON/OFF HVAC system the compressor motor speed fluctuates from equivalent 635W to full speed and it cycles for several times as the blower motor is set on the fixed mode and it is working continuously during the whole day. The simulated power consumption is similar to the measurement result (5.6 kW rated value), where the number of the ON/OFF HVAC system pulses are also equal 91 pulses. However, the operation time for simulation is (708 min = 11.8 hours and for measurement is (710 min = 11.833 h). The experimental data show that the compressor and condenser consumed 39.6583kWh/day and the blower fan consumed 19.9416kWh/day. The total energy consumption by the simulation and measurement are 59.608kWh/day and 58.4kWh/day, respectively.

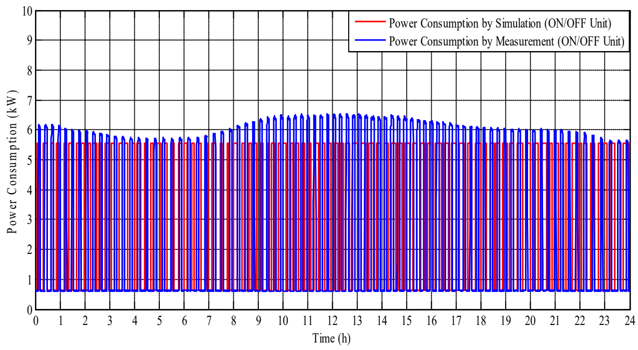

Fig. 5. Validation of simulated and measured power consumption of ON/OFF HVAC system on 5th of Sept, 2016.

B. VFD -HVAC with PID Performance: Indoor Temperature Distribution and Power Consuption

Figure 6 shows the validation of simulated and actual indoor air temperature of VFD-PID HVAC system on the 5th of Sept, 2016. The results indicate that the simulated indoor temperature has a similar pattern of the actual indoor air temperature throughout the day. However, in the early morning until 5:00 AM a slight variation happens on the actual indoor temperature above the simulated indoor air temperature. This is actually the impact of the outdoor air temperature as it fluctuates between 32^{o}C and 34^{o}C, and then it increases when the sun rises at 6:00AM. It rises continuously until it reaches 48^{o}C in midday. This action is having a great influence in the actual air indoor temperature which goes below the simulated temperature and reaches 23^{o}C.

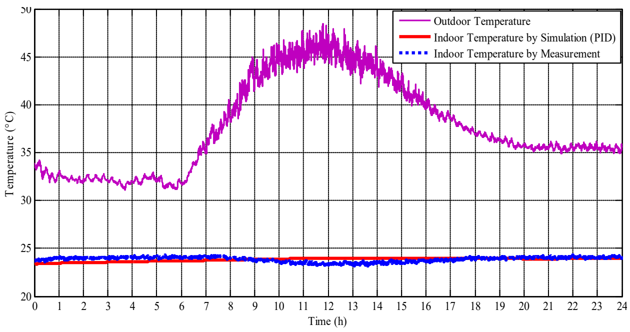

Fig. 6. Validation of simulated and actual indoor temperature of VFD-PID HVAC system on 5th of Sept, 2016.

Figure 7 shows the validation of simulated and measured power consumption of a VFD-PID HVAC system on the 5th of September, 2016. The simulated power consumption appears similar to the measured power consumption. It is clearly shown from Figure 7 that a considerable amount of power consumption varies between 1500W to 3000W. However, the amount of power consumption increases and decreases smoothly depending on the internal house activities and the outdoor temperature.

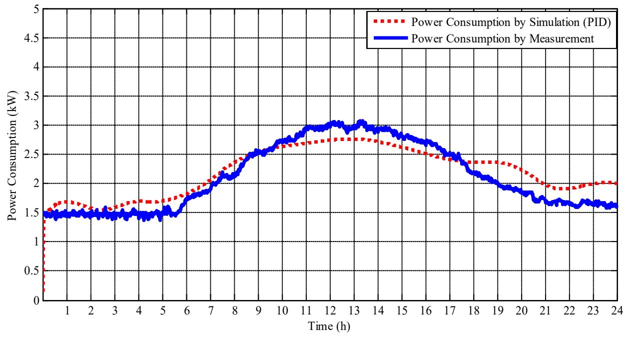

Fig.7. Validation of simulated and measured power consumption of VFD-PID HVAC system on 5th of Sept, 2016.

It can be noticed that the power consumption flow starts to rise at 05:30 AM as the starting of the sunrise and the power consumption reaches maximum simulated power around 3 kW and 2.5 kW, from 11:00 to AM 14:00 PM due to the house use of activities, such as cooking breakfast/lunch, washing machine, opening/closing windows and door, ..etc.), and effect of outdoor air temperature. The power consumption decreases slowly till reaching 2.5 kW at 17:00 and then it is dramatically deceases, due to drop in outdoor air temperature with the sunset and it continues to reach 1.6 kW throughout the remaining time of the day. The energy consumption using VFD-PID HVAC approach is 46.67 kWh/day and the actual energy consumption is 45.8418 kWh/day.

C. VFD -HVAC with FLC Performance: Indoor Temperature Distribution and Power Consuption

The simulation is conducted under the same conditions (outdoor air temperature & house activities) as that used for the VDF-PID. The simulated indoor temperature using VFD-FLC is compared with the measured data. Figure 8 shows the comparison of the simulated indoor air temperature with actual indoor air temperature of VFD-FLC HVAC system on the 5th of Sept, 2016. FLC provides the thermal comfort linguistically and, therefore, can describe the thermal comfort levels rather than temperature or humidity levels which results in improving thermal comfort.

Figure 9 shows the validation of simulated power consumption of the VFD-FLC system on the 5th of Sept, 2016 compared to VFD-PID system measurement. The simulated power consumption is using the VFD-FLC giving a better result compared to the VFD-PID measured power consumption. It is clearly presented in Figure 9, which the amount of the power consumption varies between 1500 watts to 3000 watts through the day for the compressor motor.
The data could be observed by three distinct periods: 1:00 AM to 6:00 AM, 6:00 AM to 19:00 PM and 19:00PM to 12:00 PM for this particular day as shown in Figure 9. During the first time period both power consumptions simulated and measured are varying in the level of the 1.5 kW and the trend lines fit to each other until matching the second period of time, when outdoor temperature air temperature begins to increase as the sun goes up and the occupants start their activities in the house.

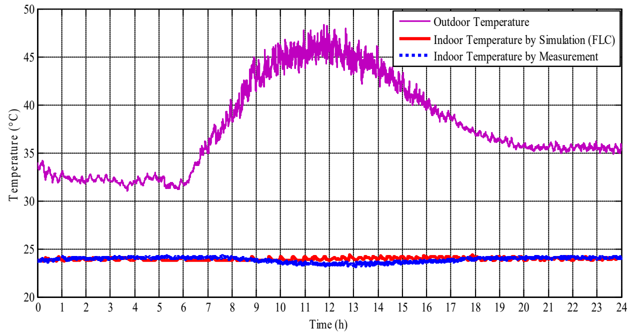

Fig. 8. Validation of simulated and actual indoor temperature of VFD-FLC HVAC system on 5th of Sept, 2016.

This affects the performance of the HVAC system and the power consumptions dramatically increase until reach 3 kW in the midday.

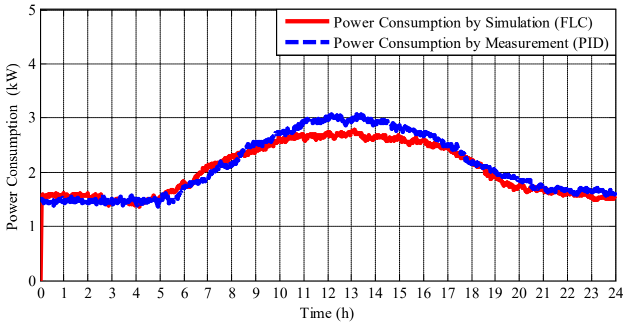

Fig.9. Validation of simulated and measured power consumption of VFD-FLC HVAC system on 5th of Sept, 2016.

Furthermore, the simulated trend line is slightly below the measured power consumption pattern. This is due to the accurate performance of the FLC controller, which can achieve the desired temperature setpoint with minimum power consumption. Regardless of slight variations, however, the power of the VFD-FLC HVAC system shows a strong relationship to outdoor air temperature. Moreover, Figure 10 reveals that the indoor air temperature dropped as the compressor ran at higher speed. Consequently, increasing the internal heat load (house activities) will cause the response of using the FLC controller to be much faster than that controlled by PID controller. The VFD-FLC HVAC system gives the highest saving in comparison with other approaches studied. The energy consumption using VFD-FLC HVAC technique is 43.23 kWh/day and the actual energy consumptions is 45.84 kWh/day.

IV. ENERGY ANALYSIS

The energy consumption is investigated experimentally and numerically. The total energy consumptions for both HVAC units are obtained for evaluation and analysis. Table 5 gives the total energy consumptions for both measurement and simulation results. Also, it provides a clear comparison for one particular day measurement. The table shows that the VFD-FLC HVAC unit consumed less energy compared to other VFD HVAC approaches and ON/OFF HVAC units.

Based on the power consumptions data measurements for both units, it is possible to calculate and evaluate the energy consumption for compressor with condenser motor and the blower fan motor for selected day. Table 5, presents clearly the compressor energy consumption compressor and blower fan for both units.

TABLE 5. ENERGY CONSUMPTION OF ONE DAY (5th of Sept. 2016)

Energy consumption for HVAC VFD (kWh)			
Simulation		Measurement	
PID-Controller	FLC-Controller	PID-Controller	
46.67	43.23	45.824	
		Comp. + Con	Blower
		24.124	21.7
Energy consumption for HVAC ON/OFF (kWh)			
Simulation		Measurement	
58.40		59.6	
		Comp. + Con	Blower
		39.66	19.94

V. ENERGY SAVING

The energy saving is calculated and presented in terms of percentage based on the difference between energy consumed by the ON/OFF control and energy consumed by the VFD control. Table 6 provides the results of energy savings for the simulated VFD HVAC approaches with the simulated ON/OFF unit as well as for the measurements. The energy saving for the measurement test is also given in Table 6. It is observed that the energy saving by the VFD-PID HVAC is lower than the energy saving by the VFD- FLC HVAC. Moreover, the implemented simulation of the VFD-FLC HVAC approach proved efficient in terms of model development energy consumption and most energy saving.

TABLE 6.ENERGY SAVING ON (5th of Sept. 2016)

Simulation	Simulation	Measurement
ON/OFF vs. VFD-PID controller	ON/OFF vs. VFD-FLC controller	ON/OFF vs. VFD-PID controller
20.08%	25.97%	23.09%

It can be concluded that the use of a VFD to save energy in an air conditioning system is justified. Although different simulation approaches have been studied, and they had produced significant energy saving. However, VFD-FLC HVAC gives the most energy savings and performs better than the other control systems investigated.

VI. CONCLUSION

The ON/OFF controller and the two control strategies of the VFD were integrated with the thermal model for determining the compressor energy consumption. The experiment was developed using LabView based data acquisition for monitoring and data measurement. The developed thermal models were simulated by using Simscape physical components in a Matlab/Simulink environment. The prediction of the energy consumptions of the HVAC system have been compared with those of the measured data. In general, the variable frequency drive controllers provide higher efficiency and lower operation cost of the HVAC system. The energy consumptions by using different controllers' results of the energy savings were investigated for one day (5th of September, 2016). The performance of the ON/OFF HVAC unit and the VFD HVAC has been compared with simulation against measurements. It was found that all the VFD control strategies HVAC units consumed less energy than the ON/OFF HVAC unit. It was found that the VFD-FLC is the more superior controller which consumed less energy than the VFD-PID.

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