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Domestic Power Efficiency using Sensors and a Programmable Logic Controller (PLC)

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ABSTRACT

A well designed sensors – PLC based domestic power efficiency system is developed. This system allows the user semi–automatic control over time usage of systems commonly used in the home on a daily basis and thus control of consumption rates and costs. Use was made of four kinds of sensors, light, occupancy, motion and fire cum smoke sensors and a Trilogi–programmed PLC software. A centralised system of protection against in-bound system voltage fluctuations was incorporated. Efficient and effective maintenance and diagnosis of the system are achieved using an easily manageable PLC software tool. Costing the new system gave GH¢ 1182.69. Aside, computations of consumed power units and the associated cost for a two to five year period confirmed superiority of the PLC managed system over the existing system giving a breakeven point of 3 years, 7 months.

Key words: *Home automation, power efficiency, Programmable Logic Controller (PLC), sensors*.

LIST OF ABBREVIATIONS

BRm	Bedroom
Bth	Bathroom
Cor	Corridor
CPU	Central Processing Unit
DEMAC	Distributed Energy Monitoring and Control Application
DRm	Dining Room
ECG	Electricity Company of Ghana
ExT	External
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
GRm	Garage
GSM	Global System for Mobile Telecommunication
HA	Home Automation
HRm	Hall
HTML	Hyper Text Mark-Up Language
I/O	Input-Output
Kit	Kitchen
KStore	Kitchen Storeroom
MW	Microwave
PIR	Passive Infra Red
PLC	Programmable Logic Controller
RDF	Resource Description Framework
SHN	Smart Home Network
TempCRM	Temporal Context Reasoning Model
VCN	Virtual Cluster Node
VPAN	Virtual Private Area Network
Vr.	Veranda
WOL	Web Ontology Language
VHDL	VHSIC Hardware Description language

1. INTRODUCTION

Buildings suitable for human habitation are termed as domestic housing. The various types of housing facilities that fall under this class include compound housing where a family of two or more share a compound of a single building with many apartments. The Flats type of housing are like compound houses but some utilities are not shared. The semi-detached and detached are basically self-contained housing units. The difference however, between the two is that the semi shares a wall with another house while the detached stands alone. Detached housing units are usually multiple storey and single floor buildings.

Currently, an analysis of housing conditions reveals that on a national basis, 48.9 % of all Ghanaian households live in accommodation associated with the compound housing type (44.5 % of it live in compound rooms). Another 25.3 % live in separate houses and 15.3 % reside in semi-detached houses. Traditional housing in Ghana takes the form of compounds. The design accommodates room re-allocation and some privacy. Moreover, 57.4 % claim ownership of their dwellings (40.4 % in Greater Accra). Two percent of households live in public property set aside as rentals for civil servants and private employers provide housing for 4.5 % of formally employed households. Also, 22 % rent their dwellings (37.5 % of it in Accra). Another 19.5 % live rentfree (20.5 % of it in Accra). Households comprising this latter group probably know the head of household and/or landlord and are exercising their kinship rights (CHF International, 2004). Electricity is billed to the consumer by the kilowatt-hour (kWh). The capacity of power delivered to the house is usually single phase of 240 Volts or three phase of 415 Volts.

Sometimes, two phase voltages are delivered which is on rare occasions.

The overall power efficiency (Equation 1) of a system is the ratio of the useful output power to the total input power, in whatever form (Theraja and Theraja, 2005; Warne, 2005).

$$\eta = \frac{p_{out}}{p_{in}} \qquad (1)$$

where, η is electrical power efficiency, P_{out} is useful or output power and P_{in} is input power.

Issues of optimisation of domestic electrical power efficiency have been reported in the literature. Yilmaz (2010) designed a PLC-based home automation system. It is easy to build, service, modify, gives reduced cost, easily programmable, yields to the efficient use of energy and offers convenience in maintenance and repair. Richter (2000) reported on the design and construction of a home automation system comprising one master unit and four slave units communicating across the powerline. Use was made of the softwares JavaScript, Hyper Text Mark-Up Language (HTML) and C++ in the design. The system is capable of improving the quality of life of the owner, security and provision of off-site control. Alheraish, Alomar and Abu-Al-Ela (2006) presented a low-cost and simple approach to designing an intelligent home security system using the concept of mobile-to-machine communication. The design, based on PLC comprises microcontroller, adaptation circuit, power circuit and RS 232 interface. Xiaohu and Guangxi (2006) proposed an architecture which integrated ad-hoc network and OSGi framework to support the ubiquitous services in next-generation smart homes. The new architecture included three-level network entities namely VCN, VPAN and SHN each of which has its own capability and infrastructure. A new model of protocols stack was designed so as to realise information communication in the new architecture.

Liao and Tu (2007) proposed a Temporal Context Reasoning Model (TempCRM) based on Resource Description Framework (RDF) and Web Ontology Language (WOL) for the smart home. The TempCRM is used for inferring the dangerous levels of a smart home. A potential dangerous situation is caused by a series of temporal events in a home environment. A smart home ontology is defined for the terms and relationships used in the temporal context. In a simulation study, a script with dangerous situations was designed to evaluate the dangerous level generated by TempCRM. The result validated TempCRM as useful in the alarming of the inhabitants and thus prevents the occurrence of an incident from the temporal contexts. TempCRM thus is useful in increasing the safety of a smart home. El-Medany and El-Sabry (2009) gave a design for remote sensing based on use of Field Programmable Gate Array (FPGA) and Global System for Mobile Telecommunication (GSM). The system designed is found suitable for real time monitoring in home security as well as controlling and sensing in home automation with a large number of controlled devices. Hardware using VHDL language and Xilinx Spartan 3 FPGA were used for the design and implementation. Maxon GSM was used in testing the sensing part. Paris *et al* (2008) investigated ways of improving the energetic performance of buildings by introducing a performance indicator expressed in $kWh/m^2/yr$. A processor-based prototype of a real-time data-acquisition and monitoring system was developed in collaboration with two industrial companies to improve the value of the performance indicator. Control algorithms are tested in simulation to improve renewable energy consumption while reducing fossil energy dependence. Simulations regarding control and optimisation as applied to two warmers in a room show large potential for fossil energy consumption reduction. Rashidi and Cook (2008) observed that many smart home technologies do not adapt to the user's wishes or changes in residents' habits and lifestyle. They proposed an integrated set of components that aim toward applying machine learning and data mining techniques to a smart home environment to discover patterns in user behavior and to automatically mimic these patterns. The aim is to keep the resident in control of the automation whereby the user provides feedback on proposed automation activities, modify the automation policies and introduce new requests. Mainardi *et al* (2009) discussed the potentialities of ethernet power link in the home automation field. Use of ethernet communication allows a wide series of advantages such as velocity, content flexibility and standardisation. Ethernet powerlink as an open protocol could be suitable to be successfully applied to the Home Automation (HA) field. Kevitt (2010) focused attention on the design, development and evaluation of a Distributed Energy Monitoring and Control Application (DEMAC) purposefully for use in intelligent building systems focusing on energy consumption reduction. The application fulfilled 14 out of 16 requirements. It offers simplicity, usability and extensibility while maintaining a significant performance benefit during operation.

This paper investigates and implements an array of sensors–programmable logic controller (PLC) based system to meet the demands of better power efficiency, intelligent control and overall protection to satisfy the current needs while improving the system of domestic power consumption. A sample house was considered for a case study. The PLC system integrated into the home is as shown in Figure 1.
The input section of the PLC system has the control block representing the system components necessary for control of the load units located in the output section. Power supply to the input section is through a bridge rectification unit built purposely for the PLC system. Thus the control block shares direct current power with the PLC system

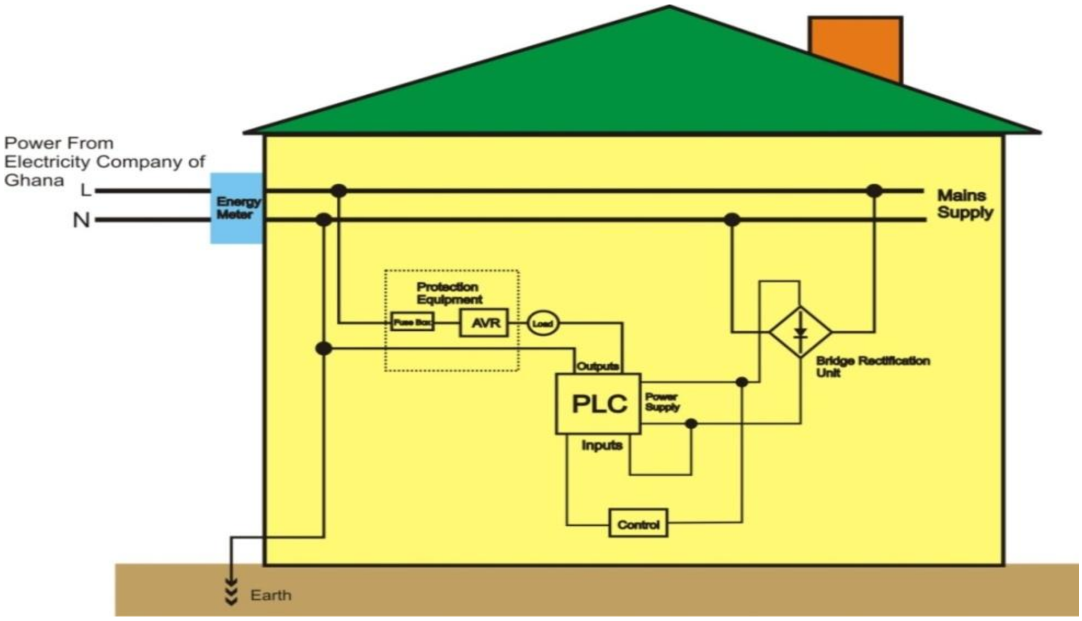
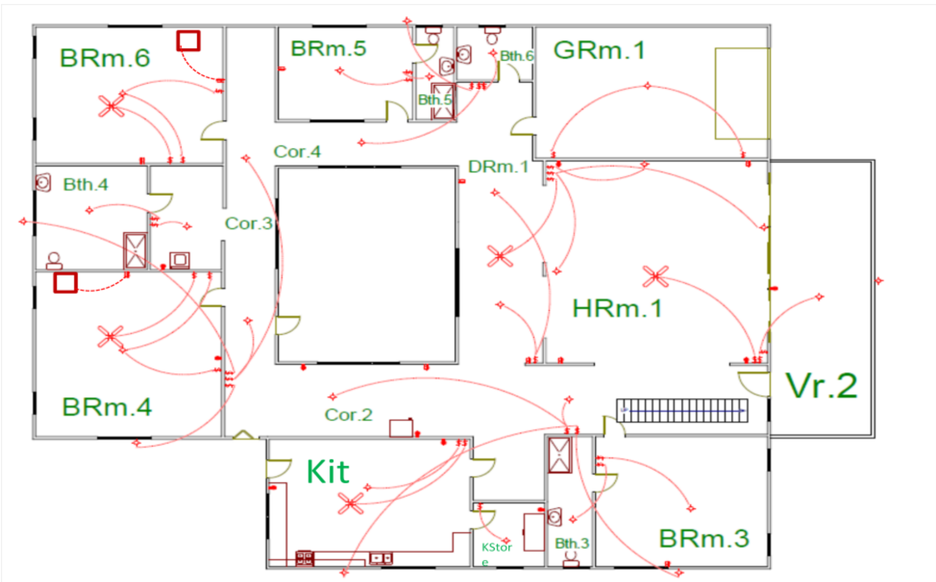


Figure 1: Basic Connections of the PLC System Integrated into the Home



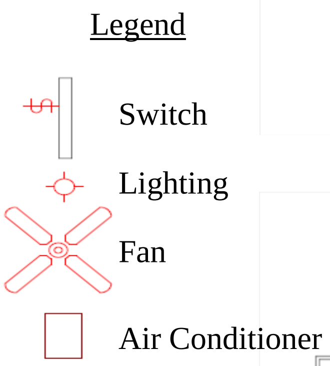


Figure 2: Electrical Plan of Ground Floor

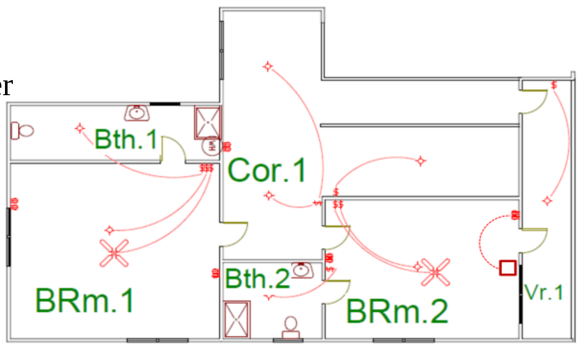


Figure 3 Electrical Plan of First Floor

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 One Storey House

The house case studied is located in Kumasi in the Ashanti region of Ghana. It is a one storey building that basically receives a two-phase power supply to the mains. This power is distributed between domestic appliances, wall sockets, lighting and ventilation systems. Figures 2 and 3 show the electrical plan of ground flour and first flour respectively.

2.1.2 Sensors

Sensors employed include occupancy, light, motion and integrated fire cum smoke sensors. The occupancy sensors detect the presence of people and sometimes animals in a monitored area. The light sensors detect the amount of light being emitted to determine the time of day. The motion sensors respond only to moving objects and the integrated fire cum smoke sensor is for fire and smoke sensing within a given defined area. Different sensor models were selected for the occupancy, light, motion and fire-smoke sensors. A passive infrared (PIR) ceiling mounted occupancy sensor with model number DPS28B was selected. This sensor incorparated both light and occupancy sensing functions in one unit making it suitable for room installations. A photometric light sensor with model number LI-210 was selected. The LI-210 sensor utilises a silicon photodiode. The sensor integrates well with the PLC system and gives a digital output. A doppler effect type motion sensor with model number DDT-7306 is used. This sensor utilises a fully protected 4-beam microwave (MW) head plus an infrared dual-element. The MW transmission adopts the most advanced plane antenna Field Effect Transistor (FET) oscillator. Its fully-protected structure admits it to operate in any severe environment. It automatically compensates for temperature effects. For the integrated fire-smoke sensor, the series 300 2351TEM is a photoelectric smoke/fire detector which incorporates an optical chamber and a thermal element. They are continually monitored by an on-board processor by using algorithms developed specifically for the unit. An alarm signal is only enabled in the detector once the processor is satisfied that smoke has been detected. By using a combination of inputs, the incidence of nuisance alarms is reduced while at the same time, the response time to an actual fire is also improved.

2.1.3 Trilogi 6.2 Programmable Logic Controller (PLC) Software

The Trilogi 6.2 PLC software is a very simple and easy to understand programming language for the programming of the microprocessor based PLC. The software uses ladder logic circuit diagram as the programming language. The written program is loaded into the PLC system from a personal computer through a connection made through a RS232C port on the PLC system. The PLC system runs on the loaded program written by the user. During its operation, the CPU or processor completes three processes in a scan:

- It reads or accepts the input data from the field devices via the input interfaces
- It executes or performs the control program stored in the memory system
- It writes or updates the output devices via the output interfaces.

2.2 Methods

2.2.1 Location of Sensors

The relevant installation positions of the sensors were determined (Figures 4 and 5). Occupancy sensors and fire-smoke sensors were located in the centre of the rooms on the ceiling to widen the sensor catchment area in the room. The occupancy sensors help to control fans, air conditioners and light in the rooms. Fire-smoke sensors are found in critical fire prone areas such as the kitchen and also near electrical sockets. Control of valves connected to the water reservoir is localised for each room, meaning should a fire break out in room A, room B will not be affected when the fire extinguishing mechanism is operational in room A. This mechanism allows for efficient, effective and localised management of electrical power for the control of fire detection and prevention. Occurrence of fire first sets the alarm to alert the user then, after 10 seconds the fire valve operates to release water to extinguish the fire totally. Light sensors are positioned close to the windows to receive enough light to determine the amount of light coming into the room (Figure 4). In intruder prone areas such as the doors and windows, motion sensors are located on the ceiling of the monitored area to detect the movement of intruders that breach physically into the home (Figure 5). Sensing of motion is transmitted to an alarm which sounds an audible warning on the intruder. The intruder alert system can be activated or deactivated by the user as deemed fit.

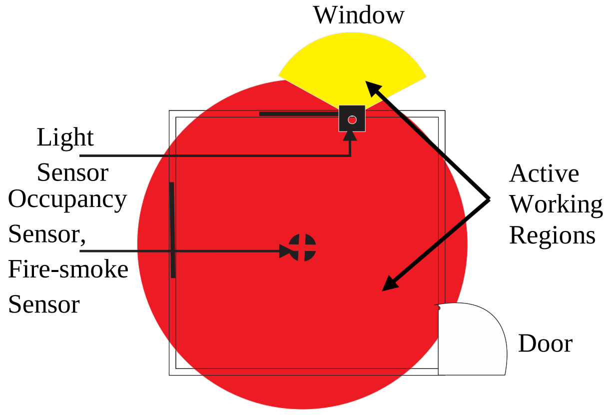


Figure 4 Plan of Room Showing Occupancy, Fire-smoke and Light Sensor Positions and Catchment Areas.

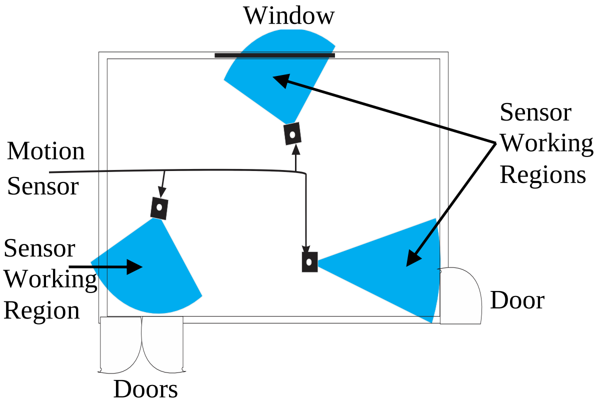


Figure 5: Plan of Room Showing Motion Sensor Position and Active Working Region for the Intruder Alert System

2.2.2 Trilogi 6.2 PLC Ladder Logic Program

Stepwise approach to the development of the Trilogi 6.2 PLC ladder logic program was adopted. The input-output nomenclature used for the generation of the PLC program is given in Table 1. The complete program for the PLC-sensor based home automation system for power efficiency was realised in 7 pages. A page of the Trilogi 6.2 program is shown in Figure 6. Inputs to the PLC system are represented by normally open or closed contacts and outputs are represented by coils. In the sample program, special outputs, ILock and ILoff, have been used to implement an interlocking function where the program is controlled by a master isolator switch which gives the user access to activate and deactivate the system by the press of a button.

2.2.3 PLC Diagnostic Software Tool

The PLC diagnostic software tool was written in C++/CLI programming language. The software is fed with data from the indicators located at the outputs and inputs of the PLC system. This data in turn is used by the program to visually show the user what is happening at the outputs and the inputs. An illustration of the user interface of the software tool is given in Figure 7. In Figure 8 is presented the diagnostic software code.

Table 1: Input-Output Nomenclature Used in the PLC

I/O Device	Description
Input Contacts	
Main Isolator	Main push button which activates PLC system
LSi	Internal light sensor in building
OSi	Internal occupancy sensor in building
LManual	Manual toggle or push button switch for lighting systems
LSe	External light sensor outside building
FS	Integrated fire cum smoke sensor
EmergSt	Emergency stop push button for FS
MS	Motion sensor
Act	Push button which activates MS
AManual	Manual toggle or push button switch for ventilation systems
OSa	Occupancy sensors for ventilation systems
Output Coils	
Int_Light	Lighting system in building
Ext_Light	Lighting system outside building
SmokeAlarm	Smoke alarm system for FS
FireValve	Water valve for FS
IntrudeAlarm	Alarm system for intruder system
Fan_Aircond	Ventilation system
Timer Contacts	
T1L	Timer for lighting system
T1F	Timer for fire detection and prevention system
T1A	Timer for ventilation system
Special Coils	
ILock	In-built function for interlocking (stops interlock)
ILoff	In-built function for interlocking (starts interlock)

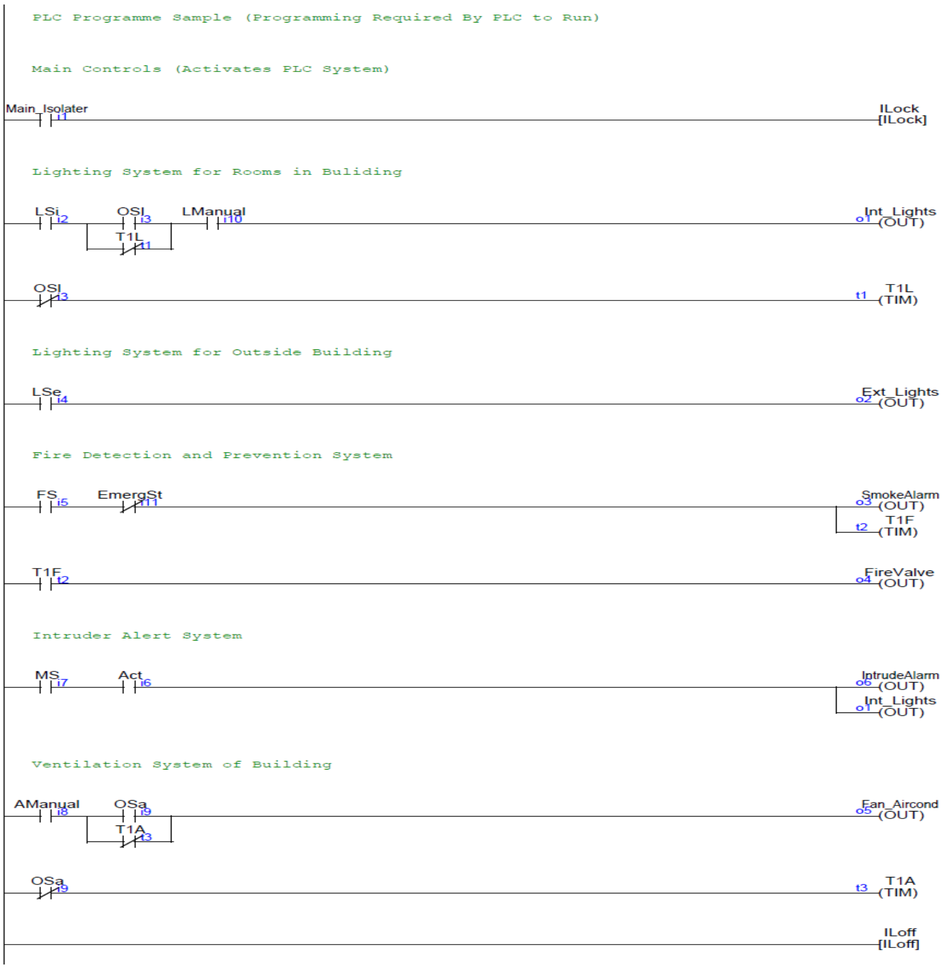


Figure 6: A Page of the Trilogi 6.2 PLC Program

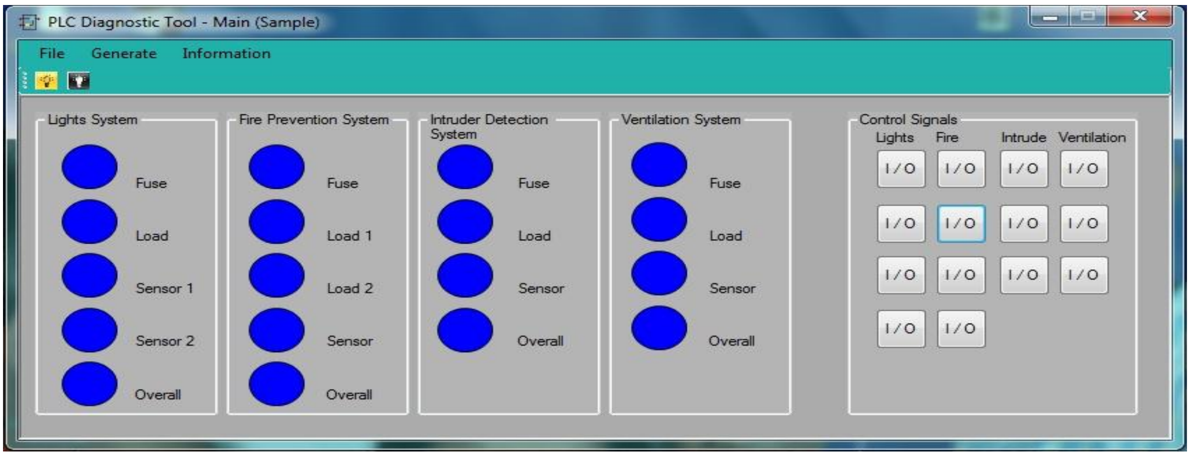


Figure 7: PLC Diagnostic Tool User Interface

```
private: System::Windows::Forms::ToolStripStatusLabel^  toolStripStatusLblMain;
	private:
		/// <summary>
		/// Required designer variable.
		/// </summary>
		System::ComponentModel::Container ^components;

#pragma region Windows Form Designer generated code
		}
#pragma endregion
	//Coding for system forms to show and dock in parent form main
private: System::Void lightingToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
					lightingSystem ^frmlight = gcnew lightingSystem;
					frmlight->MdiParent = this;
					frmlight->Show();
				}
private: System::Void firePrevetionToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				fireSystem ^frmfire = gcnew fireSystem;
				frmfire->MdiParent = this;
				frmfire->Show();
			}
private: System::Void intruderDetedtionToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				intruderSystem ^frmintruder = gcnew intruderSystem;
				frmintruder->MdiParent = this;
				frmintruder->Show();
			}
private: System::Void ventilationToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				ventilationSystem ^frmventilation = gcnew ventilationSystem;
				frmventilation->MdiParent = this;
				frmventilation->Show();
			}
			//coding for help menu  forms
private: System::Void buildingPlanToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				buildingPlan ^frmbuilding = gcnew buildingPlan;
				frmbuilding->MdiParent = this;
				frmbuilding->Show();
			}
private: System::Void aboutToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				about ^frmabout = gcnew about;
				frmabout->MdiParent = this;
				frmabout->Show();
			}
			//coding window menu list
private: System::Void arrangeToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				LayoutMdi(MdiLayout::ArrangeIcons);
			}
private: System::Void cascadeToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				LayoutMdi(MdiLayout::Cascade);
			}
private: System::Void tileHorizontalToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				LayoutMdi(MdiLayout::TileHorizontal);
			}
private: System::Void tileVerticalToolStripMenuItem_Click(System::Object^  sender, System::EventArgs^  e) {
				LayoutMdi(MdiLayout::TileVertical);
			}
};
}
```

Figure 8: PLC Software Diagnostic Software Code

3. RESULTS AND DISCUSSION

The existing and the PLC managed system are analysed with respect to power consumption, hours of usage and cost of power consumption within a specified period of 5 years. Basically, this comparison is done to ascertain the efficiency of both systems and to know which system is better.

3.1 Power Consumption

The Electricity Company of Ghana applies Equation (2) in the calculation of power consumption for both the industrial and domestic sector in Ghana.

Cost = Unit × Rate + (Government Levy + Street Lighting) × Unit + Service Charge (2)

The service charge, government and street lighting levy are fixed. The unit is the dynamic variable in Equation (2). The unit charge is based on a tariff system where for a specified range of values an amount is charged per unit. Thus, from Equation (2) the user has power over the rate of units consumption only. The units consumption is given by Equation (3)

Units = Power consumption × Time (3)

Hence, the user or customer has the final say over time usage of appliances. A lot of savings on power consumption in the home boils down to control of power utilisation for efficiency. Table 2 shows all appliances realised, their quantity, wattage, locations and hours used per week. Some appliances are rarely used and have a recorded usage of zero.

Table 2: Electrical Appliances in the Home

Room	Quantity	Appliance Type	Wattage, W	Hours/Week
BRm.1	1	Bulbs	15	42
	1	Fan	86	56
BRm.2	1	Bulbs	15	0
	1	Air conditioner	560	0
	1	Fan	86	0
Bth.1	1	Bulbs	15	1
Bth.2	1	Bulbs	15	0
Cor.1	3	Bulbs	45	0
Vr.1	1	Bulbs	15	0
BRm.3	1	Bulbs	15	42
BRm.4	2	Bulbs	30	42
	1	Air conditioner	560	0
BRm.5	1	Bulbs	15	0
BRm.6	1	Fan	86	0
	1	Bulbs	15	42
Bth.3	1	Bulbs	15	1
Bth.4	2	Bulbs	30	2
	1	Washing machine	1100	3
Bth.5	1	Bulbs	15	2
Bth.6	1	Bulbs	15	1
Cor.2	2	Bulbs	30	30
	1	Refrigerator	100	84
Cor.3	2	Bulbs	30	42
Cor.4	1	Bulbs	15	42
DRm.1	2	Bulbs	30	28

	1	Fan	86	2
HRm.1	3	Bulbs	45	10
	1	Fan	86	14
	1	Television	100	14
	1	Multi TV Decoder	20	14
	1	VCR	20	0
	1	DVD Player	15	0
Vr.2	3	Bulbs	45	42
GRm.1	1	Bulbs	15	1
Kit.	1	Bulbs	15	42
	1	Fan	86	7
	1	Microwave	1100	1
	1	Deeper Fryer	500	0
	1	Blender	40	1
	1	Rice Cooker	400	1.5
KStore	1	Bulbs	15	7
	1	Freezer	0	84
	1	Iron	750	2
ExT.	6	Bulbs	90	84

Table 3: Monthly Units Consumption for the Existing and the PLC Managed System

Appliance	**Existing System**			**PLC Managed System**		
	Total Hrs/Mth	**Wattage, W**	**Units (Watt-Hrs)**	**Total Hrs/Mth**	**Wattage, W**	**Units (Watt-Hrs)**
Lighting	2008	600	70260	1384	600	50250
Ventilation	316	430	26488	178.4	430	17750.4
Washing Machine	12	1100	13200	12	1100	13200
Refrigerator	336	100	33600	336	100	33600
Television	56	100	5600	56	100	5600
Multi-TV Decoder	56	20	1120	56	20	1120
Microwave	4	1100	4400	4	1100	4400
Rice Cooker	6	400	2400	6	400	2400
Iron	8	750	6000	8	750	6000
Total/Month	**2802**	**4600**	**163068**	**2040.4**	**4600**	**134320.40**

Tables 3 shows the total hours of usage per month, wattages, and units consumed per month of the various systems and appliances mostly used in the home for the existing manually controlled and the semi-automated PLC managed system. The systems and appliances considered included lighting and ventilation systems which constitute the light fixtures and fans respectively, and seven other regularly used appliances as listed in Table 3. From Table 3 it can be seen that after substantial decrease in the hours of usage of lighting and ventilation, the total units consumed per month became less. Also, the percentage usage of both hours and units consumed per month by lighting and ventilation reduced appreciably signifying an improved efficiency in power consumption on the whole. Better power consumption rates were obtained by controlling the time usage of the home systems with the help of a PLC managed system. Initial cost of the PLC managed system is shown in Table 4. Domestic tariff rates of ECG are given in Table 5.

Table 4: Initial Cost of the PLC Managed System

Model	Description	Pricing (GH₵)
T100MX-3224R+	T100MX-3224R PLC	778.77
DB9 Cable	Programming Cable	12.24
DIN-KIT-3	DIN Rail Kit for T100MX	33.66
PS-DR4524	24V, 2A Power Supply	74.97
EXP1616R	32 I/O Expansion Card	283.05
	Total	**1182.69**

Table 5: Electricity Company of Ghana Domestic Tariff Rates for September, 2005, November, 2007 and October 2010

Unit Range	Cost per Unit in Ghana Pesewa (gp/unit)		
	September, 2005	**November, 2007**	**October, 2010**
0 – 50	1.91 (Ghana cedi / month)	0.095	0.095
50 – 300	0.05	0.12	0.17
301 –600	0.11	0.16	0.21
600 - +	-	0.19	0.23
Fixed charges	0.5002	0.5002	1.5003

Source: Electricity Company of Ghana

Table 6: Comparison of Power Consumption over a Period of 5 Years

Period (Year)	Existing System (GH₵)	PLC Managed System (GH₵)	Cost Savings (GH₵)	Cumulative Cost Savings (GH₵)
1	1880	1459.22	420.78	420.78
2	3237	2473.76	763.24	1184.02
3	5384	3657.18	1726.82	2910.84
4	6904	4702.70	2201.3	5112.14
5	8559	5934.95	2624.05	7736.19

3.2 Comparison of the Existing and the PLC Managed System

A comparison of the power consumption and cost of power consumption for a period of 5 years was undertaken. It revealed an appreciable decrease in power consumption and cost using the PLC managed system in place of the existing system. Results of computations are presented in Table 6 together with the cost savings and cumulative cost savings. In the first period, a 28.8 % decrease is realised using the PLC managed system. The second period records a further decrease of 30.9 %. This could be explained that the user has fully adjusted to the PLC managed system. The third year sees an appreciable rise in savings cost due to a 46% decrease in cost due to actions taken by the user to prevent unnecessary loss of power thus, saving a lot of money that year. The fourth and fifth years continue to enjoy a rise in savings cost, however, a slight dip from 46.8 % to 44.2 % shows how the rise in tariff prices and the user's additional appliance usage affected the period's cost savings. In general, the cumulative cost savings for the 5-year period show how much power and money are conserved when the PLC managed system replaces the existing system. Figure 9 shows a line graph of the performance of the existing and PLC managed system over the 5-year period. Within a period of 3 years and 7 months the user gains all the money invested into the PLC managed system. Thus, the PLC managed system is not only efficient but also cost effective.

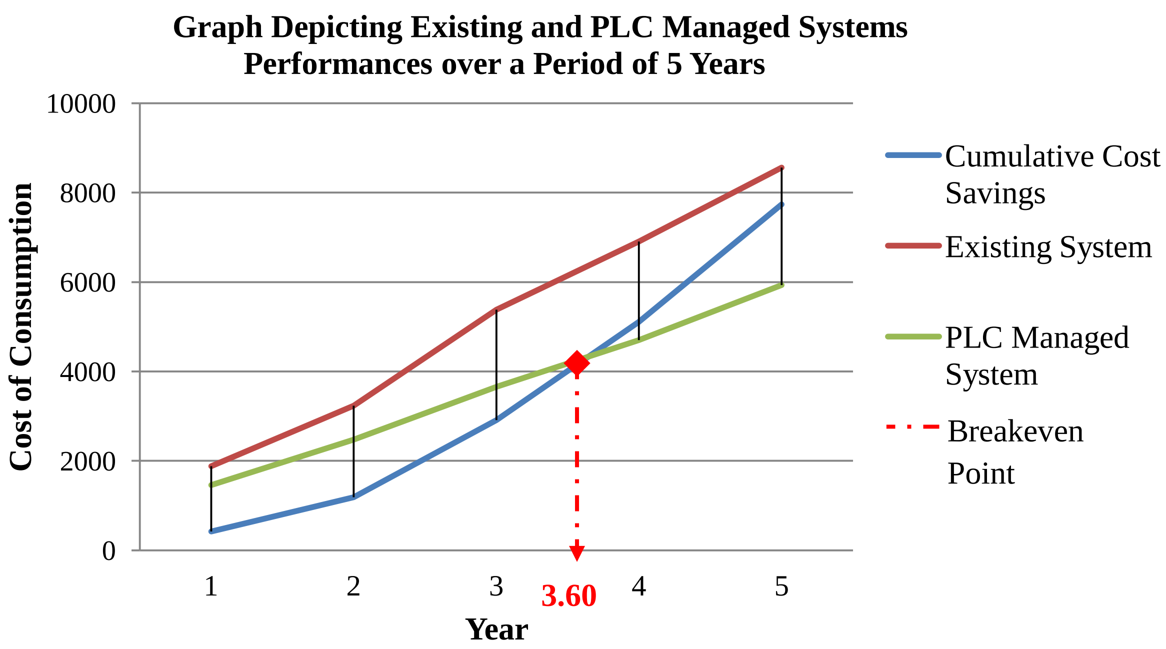


Figure 7: Line Graph Showing Performance of the Existing and the PLC Managed Systems Over a Period of 5 Years

4. CONCLUSION

Domestic power efficiency using sensors and a PLC has been successfully developed. The PLC system protects the home efficiently from voltage fluctuations through a centralised protection system. A centralised semi-automatic control of home systems gives the user a level of control over power consumption in the home. An effective maintenance and diagnostics system using a soft tool was installed and implemented. Further, cost considerations give impetus to the implementation of the PLC-sensors based power efficient home considered.

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