Design and Implementation of Load Balancing System for a Smart Home

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***Abstract*— The electrical energy measurement, controlling, monitoring and saving for homes are today have a great interested in the field of research. In this paper, a new management system is designed and constructed in order to perform measurement, controlling, monitoring, and saving the electrical energy. A three phase load balance system has been designed for home smart meter. The principal work of this system is based on measure the current of the three-phase lines, and then adjusts the distributed current by replacing the load of some power outlets. The energy measured by this system can be arranged in a time schedule to produce a monitoring platform with graphical user interface (GUI). This GUI displays the real-time power information to give an idea about the amount of consumed energy and also can be used for a smart meter system.**

Keywords—Monitoring system; Load balance; Smart meter; Contactors.

I. Introduction

Currently, consumption of electrical energy is the most common problem in smart home and building environments which the amount of electrical energy consumed by each device in real time is unknown. Accordingly, the monitoring of electrical energy consumption data of electrical equipment is becoming progressively important. In recent field of research, the design of efficient electrical management system for homes or buildings is an active subject.

Electrical energy management system is the combination of technologies and services through home networking for an intelligent living environment. Smart power outlets are considered as the most commonly used electrical devices in modern home environments. They could measure consumption of electrical energy and control the operation of the electrical equipment. The intelligent power outlets have recently appeared as a new form for home energy management that can control electrical equipment and produce secure electrical environment [1-3].

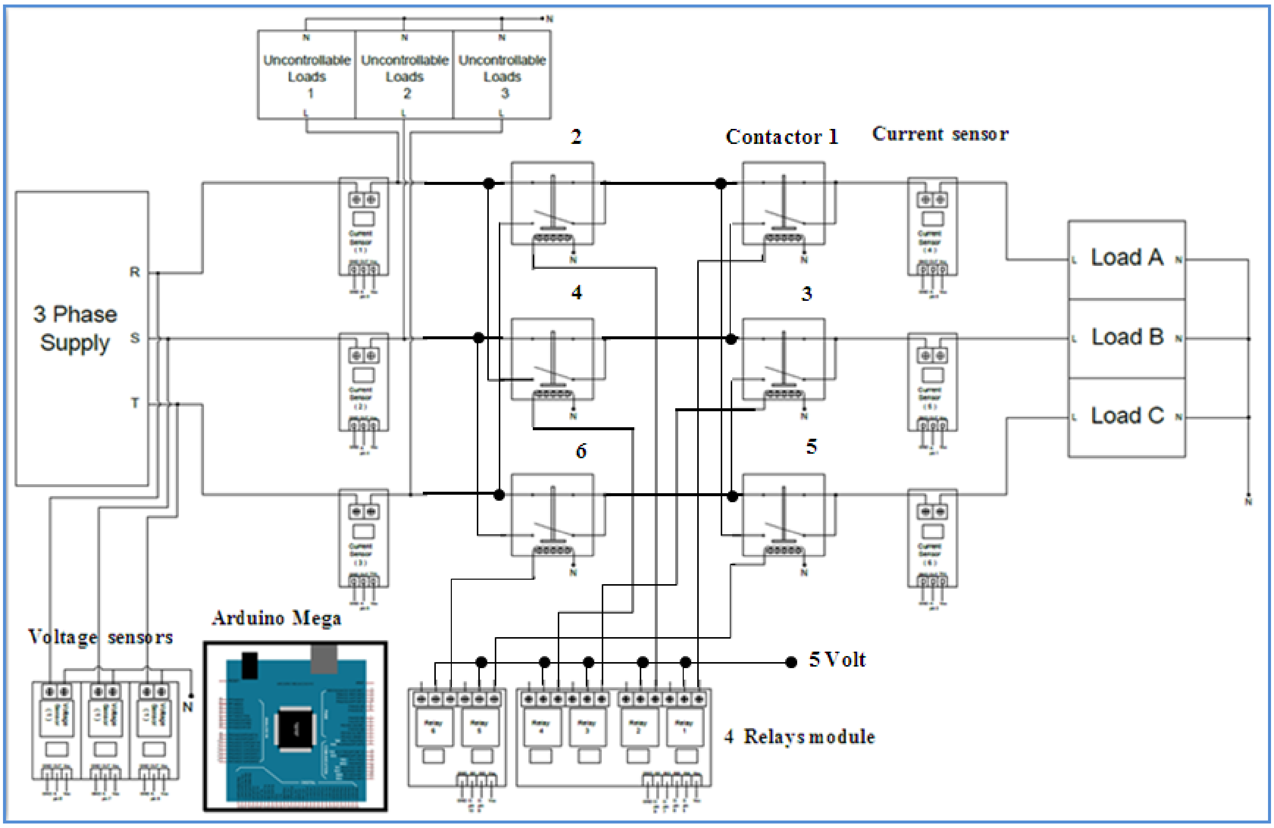
Many researchers have contributed in the development of electrical energy meters. The first generation of these meters were electromechanical meters and then evolved to emulate the most accurate measurements, less expensive and safe which represented by electronic meters. Then the researchers developed the methods of the transmitting data to the main monitoring and control unit, which were use wiring for data transmission and then evolved into wireless communication systems [4-6].

Electrical energy management system can be addressed as one of the developments in the electrical energy meters. An intelligent technique to detect any new devices installed in a smart environment is presented [7]. This technique capable to monitor and identify any load, but it is unable to accumulate power data. A smart home with a ZigBee-based power socket is constructed [8]. The weakness of this system is appearing in the measuring of the electrical energy consumption. Another system with a ZigBee-based smart power outlet network is proposed for gathering power consumption data [9, 10]. This system not has any protection in an emergency. A method that based on the ZigBee communication and infrared remote control is proposed to perform active control for reducing standby power using sensor information, but it lacks to overload protection and detection [11]. A ZigBee-based monitoring system with self-protection is constructed [12]. This system is equipped each power socket with an energy metering integrated circuit IC to compute power parameters from the socket. It produces a higher device costs and more complex circuit structure. In addition, they just focused on two sockets protection in a branch.

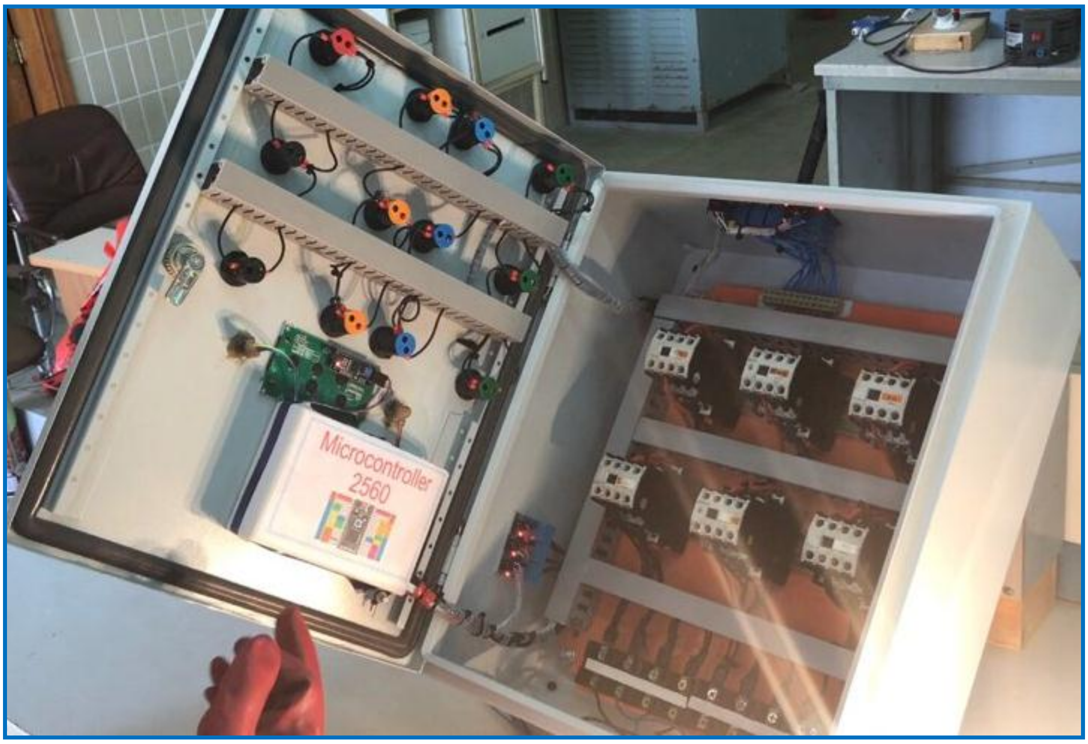
In this paper, the electrical energy management method has been designed and implemented to control, monitor, and save the electrical energy. A three-phase load balance system is constructed by replacing the loads of some power sockets while the energy measuring system gives an idea about the amount of consumed electrical energy. Finally, the proposed comprehensive system can be represented as a three phase load balance smart meter.

II. System Architecture and Operation

Load balance, power monitoring and controlling can be achieved by three-phase power management system (TPPMS). This section presents the architecture of TPPMS realization. Fig. 1 (a) shows the circuit diagram of TPPMS for one home while the realization of load balance system is shown in Fig. 1 (b). The following subsections describe the measuring module; the monitoring and the load balance modules where all installed in the main home breaker.



(a)



(b)

Fig.1. The three phase load balance system (a) The circuit diagram (b) The realization of three phase load balance system

A. The measuring module

The measuring module works as a three-phase metering circuit. The electrical power meter is designed to sense and measure the consumed electrical energy in home to provide a balance load for the three-phase supply and monitor the current, voltage and electrical power per hour. The design and implementation of the three-phase energy metering circuit is achieved by using an Atmega2560 microcontroller circuit. Three ZMPT101B voltage sensors are used in this module to measure the voltage of each phase of the three-phase supply as shown in Fig.2 (a). The current passes at each phase in this module is measured by using the ACS712 Fully Integrated, Hall Effect-Based Linear Current Sensor IC as shown in Fig.2 (b). This sensor has a copper conduction path. The current passes through this path produce a magnetic field that converts by the Hall IC into a proportional voltage.

a. The ZMPT101B voltage sensor. b. The ACS712 current sensor.

Fig.2.Voltage and current sensors.

Six current sensors are used in this system. Three of these sensors are connected directly to the three-phase supply to measure the total three-phase supply currents. The other three current sensors are connected across the three controllable loads to measure the three-phase current drown by these loads. The controllable loads have the ability to change their connections to the three-phase supply. The difference between the supply currents and the controllable load currents represent the currents drawn by the uncontrollable loads. By knowing the currents drawn by the uncontrollable loads we can rearrange the connection of the controllable loads in a manner that gives the best balance to the three-phase supply currents.

The electrical energy measurement in this module depends on the reading of both the current and voltage sensors. The real power is computed by taken the sum of the instantaneous values of current and voltage for several times and divide it by the number of these times [13].

$$W = \frac{1}{N}\sum_{j=1}^{N} v_j i_j \qquad (1)$$

Where v_j and i_j represent the instantaneous voltage and current at j time respectively. N is the number of period. Since the sampling rate of the voltage is V_{rms} and the sampling rate of the current is I_{rms} then the real power is computed by the following equation:

$$W = v_{rms} i_{rms} pf \qquad (2)$$

Where pf is the power factor. v_{rms} and i_{rms} are computed from the following equations:

$$v_{rms} = \sqrt{\sum_{j=1}^{N} \frac{{v_j}^2}{N}} \qquad (3)$$

$$i_{rms} = \sqrt{\sum_{j=1}^{N} \frac{{i_j}^2}{N}} \qquad (4)$$

B. The monitoring module

The monitoring module could monitor the current, voltage, power factor and electrical energy that consumed at each phase in main home breaker. The data which collected by the monitoring and control module are necessary to work of other modules and can be used to implement a smart meter system. The periodically monitoring of electrical energy consumed in home helps the customer to control and save the electrical energy. The HD44780 LCD has been used for the monitoring module which displays the information in 4 rows with 20 characters for each row.

C. The load balance module

The three phase load balance system is characterized by a three-phase balancing unit that represents the important part because it contributes in the load balancing of the three phase supply in order to reduce the probability of damages. This module can detect any device connected to the power outlet and then this module replaces the connection of this outlet to a suitable phase that satisfy the best balance among phases which, several contactors have been used for replacement process. If all homes in distribution station have the same balance system then this process make the load is balance which leads to prevent the phase fault, and also helps to use most of the electrical energy that generated by main station. Six relays (see Fig. 3) and six contactors are used in this module to swap three controllable loads (load A, load B and load C) among the supply phases as shown in Fig. 1. The relay boards are used as complete electrical isolation between the control signal and the controlled circuits.

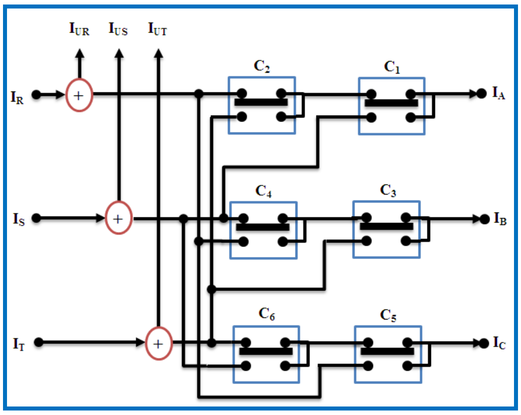
(a) Two channels (b) Four channels.

Fig. 3. The relay modules.

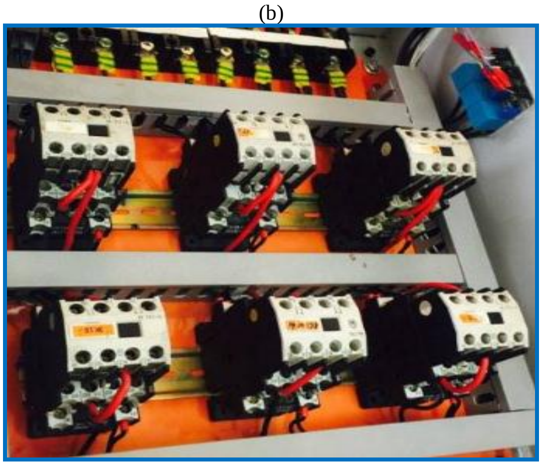
A contactor is an electrical control switch used for switching an electrical power circuit, similar to a relay except with higher current ratings. The contactor has four components (see Fig. 4 (a)): The contacts are the current carrying part of the contactor. This includes power contacts and auxiliary contact. The coil provides the driving force to close the contacts. Auxiliary Block this is for additional auxiliary contacts. Unlike general-purpose relays, contactors are designed to be directly connected to high-current load devices.

Fig. 4 (b), shows the block diagram for contactors (C_1, C_2, C_3, C_4, C_5 and C_6), where each two contactors are used to swap one of the controllable loads (A, B and C) among the three supply phases. The implementation of contactors board is shown in Fig. 4 (c).

(a)



(b)



(c)

Fig. 4. The contactors board. (a) The contactor (b) The block diagram (c) The contactors circuit implementation.

D. *The load balance algorithm*

This section describes the algorithm for measuring current, voltage, power factor, and electrical energy consumed by each phase. Also, this algorithm used to control the balancing of the three phase supply currents. The steps for investigation this algorithm is as follows:

1. Measuring the total current of each phase of the three phase supply I_R, I_S, and I_T. Assume load A is connected to phase R, load B is connected to phase S and load C is connected to phase T.
2. Measuring the voltage of each phase of the three phase supply V_R, V_S, and V_T.
3. Measuring the current of each the three controllable loads I_A, I_B, and I_C.
4. Calculating the currents of the uncontrollable loads.

$$\left.\begin{aligned} I_{UR} &= I_R - I_A \\ I_{US} &= I_S - I_B \\ I_{UT} &= I_T - I_C \end{aligned}\right\} \quad (5)$$

5. Construct the second column in table 1 which represents the connectivity between the supply phases and the controllable loads. This connectivity depends on all the predicated status of the contactors which shown in the first column.
6. Construct the index values (third column) according to the following equation.

$$Index = i + 4j + 16k \quad (6)$$

Where the variable i, j and k represent the status of contactors in load A, B and C. Values of these variable for each load are:

(0) for contactors status (C_2,C_4,C_6 = OFF, C_1,C_3,C_5 = OFF)

(1) for contactors status (C_2,C_4,C_6 = OFF, C_1,C_3,C_5 = ON)

(2) for contactors status (C_2,C_4,C_6 = ON, C_1,C_3,C_5 = OFF).

7. The total current of each phase at each row is computed in fourth column according to the contactors status in first column and the index value (third column). When any contactor is OFF then it represents by logic 0 else it represents by logic 1 as shown in first column in table 1. For each value of index the total currents for all phase are computed as follows:

$$\left.\begin{aligned} I_R(index) &= I_{UR} + NOT(C_1)NOT(C_2)I_A + C_4 I_B + C_5 I_C \\ I_S(index) &= I_{US} + C_1 I_A + NOT(C_3)NOT(C_4)I_B + C_6 I_C \\ I_T(index) &= I_{UT} + C_2 I_A + C_3 I_B + NOT(C_5)NOT(C_6)I_C \end{aligned}\right\} \quad (7)$$

8. For each index value compute the maximum and minimum values for the total currents.

$$Max(index) = Max(I_R(index), I_S(index), I_T(index)) \quad (8)$$

$$Min(index) = Min(I_R(index), I_S(index), I_T(index)) \quad (9)$$

9. For each index value compute the deviation D which represents the difference between maximum and minimum values.

$$D(index) = Max(index) - Min(index) \quad (10)$$

10. The minimum value from the deviation column in table 1 means the best case for balancing. The full balance is occurs when this value of deviation equal to zero.

Table 1. List all the contactors status to choose the best load balances.

Contactors status						Connectivity			Index	Total currents			Deviation
C_6	C_5	C_4	C_3	C_2	C_1	C	B	A		I_T	I_S	I_R	D
0	0	0	0	0	0	T→C	S→B	R→A	0	$I_{UT}+I_C$	$I_{US}+I_B$	$I_{UR}+I_A$	D(0)
0	0	0	0	0	1	T→C	S→B	S→A	1	$I_{UT}+I_C$	$I_{US}+I_B+I_A$	I_{UR}	D(1)
0	0	0	0	1	0	T→C	S→B	T→A	2	$I_{UT}+I_C+I_A$	$I_{US}+I_B$	I_{UR}	D(2)
0	0	0	1	0	0	T→C	T→B	R→A	4	$I_{UT}+I_C+I_B$	I_{US}	$I_{UR}+I_A$	D(4)
0	0	0	1	0	1	T→C	T→B	S→A	5	$I_{UT}+I_C+I_B$	$I_{US}+I_A$	I_{UR}	D(5)
0	0	0	1	1	0	T→C	T→B	T→A	6	$I_{UT}+I_C+I_B+I_A$	I_{US}	I_{UR}	D(6)
0	0	1	0	0	0	T→C	R→B	R→A	8	$I_{UT}+I_C$	I_{US}	$I_{UR}+I_B+I_A$	D(8)
0	0	1	0	0	1	T→C	R→B	S→A	9	$I_{UT}+I_C$	$I_{US}+I_A$	$I_{UR}+I_B$	D(9)
0	0	1	0	1	0	T→C	R→B	T→A	10	$I_{UT}+I_C+I_A$	I_{US}	$I_{UR}+I_B$	D(10)
0	1	0	0	0	0	R→C	S→B	R→A	16	I_{UT}	$I_{US}+I_B$	$I_{UR}+I_C+I_A$	D(16)
0	1	0	0	0	1	R→C	S→B	S→A	17	I_{UT}	$I_{US}+I_B+I_A$	$I_{UR}+I_C$	D(17)
0	1	0	0	1	0	R→C	S→B	T→A	18	$I_{UT}+I_A$	$I_{US}+I_B$	$I_{UR}+I_C$	D(18)
0	1	0	1	0	0	R→C	T→B	R→A	20	$I_{UT}+I_B$	I_{US}	$I_{UR}+I_C+I_A$	D(20)
0	1	0	1	0	1	R→C	T→B	S→A	21	$I_{UT}+I_B$	$I_{US}+I_A$	$I_{UR}+I_C$	D(21)
0	1	0	1	1	0	R→C	T→B	T→A	22	$I_{UT}+I_B+I_A$	I_{US}	$I_{UR}+I_C$	D(22)
0	1	1	0	0	0	R→C	R→B	R→A	24	I_{UT}	I_{US}	$I_{UR}+I_C+I_B+I_A$	D(24)
0	1	1	0	0	1	R→C	R→B	S→A	25	I_{UT}	$I_{US}+I_A$	$I_{UR}+I_C+I_B$	D(25)
0	1	1	0	1	0	R→C	R→B	T→A	26	$I_{UT}+I_A$	I_{US}	$I_{UR}+I_C+I_B$	D(26)
1	0	0	0	0	0	S→C	S→B	R→A	32	I_{UT}	$I_{US}+I_C+I_B$	$I_{UR}+I_A$	D(32)
1	0	0	0	0	1	S→C	S→B	S→A	33	I_{UT}	$I_{US}+I_C+I_B+I_A$	I_{UR}	D(33)
1	0	0	0	1	0	S→C	S→B	T→A	34	$I_{UT}+I_A$	$I_{US}+I_C+I_B$	I_{UR}	D(34)
1	0	0	1	0	0	S→C	T→B	R→A	36	$I_{UT}+I_B$	$I_{US}+I_C$	$I_{UR}+I_A$	D(36)
1	0	0	1	0	1	S→C	T→B	S→A	37	$I_{UT}+I_B$	$I_{US}+I_C+I_A$	I_{UR}	D(37)
1	0	0	1	1	0	S→C	T→B	T→A	38	$I_{UT}+I_B+I_A$	$I_{US}+I_C$	I_{UR}	D(38)
1	0	1	0	0	0	S→C	R→B	R→A	40	I_{UT}	$I_{US}+I_C$	$I_{UR}+I_B+I_A$	D(40)
1	0	1	0	0	1	S→C	R→B	S→A	41	I_{UT}	$I_{US}+I_C+I_A$	$I_{UR}+I_B$	D(41)
1	0	1	0	1	0	S→C	R→B	T→A	42	$I_{UT}+I_A$	$I_{US}+I_C$	$I_{UR}+I_B$	D(42)

III. Experimental Results

Two experiments are implemented to test the performance and accuracy of the load balance and monitoring system. The first experiment (see Fig. 5) is used to test the accuracy of the load balance system with respect to the laboratory reading. The experiment is repeated for different loads and the results recorded in three tables. The table 2 is for measuring the currents with respect to (Fluke 325) clamp meter which has 2% accuracy. The table 3 is to compare the voltage reading with respect to the (Fluke 83V) Industrial Multi-meter which has ±(0.5% + 2) accuracy . The table 4 is to compare the power factor and consumed power for different values of loads with respect to the (Fluke) wattmeter has ±(0.5% + 2) accuracy. All the results show that the designed system produces good accuracy with respect to the laboratory reading.

Table 2. Comparison the current reading of our system with the clamp meter.

Clamp meter (Amp.)	ACS712 Current Sensor (Amp.)
0.81	0.821
1.64	1.643
3.25	3.227
6.4	6.436

Fig. 5. The measuring of the currents, the voltages, the power and the power factor.

Table 3. Comparison the voltage reading of our system with the voltmeter.

	Voltmeter (V)	AC Voltage sensor (V)
Phase 1	219.5	220
Phase 2	218.7	218
Phase 3	219.9	219.5

Table 4. Comparison the power reading of our system and the Wattmeter.

Wattmeter reading		Smart meter	
Power / phase (Watt)	Power factor	Power / phase (Watt)	Power factor
95	0.952	94.05	0.95
190.2	0.951	188	0.948
376.02	0.947	357.1	0.944

The second experiment (see Fig. 6) is to test the performance of the designed balance system with respect to number of controllable loads. That is mean, the experiment is repeated for different number of contactors since each controllable load needs two contactors for swapping among supply phases. Fig. 7 shows that as the number of controllable loads increases the currents balancing among supply phases also increase. From this figure we found that five controllable loads give about 90% currents balancing accuracy and 100% accuracy needs more than five controllable loads. The increasing of the controllable loads leads to increase the cost because the numbers of contactors also increase.

Fig. 6. The performance analysis for different number of controllable loads.

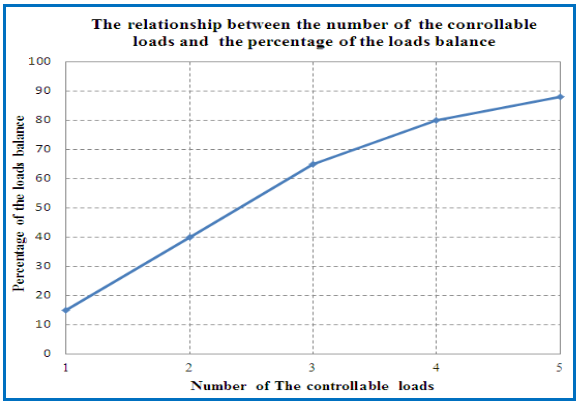


Fig. 7. The percentage of loads balance with respect to the number of the controllable loads.

IV. Conclusions

In this paper a proposed system for measuring, balancing and monitoring the three-phase supply in smart meter is introduced. This system has a good accuracy with respect to the laboratory reading when measuring the three-phase currents, voltages, powers and power factor. This system investigates the load balancing with a good percentage when used three controllable loads. The measuring system helps the user to take an idea about the amount of kilowatt hours consumed by customer that helps to take a right decision to minimize the using of electrical energy and also, it is useful in design a smart meter for each home. The designed system has the feature to use the local wire for each power socket in main electricity circuit. This means we not need to use a wireless system to transfer the measuring data to main control system.

This system can be scalable to balance the loads on the reign power transformer by applying it on all the homes connected to this power transformer. This process helps to reduce the occurrences of phase fault and helps to balance the loads on the main power station.

V. Acknowledgment

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