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Smart Control System for Electrical Current and Energy Consumption Limiter

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***Abstract*—This study designs an electronic smart control system to replace thermal and electromagnetic circuit breaker, as well as traditional energy meter. With voltage and current sensors, several values can be calculated. RMS value of voltage and current are the first result, followed by power factor, load, and energy consumption. This system produced 3-channel line output that can be controlled by means of current and energy consumption. According to all testing, it is known that the device developed based on the system can perform measurements into acceptable accuracy. The RMS value of voltage measured is as accurate within 0.5% of its maximum capacity. In the other side, all channels have current RMS value accuracy of 0.3%. Both parameters reach such accuracy thanks to the 1-millisecond resolution of sensors acquirement. The power factor can also be measured as accurate as 2% according to cos phi meter with resolution of 0.01. The combination of those accuracy resulting in current limiter and energy consumption limiter within very small resolution. For energy consumption average error, it displays 2% as the accuracy. Current limiter can be achieved automatically and dynamically with response time under 50 milliseconds. The energy consumption limitter operated in resolution below 0.001 kilowatt-hour. All testing result indicates that the goal of the research is achieved.**

Keyword: current limiter, energy consumption limiter, power factor, smart device.

I. INTRODUCTION

Today the majority of the system of distributing and limiting electricity to households or small businesses applies static methods. The current limiter used in the kWh meter (the customer's installation connection center point) uses a circuit breaker with a certain nominal limit. The current limiter in the split circuit also uses several circuit breakers in the distribution channel with a certain limit, each of which is smaller than the limiter at the center point, but has a collective capability that is often greater than that of the center point limiter. This allows for a circuit break at the center point before each delimiter in the distribution channel breaks. This condition will reduce the performance of small businesses, which will be inefficient in terms of costs if they add power to the connection contract. [1] [2] [3]

The use of static current limiter will not solve the problem. Adjustment of the power limiter for each channel so that the total limit does not exceed the limiter at the center point can be done. However, in certain conditions where several channels require a higher power limit priority, this method cannot be applied. [4] [5]

To provide a solution to this case, dynamic current limiting is carried out. This method uses a system that has the ability to detect the current being supplied to each channel, and can then disconnect channels that could potentially overload the center point, thereby avoiding a complete cutout of the power supply. Each existing channel is given a certain priority value to distinguish groups that are important and those that are less important.

A tool for monitoring and management of sharing and limiting power and electrical energy will be developed with a dynamic system. This device will be equipped with an electronic limitation setting for each channel, so that if there is a change in load priority or a change or change in the load limit of each group, it can be done quickly without changing the circuit physically. In addition, the device being developed will be able to monitor the voltage, current, power, and electrical energy consumption of each channel. Thus, this device will also be able to be used to regulate the quota of electrical energy consumption which will automatically break the circuit if the energy consumption exceeds the set quota. The monitoring process and settings on these devices can be done remotely using SMS media. The development of the device will be carried out using a microcontroller as a control device.

Based on the background, this research has several problems that will be examined, including:

1. How to monitor loads and electricity consumption using voltage and current parameters.
2. How to perform electronic disconnection and circuit connection management based on the measured load or the amount of electrical energy consumed.
3. How to program to apply different priorities to channels, apply maximum load to each channel, monitor circuit load, monitor circuit electrical energy

consumption, break the circuit, and reconnect the circuit.

4. The extent to which management of distribution and limitation of electric power dynamically is able to avoid breaking the whole circuit and is able to control the consumption of electrical energy in each channel.
5. How to provide remote monitoring and management capabilities using SMS media.

Therefore, there are two goals of this study, the first is to design and develop a monitoring and management tool for the distribution and limitation of single-phase power and electrical energy in priority groups with remote capability using SMS media; the second is is to test the performance of monitoring and management tools for sharing as well as limiting one-phase power and electrical energy in priority channel through short distances (control panel) and long distances (SMS media).

II. THEORETICAL BASIS

A. Alternating Current (AC)

In contrast to direct current (DC) electricity, alternating current (AC) electricity is the flow of electricity that changes its current direction periodically. Usually the frequency of changes in the direction of the current has a standard of 50 Hz or 60 Hz. In the electricity network system in Indonesia, the nominal voltage system used is 380 V (three phase) and 220 V (single phase) with a frequency of 50 Hz.

B. Calculation of AC Power

Voltage is energy per unit charge, while current is charge per unit time. So that the power or electrical energy per unit time on a resistance can be expressed as in Eq (1).

$$p = vi = I^2 R = \frac{v^2}{R} \tag{1}$$

For voltage and current varying sine, the instantaneous value of the power is also periodic. Therefore, the power of alternating electricity in a resistance can be expressed in Eq. (2). The effective value of this power is calculated by means of root means square method (RMS). [5] [3]

$$P = \frac{1}{T}\int_t^{t+T} i^2 R \, dt = I^2 R = \frac{V^2}{R} \tag{2}$$

This current or voltage value is most widely used and is written without an RMS postfix. [1] [2] [3]

C. Complex Power System and Power Factor

The power triangle is a way of describing complex power. Power in alternating current can be described as complex power, where the actual components represent active power (the power absorbed by the device and do useful work), and the imaginary components represent reactive power (power that is useless and returned back to the source). Fig. 1 shows an illustration of the power triangle.

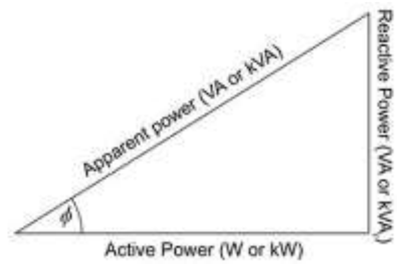

Figure 1. Power triangle.

Eq. (3) through Eq. (6) show the relationship between the components in the power triangle.

$$\boldsymbol{S} = P + jQ \tag{3}$$

$$|S|^2 = P^2 + Q^2 \tag{4}$$

$$P = Re[\boldsymbol{S}] = |S| \cos \varphi \tag{5}$$

$$Q = Im[\boldsymbol{S}] = |S| \sin \varphi \tag{6}$$

Active power is represented by P, while reactive power is represented by Q. Complex power is represented by S, while apparent power is the absolute value of complex power. The power factor is symbolized by cos φ where φ is the angle at which the current lags against the voltage.

The power factor, in this case, is a quantity of 1 when the load is purely resistive, where all the absorbed power is used to do useful work. When the load is capacitive or inductive, the power factor can be anywhere from 0 to 1. When the power factor is 0, the active power is not present, or in other words, all the apparent power supplied to the device is completely converted to heat. [1]

D. Electric Current Limiter

The unit of current is amperes, while the power unit is volts ampere. Therefore, the electric current limiter uses amperes. The use of constraints is referred to as determining user requirements. The maximum trip current of the fuser or breaker used as the limiter is set at 10% above the nominal current of the protected equipments. The use of a limiter is as one of the interfaces between electrical company and the customer. In case of the customer uses excess power, the limiter will disconnect the circuit.

Figure 2. Electric current limiting device, combination of thermic and electromagnetic type.

The types of electric current limiting devices that are most widely used are the thermic and electromagnetic types. Several types of barriers consist of one-pole, two-pole, and three-pole barriers. [4]

E. Control System

A control system is a system consisting of a set of devices that manages, directs, directs, or regulates the behavior of other devices or systems to achieve the desired requirement [6]. In addition to getting input in the form of a set of commands from the operator, the control system also analyzes the feedback of the object's action to correct (provide correction) for errors that arise, a main characteristic of the closed loop control system [7] [8].

A control system has four functions, namely measuring, comparing, calculating, and improving. The four functions are carried out by five elements, namely the detector, transducer, transmitter, controller, and final control element [8]. The measurement function is carried out by the detector, transducer, and transmitter, which are usually in the practical application of all three elements in one unit. The comparison and calculation functions are carried out by the controller. While the repair function is carried out on the final control element [7] [9].

Control system accomplishment can be measured by several criteria [8]:

- Overshoot and undershoot;
- Ringing;
- Steady state;
- Steady state error (error band);
- Rising time; and
- Settling time.

F. Microcontroller

Microcontroller is a complete microprocessor system that is contained on a chip. Microcontrollers are different from multipurpose microprocessors used in a PC, because in a microcontroller generally also contains minimal microprocessor system supporting components, namely memory and input-output interface, whereas in microprocessors generally only contain CPU (central processing unit) [10] [6] [11].

Unlike a multipurpose CPU, a microcontroller does not always need external memory, so the microcontroller can be made cheaper in smaller packages with fewer pins. This research uses Arduino Mega 2560 as the microcontroller, which has 54 digital pins, 16 analog pins, and 256 kilobytes of memory [12].

G. AC Voltage Sensor

A voltage sensor is a device that is able to detect the voltage that occurs between two points, then it is converted into a control signal in the form of a low voltage whose value is proportional to the magnitude of the voltage. There are two types of voltage sensors, first using a transformer, and second using a resistor. For voltage sensors that use a transformer, basically reduce the voltage to half of the control voltage, then increase the offset by half of the control voltage, so that a miniature DC signal that resembles the original AC voltage is obtained but only has forward potential.

Voltage sensors that use transformers can only be used for AC voltages. Meanwhile, a voltage sensor that uses a resistor can be used for AC or DC, because it basically reduces the voltage with the principle of voltage dividing. However, the use of voltage dividing devices on high voltage raise concern over the excessive heat produced by Joule heating principle.

Figure 3. Transformer type AC voltage sensor, ZMPT101B.

In this study, a transformer type voltage sensor with the ZMPT101B series is used as shown in Fig. 3. This voltage sensor is capable of detecting an effective voltage of up to 250 V AC (RMS value).

H. Electric Current Sensor

A current sensor is a device that detects an electric current in a conductor and produces a signal proportional to the magnitude of the current. The signal generated can be in the form of an analog or digital voltage, which can be further processed or simply displayed on a display. The detected electric current can be either direct current (DC) or alternating current (AC).

Figure 4. Hall Effect current sensor, ACS712.

In this study, electric current sensors will be used in the form of a device with the ACS712 series capable of detecting AC electric currents with a maximum capacity of 20 A (peak-to-peak), as shown in Fig. 4. Hence, its maximum capacity in RMS value is 14.2 A. The electric current sensor uses the Hall Effect principle to convert the current into a DC control voltage.

III. Methods of Research

A. Steps of Study

Illustration of the flowchart of the research methods is presented in Fig.5. In accordance with the flowchart, the steps undertaken in this study are as follows:

1. Literature Study.
2. Design of Control System.
3. Design and Development of Main Device.
4. Testing of Device.
5. Analysis of Testing Result.
6. Checking Specification.
7. Conclusion.

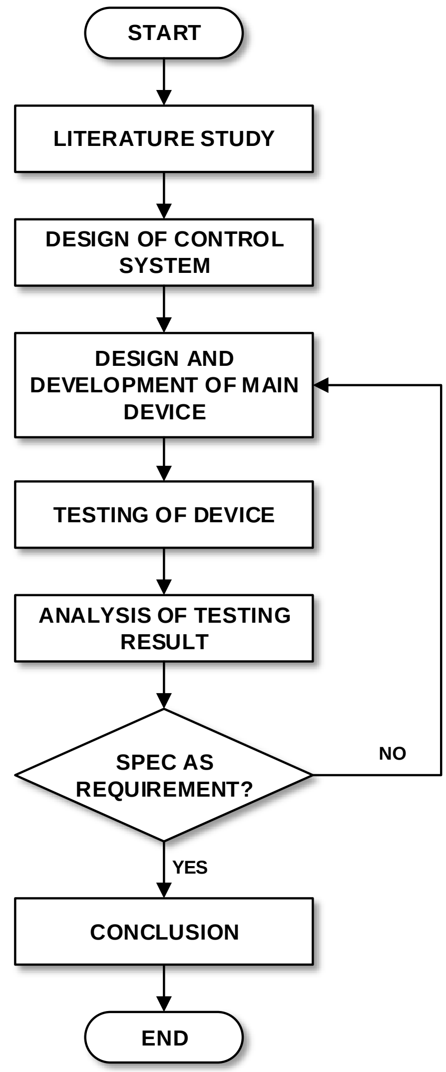

Figure 5. Flowchart of the research methods.

B. Diagram of Research Design

In the concept design of the devices to be built, as seen on Fig. 6, the red entity is related to electric power, the blue entity is related to the control device, and the green entity is the external part that interacts with the system through the interface. The red line represents the flow of electricity with a voltage of 220 V AC, while the green line represents the flow of electricity with a voltage of 12 V or 5 V DC. The blue line represents the direction of the control signal, and the brown line shows the interaction with the outside (operator).

In general, the microcontroller receives settings from the operator and is stored in memory for further use. These settings include overall power capability, power capability for each channel, priority for each channel, electrical energy quota for each channel, reconnection delay time, and reconnection difference. 220 V AC electricity from the main line is connected to the voltage sensor and forwarded to the relay module. Each of the relay modules will forward the flow of electricity to the current sensor, before being forwarded to the channels. The power supply used is also supplied from the main line.

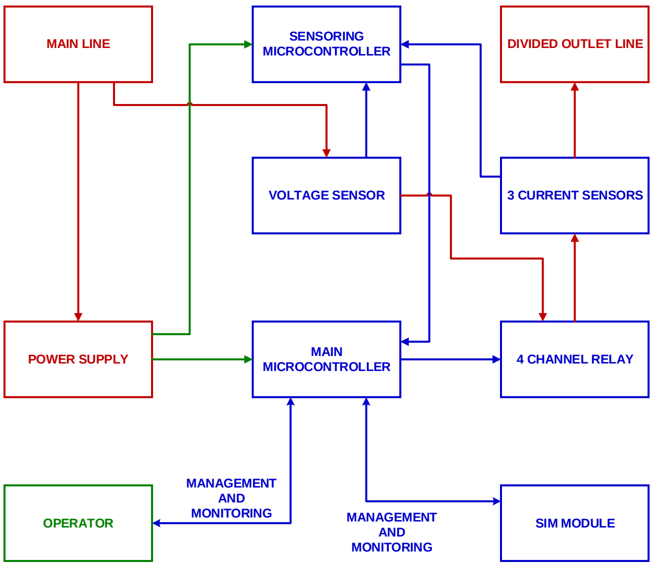

Figure 6. General diagram of smart electric current limiter and management.

The power supply will output DC electricity with a voltage of 12 V and 5 V (through a regulator), which is channeled to provide power to the microcontroller, voltage sensor, current sensor, and relay module. Based on input from the voltage sensor and current sensor, it is known that the load power is currently active.

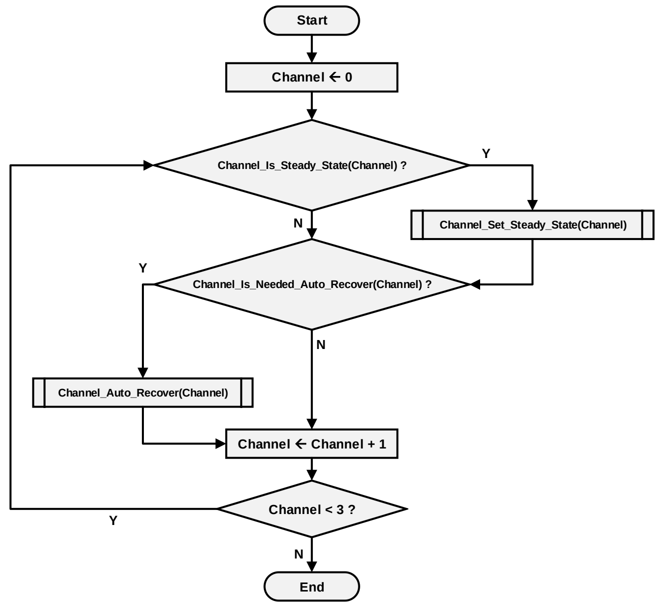

Figure 7. The main algorithm of smart current limiter and monitoring.

As seen on Fig. 7, the microcontroller will compare the overall load with the allowable load on the currently active option. If an overload occurs, the microcontroller will disconnect the channel starting from the one with the lowest priority to the highest priority. After a disconnection occurs, if the residual load plus the interrupted load is projected to not exceed the predetermined limit, then the disconnected load will be reconnected after the specified delay time. In addition, if the quota of one of the channel has been exceeded by its consumption, the channel will be automatically disconnected.

The device will also monitor the profile of voltage, current, power, and electrical energy consumption on each channel. If a USB cable connection is detected with a PC or laptop and the data logger software is active, the monitor data will be streamed to the PC. The monitoring process and the regulatory process can also be carried out by operators remotely, using SMS media via the SIM900A module.

TABLE I. THE IPO DIAGRAM OF THE SMART CURRENT LIMITER AND MANAGEMENT SYSTEM

Input	Process	Output
• Effective voltage (RMS). • Effective current (RMS) of every channel. • Setting.	• Channel connection based on setting. • If effective current below maximum, then no action taken. • If effective current between maximum and overload, then activate the delay integral countdown. • If delay integral reaches zero, then disconnect the channel. • If effective current above the overload, then disconnect the channel.	• Circuit connection of every channel.
• Power factor of every channel. • Setting.	• Channel connection based on setting. • If power factor drop below minimum, then disconnect the channel.	• Circuit connection of every channel.
• Energy integral of every channel. • Setting.	• Channel connection based on setting. • If energy consumption approaching quota, then sound the alarm. • If energy consumption reaching quota, then disconnect the channel. • If set by operator, then reset the quota.	• Circuit connection of every channel.

A diagram of input, process, and output is presented by Table 1, that contains correlation between inputs and outputs as well as all of the process.

IV. RESULTS AND DISCUSSIONS

A. *Testing of the Effective Voltage and Effective Current Measurement*

Effective voltage shown in the display is the RMS value. Every testing conducted, the display value is compared to the reading true-RMS multimeter. As long as the value tested is voltage, then the connection is simply put the probes in parallel with the line. Voltage value displayed on the device has resolution of 1 volt.

TABLE II. TESTING OF THE EFFECTIVE VOLTAGE DISPLAY

Time of Day	Device Reading (volt)	Multimeter Reading (volt)	Error (% of 250 volt)
06:00	215	216	0.4
12:00	210	212	0.8
15:00	212	214	0.8
18:00	203	204	0.4
22:00	206	206	0.0
00:00	218	219	0.4
Mean of Error (% of 250 volt)			**0.5**

As of Table I, it is known that the displayed value on the device deviates 0.5% from its maximum measurement capability.

TABLE III. TESTING OF THE EFFECTIVE CURRENT DISPLAY

Channel	Device Reading (amp)	Multimeter Reading (amp)	Error (% of 14.2 amp)
1	1.5	1.6	0.7
1	3.0	3.0	0.0
1	8.2	8.3	0.7
2	1.5	1.6	0.7
2	3.0	3.0	0.0
2	8.3	8.3	0.0
3	1.6	1.6	0.0
3	3.1	3.0	0.7
3	8.2	8.2	0.0
Mean of Error (% of 14.2 amp)			**0.3**

For current testing, there are three types of electric appliances used, namely 350-watt heater, 650-watt stove, and 2-hp air conditioner. To test the current, a series connection is made on the wire to the AC current true-RMS multimeter probes. Electric current vealue displayed on the device has resolution of 0.1 ampere. The average of error of the device in reading the current is 0.3% from its maximum RMS value measurement of 14.2 amperes, as shown in Table II.

B. *Testing of the Power Factor Measurement*

As result of new algorithm implemented on the sensor microcontroller, power factor (cos phi) of each channel can be measured. The resolution of power factor measurement is 0.01 in this device. By using a digital cos phi meter as reference, each channel are tested for power factor measurement accuracy. The power factor testing is using three types of electric appliances as used in current testing.

TABLE IV. TESTING OF THE POWER FACTOR DISPLAY

Channel	Device Reading	Cos Phi Meter Reading	Error (%)
1	1.00	0.99 lag	1
1	0.95 lag	0.92 lag	3
1	0.89 lag	0.85 lag	4
2	1.00	0.99 lag	1
2	0.94 lag	0.91 lag	3
2	0.86 lag	0.85 lag	1
3	1.00	1.00	0
3	0.94 lag	0.92 lag	2
3	0.88 lag	0.85 lag	3
Mean of Error (%)			**2**

All testing result of power factor reading shows error of about 0% to 4%. Note that power factor is a dimensionless value with two direction of reading toward 1, namely lagging and leading. Therefore, according to the result on Table III, the average error for power factor reading is 2%.

C. *Testing of Energy Consumption Measurement*

The energy consumption measurement display of each channel of the device can be switched to three types: watt-second, watt-hour, dan kilowatt-hour. All measurement has internal resolution of 1 watt-second (0.000277778 watt-hour or 2.77778E-7 kilowatt-hour). The display for these three types, however, have resolution of 1 watt-second, 0.1 watt-hour, and 0.001 kilowatt-hour, respectively.

Since the kWh meter used for reference has 0.001 kilowatt-hour resolution, and the three types of display has single internal resolution, then the testing is conducted in kilowatt-hour type. For each channel, the testing for this power factor are conducted by:

1. A 350-watt heater running for 2 minutes (exactly 120 seconds), called testing A, theoretically 11.6 watt-hour.
2. A 650-watt stove running for 2 minutes (exactly 120 seconds), called testing B, theoretically 21.6 watt-hour.
3. A 2-hp air conditioner running in cooling mode for 2 minutes (exactly 120 seconds), called testing C, theoretically 49.7 watt-hour.

TABLE V. TESTING OF THE ENERGY CONSUMPTION DISPLAY

Channel	Testing Label	Device Reading (kWh)	kWh Meter Reading (kWh)	Error (% of 1 kWh)
1	A	0.013	0.015	2
1	B	0.021	0.026	5
1	C	0.057	0.061	4
2	A	0.012	0.012	0
2	B	0.023	0.025	2
2	C	0.060	0.062	2
3	A	0.013	0.012	1
3	B	0.024	0.025	1
3	C	0.061	0.064	3
Mean of Error (%)				**2**

Based on Table V as result of the energy consumption measurement, it is found that the device has average error of 2% on each channel.

D. Testing of Current Limiter and Energy Consumption Limiter

The final testing for this device are current and energy consumption limiter based on setting and measurement. Current limiter should work in two manners: one in between maximum and overload current the disconnection must occur in a matter of 5 seconds to 10 seconds mimicking thermal trip, and one above overload current the disconnection must occur in less than 50 milliseconds mimicking electromagnetic trip.

Method to measure trip time in less than 1 second can not be conducted with stopwatch since it needs human operator (which is barely inaccurate). Therefore, disconnection action below 1 second can be categorized as “instantaneous” or “less than 1 sec” in this testing.

The testing for current limiter sets 2.0 amperes for maximum current and 2.5 amperes for overload current. The setting identically duplicated for all channels. It used electric jigsaw machine which consume 0 watt to 600 watts according to the speed. In top speed, theoretically it draws 2.7 amperes which 0.2 ampere higher than overload limit. For each channel, the testing for this current limiter are conducted within three scenarios:

1. Testing A, speed is set so that the current shows below 2.0 amperes.
2. Testing B, speed is set so that the current shows between 2.0 amperes and 2.5 amperes.
3. Testing C, speed is set to maximum so that the current shows above 2.5 amperes.

TABLE VI. TESTING OF THE CURRENT LIMITER

Channel	Testing Label	Last Current (ampere)	Trip Time (second)	Within Specification
1	A	1.2	N/A	Yes
1	B	2.3	6	Yes
1	C	2.5	< 1	Yes
2	A	1.5	N/A	Yes
2	B	2.2	6	Yes
2	C	2.5	< 1	Yes
3	A	1.3	N/A	Yes
3	B	2.2	8	Yes
3	C	2.6	< 1	Yes

As shown in Table VI, all current limiter testing passed on every channel as required by specification.

For energy consumption limiter testing, the quota will be set to a very small value to mimic the consumption accuracy. Resolution of 1 watt-second is very small compared to everyday experience. It equals 2.77778E-7 kilowatt hour, while 1 kilowatt-hour energy price in Indonesia is below $1. The testing is to measure quota remaining after the device disconnects specific channel. Ideally, the quota remaining will be zero after the channel disconnect. However, in reality, the quota will be dropped below zero (negative value) because the rate of consumption so high compared to the resolution. For instance, 350-watt heater will consume 350 watt-second in one second, so if the response time for the device is 50 millisecond, then it will run 17.5 watt-second below zero before the disconnection occur, resulting in -18 watt-second quota remaining.

TABLE VII. TESTING OF THE ENERGY CONSUMPTION LIMITER

Channel	Testing Label	Quota Remaining (Ws)	Quota Remaining (kWh)
1	A	-20	-5.5556E-6
1	B	-35	-9.7222E-6
1	C	-115	-3.1944E-5
2	A	-18	-5.0000E-6
2	B	-34	-9.4444E-6
2	C	-102	-2.8333E-5
3	A	-18	-5.0000E-6
3	B	-38	-1.0556E-5
3	C	-124	-3.4444E-5

As shown in Table VII, all the quota remaining is below 0.001 kWh, indicates that it fall inside specification.

E. Testing Result Analysis

According to all testing, it is known that the device developed based on the system can perform measurements into acceptable accuracy. The RMS value of voltage measured is as accurate within 0.5% of its maximum capacity. In the other side, all channels have current RMS value accuracy of 0.3%. Both parameters reach such accuracy thanks to the 1-millisecond resolution of sensors acquirement.

The power factor can also be measured as accurate as 2% according to cos phi meter with resolution of 0.01. The combination of those accuracy resulting in current limiter and energy consumption limiter within very small resolution. For energy consumption average error, it displays 2% as the accuracy. Current limiter can be achieved automatically and dynamically with response time under 50 milliseconds. The energy consumption limitter operated in resolution below 0.001 kilowatt-hour. All testing result indicates that the goal of the research is achieved.

V. Conclusions

From the results of the research conducted by testing and analysis, the following conclusions can be drawn:

1. Monitoring of current and energy consumption can be achieved using voltage and current sensors, within resolution of 0.3% and 2%, respectively, as required by mentioned specification..
2. Circuit disconnection and reconnection can be easily achieved based on load and quota of energy. It suggests that the electronic limiter can replace electro-thermal circuit breaker with better performance.
3. Locally disconnection of every channel saves all network from total disconnection. This feature can be achieved only in electronic limiters.

VI. Future Scopes

For the future development and improvement, this system should be applied for more outlet channels by choosing high speed microcontroller or field programmable gate array. In case for increasing channel number without better performance microcontroller, a stacked microcontroller system might be applied.

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