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Enhancing Cost-efficiency Trade-off for Thermoelectric Air Conditioning System in Oyo State, Nigeria

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Abstract: A variable speed thermoelectric (TE) air conditioner system is developed for efficient power management using intelligent control system. The investigation adopted Variable Voltage Variable Frequency (VVVF) regulator mode of a solid state electronic conversion system with integration of AC–DC and DC–AC Converter method. The system received power from the main 230VAC source and a step-down transformer converted it to 150VAC. The bridge rectifier converted the output voltage varying DCV by regulating the frequency. The DC voltage is transformed back into AC through Pulse Width Modulation (PWM) technique. The sinusoidal waveform is formed automatically by programmed microcontroller (PIC18F4431) Insulated Gate Bipolar Transistor (IGBT) inverter that fed the air conditional compressor motor. The investigational results revealed that as the frequency declines, speed and torque drop which resulted to substantial reduction of power intake. The study reveals that 80,280kWh of energy is expended by a conventional air conditioner (CAC) in a month under steady operation while 15,624kWh is consumed by a thermoelectric air conditioner (TEAC) at the same period. This translates to energy cost of ₦602,100 ($387.51) and ₦18,063,000 ($11625.27) by conventional air conditioner (CAC) daily and monthly respectively while TEAC accounts for ₦117,180 ($75.42) and ₦3,515,400 ($2262.50) at the same period correspondingly. The energy savings cost with the developed TE drive are ₦484,920 ($312.09), ₦14,547,600 ($9362.78) and ₦174,571,200 ($112353.31) averagely on daily, monthly and yearly respectively. The estimated electricity in the study shows that 67% of the energy and cost bill is saved periodically using the developed TE drive likened to traditional climate control system.

Key words: Thermoelectric, variable frequency, inverter, air conditioner, Pulse Width Modulation (PWM), microcontroler.

Oyo Eyaleti, Nijerya'da Termoelektrik Klima Sistemi için Maliyet-Verimlilik Takasının Geliştirilmesi

Öz: Değişken hızlı termoelektrik (TE) klima sistemi, akıllı kontrol sistemi kullanılarak verimli güç yönetimi için geliştirilmiştir. Araştırmada, Değişken Gerilim Değişken Frekans (VVVF) düzenleyici modunu içeren, AC–DC ve DC–AC dönüştürücü yöntemlerinin entegre edildiği katı hal elektronik dönüşüm sistemi kullanılmıştır. Sistem, 230V AC ana güç kaynağından beslenmiş ve bir indirgeme transformatörü yardımıyla 150V AC'ye dönüştürülmüştür. Köprü doğrultucu, çıkış gerilimini frekansı düzenleyerek değişken DC gerilime dönüştürmüştür. DC gerilim, Darbe Genişlik Modülasyonu (PWM) tekniğiyle tekrar AC'ye dönüştürülerek izole kapılı bipolar transistörlü (IGBT) inverter tarafından programlanmış bir mikrodenetleyici (PIC18F4431) aracılığıyla sinüzoidal dalga formu oluşturulmuş ve klima kompresör motoruna iletilmiştir. Deneysel sonuçlar, frekans azaldıkça hız ve torkun düştüğünü ve bunun da önemli ölçüde güç tüketimini azalttığını ortaya koymuştur. Çalışma, geleneksel bir klima sisteminin (CAC) sabit çalışmada aylık 80.280 kWh enerji tükettiğini, buna karşılık termoelektrik klima sisteminin (TEAC) aynı sürede 15.624 kWh enerji tükettiğini göstermiştir. Bu, enerji maliyetlerinin geleneksel klima (CAC) için günlük ₦602.100 ($387.51) ve aylık ₦18.063.000 ($11,625.27) olarak hesaplanmasına karşılık, TEAC sistemi için günlük ₦117.180 ($75.42) ve aylık ₦3.515.400 ($2,262.50) olarak gerçekleştiğini göstermektedir. Geliştirilen TE sürücü sistemi ile günlük ₦484.920 ($312.09), aylık ₦14.547.600 ($9,362.78) ve yıllık ₦174.571.200 ($112,353.31) tasarruf sağlanmıştır. Çalışmada tahmin edilen elektrik tüketimi, geleneksel iklimlendirme sistemine kıyasla enerji ve maliyet faturalarında %67'lik tasarruf sağlandığını göstermektedir.

Anahtar Kelimeler: Termoelektrik, değişken frekans, invertör, klima, Darbe Genişlik Modülasyonu (PWM),mikrodenetleyici.

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1. Introduction

Thermoelectric (TE) climate control is a promising solid-state tool that has the probable to substitute conventional gas compression-based central air conditioning system. It can drive heat from one side of a device to the other by electric current [1]. It possesses many benefits such as no moving parts, noiseless operation, and flexible performance with regulation of current input. Thermoelectric sub-cooling system applies Variable Frequency Drives (VFD) technique to altering the motor speed by varying voltage and frequency of the power supplied to the motor [2,3]. The volts/hertz ratio prototype is conserved to lessen undue heating and sustain appropriate power factor of the motor. VFD control speed of motor by varying output voltage and frequency through sophisticated microprocessor controlled electronics device. The modus operandi of the system consists of rectifier and inverter units. Rectifier transforms Alternating Current (AC) in Direct Current (DC) voltage and inverter changes DC voltage back in AC voltage [4,5]. The temperature rise results in increased energy and saving costs for conventional air-conditioning systems [6].

Thermoelectric cooling air con is a device using power electronics for frequency variations of power to the induction motor, thereby controlling motor speed. It varies the speed of a rotating load, including those that vary the speed of motor and linkage devices that allow constant motor speed while varying the load speed [7-9]. The system is applied to match the speed and torque of a drive to the process requirements and also for energy saving in addition to efficiency improvements. These savings are predominantly perceived with centrifugal pumps and fans, where load force upsurges as the square of the speed and power intake as the cube of the speed (the affinity laws). Substantial cost savings is realizable through this application [10-13].

Air conditioners consume a lot of electricity because the mode of operation involves recurring cycles of compressing a gas to a liquid, which consumes much power. Mechanical control rudiments such as damper and valves used to standardize flow and pressure result in inefficient of operation, great deal of energy loss because of their toggling action. Other challenges include poor efficiency of the machine, high electricity bill costs, occupants discomfort through noise output from fan and compressor, superfluous creation of wear and tear on motors and related components, reduction in equipment life span and high operating costs.

However, universal economic growth as well as imminent hot climates, over the next decades especially in tropical areas will further boost demands for air conditioning system. There is a demand for much more energy efficient way to accomplish space cooling and this is the main goal of this research. This study showcases results of the investigational positioning which proves the conservation of energy in Air Compressors cautiously by adopting TE air cooling system. As a matter of fact, it is imperative for researchers to develop energy efficient air conditioning systems which will significantly reduce the energy and saving costs.

2. Related Works

There are various scholarships thatresearched on the optimizing cost-efficiencytrade-off for thermoelectric sub-cooling climate control system. Most investigators like Kim et al. [14], Saini et al. [15], Tai-feng et al. [16] among others embraced Thermoelectric air conditioning modeling, Thermoelectric Module with Radiative and Convective Processes (TEM-RCP) by mock-up model with an all-out cooling capability, cooling load calculations, capacity estimation, and control for the heavyweight radiant systems related design and control. Some of these researchers observe the effects of convection heat transfer coefficients, air flow rates, and thermoelectric material properties on system performance. The studies relate constant and graded material properties, evaluating their effect on cooling capacity, Coefficient of Performance (COP), and power intake. The discoveries advocate that while graded materials can augment cooling, they may lessen COP equated to constant property materials. The researchers conclude that with appropriate material properties and operating conditions, thermoelectric cooling can be a competitive technology for future air conditioning applications.

The present research is compared with other previous experimental studies. The analysis and comparison are of qualitative observations and devoid of quantitative comparison. By implication, some agreements were attained in the behaviors of the characteristics and the tendency of the curves of the previous researchers. On the other hand there is no concise agreement in the present values with respect to the previous studies. It is observed that the power consumption of developed drive air conditioner is significantly less than the power usage of traditional system. This behavior of average energy consumption, energy efficiency, cooling comfort and motor behavioral characteristics were also mentioned and discussed by previous researchers. The emphasis on the compressor motor beside the blower or the fan by the previous investigators was centered on its ability to control more than 90% of cooling and energy capacity of air conditioner. The adoption of solar system to power the air conditioners by the previous researchers generated many lapses during the operation of the system. This research consolidates on necessary improvement saving technique required for the available power in the country. The AC motor embraced in the new study enhanced versatile operation of compressor compared to DC motor applied by other researchers.

Again, this study developed an energy efficient air conditioner drive using intelligent control system for effective power and energy cost management. The constant material properties and VFD technique properties are considered for the TE materials, and they are compared in terms of the degree of cooling, COP and power consumption. The available data in Nigeria proved non availability of this kind of research. The study appraising thermoelectric sub-cooling system retrofits opportunities for energy and cost savings of air conditioner by enhancing the motors proficiency.

3. Research Method

3.1. Measuring Materials

The quantifying toolsfor the research are digital multi-meter (DMM), energy meter, mercury-in-glass thermometer and air flow meter. The energy meter processes the consumed power while the air flow meter records the extent of air flows through a tube of both conventional and thermoelectric drive air conditioner. The resistance values, voltages and currents are respectively measured with digital multi-meter.

In this study, an energy meter is applied for monitoring power consumption and overall energy efficiency of the system. Power resolution of 1W and energy resolution of 0.01kWh are adopted for this design for accurate long-term monitoring, detecting minute changes in power consumption and precise energy tracking. Current and voltage resolution of 1mA and 1mV are implemented for better power systems and accurate power calculations respectively. The energy meter also has the capacity of 10ms or <1 second response time for real-time tracking of rapid variations and dynamic changes without significant delays. With these functioning requirements, the energy meter ensures efficient energy management and real-time optimization of the thermoelectric air conditioning system.

Thermometer (temperature sensor) of higher resolution 0.1°C is embraced in this design for more accurate feedback in the control loop, for monitoring and controlling the system's efficiency and reducing energy consumption by preventing overcooling or overheating. Response times of 1-5 seconds are adopted in the research to detect and report a temperature change quickly due to the solid-state nature of thermoelectric modules. A slow thermometer could delay feedback, leading to inefficiencies or instability in the system.

The airflow meter embraced in this design plays a crucial role in ensuring optimal thermal performance. Monitoring and controlling airflow is essential for maintaining system efficiency, managing heat transfer, and achieving desired cooling or heating effects. A resolution of 0.1– 0.5m³/s is implemented in this study for thermal efficiency**,** system steadiness and energy optimization to improve energy efficiency and system longevity. A response time of 1–2 seconds is required in the research for the airflow meter to register and report a change in airflow. This will enhance rapidly varying cooling loads and ensures real-time feedback for efficient system control (Dynamic Control**).** It also allows fast response to stabilize the system quickly during startup, shutdown, or sudden changes in cooling demand (Transient Conditions**).** Lastly, it enhances filtering or signal processing to lessen more noise in the measurement (Trade-offs).

In this study, a 4½-digit DMM high resolution is applied for measuring critical electrical parameters such as voltage, current, and resistance. These measurements are essential for monitoring the performance of the thermoelectric modules, ensuring proper operation, and diagnosing faults. For Voltage Monitoring, a resolution of 1mV is adopted for precise voltage control to operate efficiently and to ensure accurate monitoring of input voltage. For current measurement, a resolution of 1mA is implemented for precise current measurement and in determining the power consumption and optimizing the system's energy efficiency. For resistance measurement, a resolution of 0.1Ω is applied for diagnosing connection issues or checking the health of thermoelectric modules. A High-speed DMMs with a sampling rate of at least 2–10 Hz for dynamic measurements and response times of >10 readings per second is engaged in the study for dynamic or transient measurements.

3.2. Design Method

The block diagram in Figure 1 designates step-wise process for the invention of thermoelectric central air systems. The variable speed drive is established in this investigation by using Variable Voltage Variable Frequency (VVVF) regulator mode of a solid state electronic conversion system with incorporation of AC–DC and DC–AC Converter expertise. The project plan convoluted the congregation of DC Power Supply Unit, Monitoring & Control Units and Power Unit [16,17]. The incoming power main source of 230VAC is delivered to the entire system and subsequently converted into 150VAC by a step – down transformer. A bridge rectifier transfigures the transformer output voltage to modifying DC voltage.

The procedure is well-ordered absolutely with current ambient air temperature sampling and correct fine-tuning of compressor speed by a programmed microcontroller (PIC18F4431). Variable frequency Pulse Width Modulation (PWM) signal is produced by the automated microprocessor to confirm the regulation of the functional voltage and significant production of PWM frequency prerequisite at the output of power inverter [18,19]. The sinusoidal waveform is created automatically by microcontroller Insulated Gate Bipolar Transistor (IGBT) inverter that fed the air conditional compressor motor at a regulated frequency. The variable frequency drive efficaciously established in this study is linked with air conditional and set running at different phases in stable power condition. The speeds of the induction motor of air condition are regulated to achieve low energy consumption.

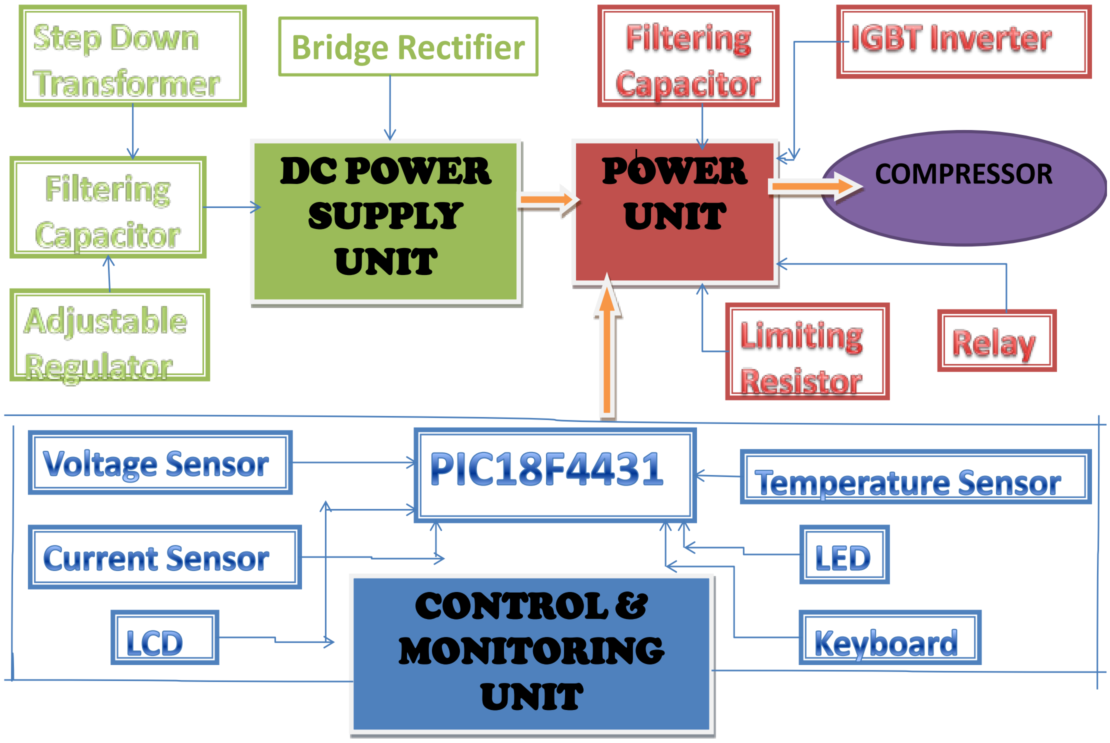

Figure 1. The block diagram of developed thermoelectric drive.

4. Results

The investigational results presenting the resultant frequency – characteristics, air flow, room temperature, power consumption, and actual speeds as observed for days from 7:30am till 6:45pm for the duo of traditional and developed TE air conditioners (Table 1 & Figures 2 – 4). The power consumption rate, cooling output, energy efficiency, estimated electricity costs are also observed for effective power management. Power consumption rate of the system increases as the speed of motor increases for both air conditioners with lesser consumption rate on thermoelectric drive (Figure 3). The rate of air flow for the new TE drive is linearly increasing with the frequency as speed of motor also varies, this result to low consumption of power (Table 1). The conventional air conditioner conversely experienced constant speed and frequency as the air flow increases, this accountable for the excessive power consumption by the device (Table 1). The study reveals that 2,676kWh of energy is consumed by conventional air conditioner in 24 hours under steady operation while 520.8kWh is consumed by thermoelectric system at similar time yielding 67% of energy saving. The estimated electricity shows that 67% of the charge bill is saved periodically using the TE drive compared to traditional system.

Table 1. Results of thermoelectric air conditioner (TEAC) and Conventional Air Conditioner (CAC).

S/N	Time (hr)	Indoor Temperature (°C)	Air Flow (m^3/h)	Energy Meter (kWh)		Motor Speed (rpm)		Frequency (Hz)	
				CAC	TEAC	CAC	TEAC	CAC	TEAC
1.	7:30am	24	50	1.5	1.0	3000	1500	50	25
2.	8:45am	25	100	2.5	1.1	3000	1680	50	28
3.	9:50am	22	150	4.0	1.2	3000	1860	50	31
4.	10:55am	23	200	5.5	1.3	3000	2040	50	34
5.	11:55pm	24	250	7.0	1.4	3000	2160	50	36
6.	12;50pm	30	300	8.5	1.5	3000	2460	50	41
7.	1:45pm	28	350	10.0	1.7	3000	2640	50	44
8.	2:58pm	30	400	11.5	1.9	3000	3060	50	51
9.	3:50pm	26	450	13.0	2.2	3000	3240	50	54
10.	4:45pm	27	500	14.5	2.5	3000	3660	50	61
11.	5:50pm	25	550	16.0	2.8	3000	3840	50	64
12.	6:45pm	26	600	17.5	3.1	3000	4260	50	71

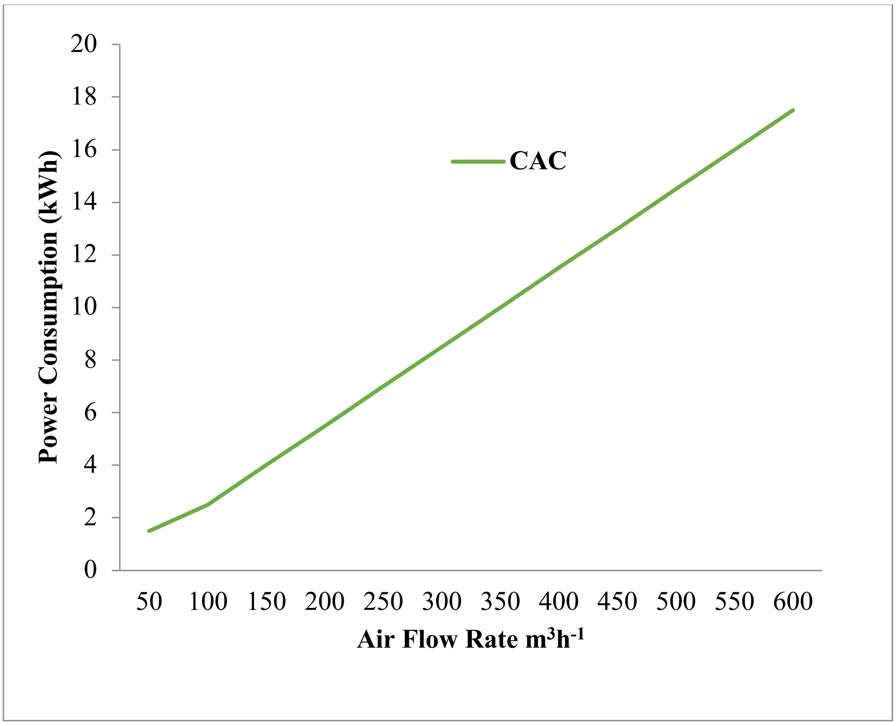

Figure 2. Power Consumption Characteristics of Conventional Air Conditioner (CAC).

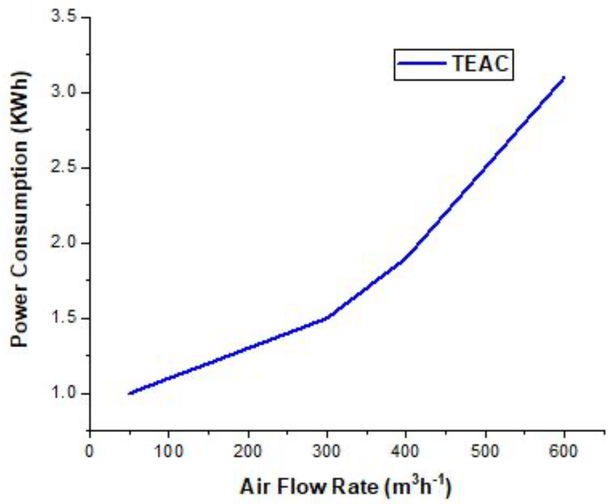

Figure 3. Power Consumption Characteristics of Thermoelectric Air Conditioner (TEAC).

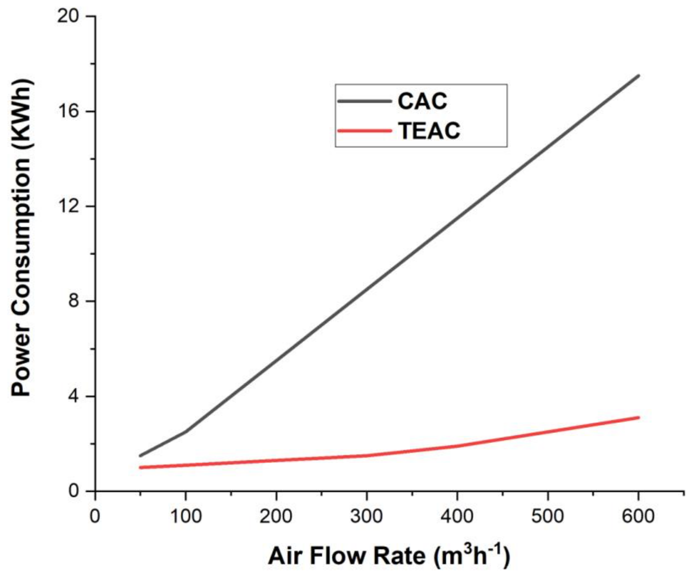

Figure 4. Power Consumption Characteristics of CAC and TEAC.

5. Discussion

The energy efficient drive successfully developed, designed and constructed in this research is connected with a conventional air conditional and set running at different periods under steady power consumption. The developed drive is implemented by a microcontroller (PIC18F4431) based PWM inverter and programmed using C language. The speeds of the induction motor are varied from 1440RPM to 4200RPM at a corresponding frequency range from 24Hz to 70Hz. The developed drive is tested for a 3 phase, 415 Volts, 1.5 H.P. Induction Motor for different frequencies, speeds and load reading.

The application of thermoelectric coordination as demonstrated in the investigation is very essential with the goal of reducing energy cost by optimizing the motors efficiency in the central air system. This is accomplished by change in frequency and speed variation of the motor in the newly invented system. There are extraordinary savings institute in characteristic presentations by using TE drive to run motor of the compressor. To evaluate the prospective savings over time, the actual load/time outline is considered. The load profile specifies the quantity of air flow rate the system necessitates substantial its loads during a typical day, month, and year or time period under study. The energy cost of both conventional and developed TE air conditioner is determined using the present electricity tariff rate of ₦225 per kWh unit by the Nigeria Electricity Regulatory Commission (NERC). Table 3 shows daily/monthly average energy consumption (kWh), energy savings by TEAC (daily/monthly/annually), energy cost by both CAC and TEAC (daily/monthly) and substantial energy savings by the new developed TEAC (daily/monthly/annually).

Table 2. Energy and Cost Analysis of Conventional Air Conditioner (CAC) and Thermoelectric Air Conditioner (TEAC).

DAILY AVERAGE ENERGY CONSUMPTION (kWh)			
CAC		**TEAC**	
80,280kWh		15,624kWh	
ENERGY SAVINGS BY TEAC			
Daily	**Monthly**		**Annually**
2,155.2kWh	64,655.99kWh		786,647.99kWh
ENERGY COST (kWh)			
CAC (Daily)	**CAC (Monthly)**	**TEAC (Daily)**	**TEAC (Monthly)**
₦602,100 ($387.51)	₦18,063,000 ($11625.27)	₦117,180 ($75.42)	₦3,515,400 ($2262.50)
ENERGY SAVINGS BY TEAC			
Daily	**Monthly**		**Annually**
₦484,920 ($312.09)	₦14,547,600 ($9362.78)		₦174,571,200 ($112353.31)

6. Conclusion

The energy efficient drive designed and constructed in this research provides reliable, efficient, cost-effective variable-frequency (V/Hz) control of air conditioner compressor motors. The integration of most recent technologies in Digital Signal Processing (DSP), PWM and IGBTs were implemented in the design to deliver finest motor performance, inclusive programmability, in addition to unfussiness of operation. In the research, an efficient air conditioner drive was realized for efficient power management using intelligent control system that significantly regulates the frequency, speed, voltage, torque, power and reduces the noise output of the fan and compressor for efficient performance at low power consumption.

The economic prominence of this newly developed TE drive is its drastically low power intake and energy cost rate. The study reveals that 80,280kWh (83.7%) of energy is consumed by a conventional air conditioner in a month under steady operation while 15,624kWh (16.29%) at the same period is consumed by a variable speed thermoelectric air conditioner. This translates to energy cost of ₦602,100 ($387.51) and ₦18,063,000 ($11625.27) by CAC daily and monthly respectively while TEAC records ₦117,180 ($75.42) and ₦3,515,400 ($2262.50) at the same period correspondingly. The energy savings cost with the developed drive are ₦484,920 ($312.09), ₦14,547,600 ($9362.78) and ₦174,571,200 ($112353.31) averagely on daily, monthly and yearly respectively. The estimated electricity shows that 67% of the energy as well as cost bill is saved periodically using the TE drive compared to traditional air conditional system.

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