Design and Evaluation of Low-Cost Load Monitoring and Control Modular Board using MQTT Protocol

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ABSTRACT

This paper proposes a modular and economical design and development of a circuit that could measure monitor and control electrical power consumption for homes, offices, or industrial plants. The proposed circuit was designed and developed using the Node MCU ESP8266 and Tasmota firmware with the MQTT protocol. The hardware circuit consisted of two circuits: the main circuit with a processor and a port for communication; and the expander circuit with 16 channels applicable for both digital and analog inputs. Power and power quality measurement utilized a digital AC power measurement module PZEM004TV3 and a ACS712 current sensor. The data was sent to display through the platform Home Assistant program with the MQTT broker installed on the Raspberry Pi board. The analysis and tests of the developed circuit showed that the circuit could measure and control the power consumption as designed, having the ability to operate in a modular manner. The investment cost was 412.5–931 Baht (11.3 – 25.4 USD), 2–5 times less expensive than the existing circuits in the marketplace, and the capability of long-distance data transmission. The accuracy and completion of the transferred data was more than 98.36% with a low average power consumption of 8.5 watts and achieved 1.64% higher power quality estimation accuracy than the standard equipment. The advantages are easy to connect to various platforms, economical price, can add measurement circuit. Note that a server is required for the MQTT protocol.

Keywords: Load monitoring board, MQTT Protocol, Tasmota firmware

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Introduction

Technology and innovation advancements allow humans' daily life to be more convenient and precise than in the past. This also accounts for the way of using and controlling electricity. In the past, it seems that only the on-off switching via a timer should be sufficient for the optimum control of electricity usage. At present, the complexities of the electricity networks due to the variety of power sources (i.e., solar and wind power, etc.) and loads (i.e., electric vehicles, etc.) that are connected to the power grid authority leads to the need for the smart devices or systems to monitor and control the reliability of the electricity [1]. Internet of Thing (IoT) is smart technology for many applications. IoT allows electronic devices to display, link, or transmit information to each other via the internet and command or control [2]. Many devices have become more intelligent as smart devices, such as heart rate or body temperature measuring and monitoring via a mobile phone [3]. Therefore, IoT could be useful for monitoring and controlling the electricity, i.e., voltage, current, power, etc., used by the loads [4]. However, smart load monitoring and control devices have some limitations in usage because of their relatively expensive and require high technical skills for their operation and maintenance [5]. These issues become a challenge for researchers to determine suitable solutions. Fortunately, high precision and resolution would not be necessary in some power monitoring and control applications. The estimated or calculated data/information would be enough for their proper operations. For example, the applications that only the primary data collection are needed for the analysis or maintenance purposes on a regular basis [6-8].

The Message Queue Telemetry Transport (MQTT) Protocol, the telecommunication technology, was invented by Andy Stanford Clark of IBM and Arlen Nipper of Eurotech in 1999 to apply oil pipe valve control [9]. The communicated data were the data along a 17-kilometer-long oil pipeline. All data must be transmitted via the satellites that remember the leased data's usage rate. The problem arose in the cost of data communication. Therefore, to overcome this problem, Message Queuing Telemetry Transport (MQTT) protocols have been developed to reduce these costs. This MQTT Protocol consists of 2 devices: [10].

1. Clients: clients can be either a publisher or subscriber or publisher/subscriber simultaneously and on any device. The MQTT client library can be run on the TCP/IP stack. MQTT uses the publish/subscribe model. Most of the logics then fall on the broker side, making the library small and easy to install and compatible with devices with limited resources. The clients need to keep the TCP connection open so the broker can push the message. If the connection is disconnected, the broker keeps all incoming messages until the clients return online.

2. A broker: a broker is a central point of sending and receiving messages between clients. The routing method is done via topic by the client subscriber to the topic of their choice, and then the broker sends all statements published on that topic [11-13].

This research proposes the design and construction of modular power monitoring and control circuits that, in the future, must be able to add peripherals. It is economical to transmit long-distance data that can be used with standard sensors on the market and the MQTT protocol communication in conjunction with the Tasmota firmware [14]. By displaying those data via the Home Assistant [15], the prototype and the device design are presented in Section 2. Test methods and related results in Section 3. Analytical results in Section 4; following by the summary and discussions in Section 5.

Configurations of the Proposed Board

The designed configurations of the proposed board are presented in this section: the hardware circuits, the software programming, and the experimental test rig. The details are as follows:

1. Hardware Configurations

The designed hardware circuit consists of 2 sub-circuits: the main circuit and the expansion circuit; the main circuit comprises the processor and control unit while the expander circuit comprises the connection ports and an amplifier circuit with totally 16 digital and analog channels. Configurations of these circuits are described as bellows.

1.1 Configurations of the Main Circuit

The primary circuit of the proposed load monitoring and control board consists of the following components:

(1) as MCU an ESP8266 module

(2) VCC input power supply for the control board

(3) Connectors to the expansion board (I2C)

(4) 1 Analog channels

(5) 1 Digital inputs/output

(6) I2C connector

(7) UART connector

The above components are connected as shown by the simple block diagram in Figure. 1. The core component for this circuit is the MCU (microcontroller unit) which is the ESP8266 ESP-12E Wi-Fi Module. This module is best suitable for Internet of Thing (IoT) due to its low cost, and low power consumption capability as it requires only 3.3volt, 300-350mA, built-in Wi-Fi module, integrated TCP/IP protocol stack, ease to flash and erase firmware and USB powered. As the IoT application, this module can deploy in-home automation, home appliances, industrial wireless networks, and sensor networks fields [16].

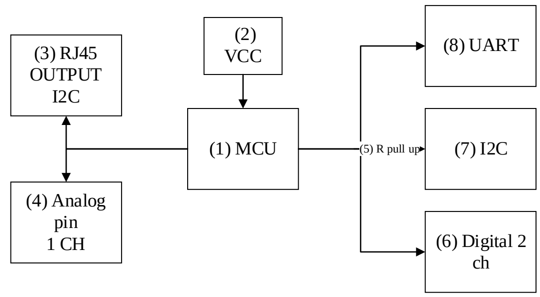


Figure 1 Block diagram of the components in the main circuit

1.2 Configuration of the Expansion Circuit

In most practices, the number of sub-circuits for the load monitoring and control board used in many manufacturers can be varied such 2, 4, 6, 8, 10, 12, 15, 16, and 20 circuits. The proposed board was therefore designed by using the average number of 8 sub-circuits. Therefore, the expansion board was required for the main board and had 8 current measurements and 8 control signals as shown in Figure. 2. The designed extension board consisted of the following main components:

(1) I/O analog consisted of 2 ADS1115 modules, which could be added upto 8 channels for I/O analog. The assign pin for power supplies feature made the board easily used in the compact slots; thus, the referred slot was used to select the address of the ADS1115 module and the I2C unit.

(2) Digital I/O connector consisted of one PCF 8574 module, which could add up to 8 channels and sophisticated slot connection capability similar to the I/O analogs.

(3) Connection channels were designed to have 2 channels to be connected: a channel expansion board or control board.

This research selected and used the ACS712 current sensors due to their economical and precise solutions for both AC and DC sensing for industrial, commercial, and communication systems. The device package was easy to implement. Typical applications include motor control, load detection and management, switched-mode power supplies, and overcurrent fault protection [17]. In addition, the PCF8574, 8-bit input/output (I/O) expander for the two-line bidirectional bus (I2C) was designed for 2.5-V to 6-V VCC operation. The PCF8574 device provided general-purpose remote I/O expansion for most microcontroller families using the I2C interface [serial clock (SCL), serial data (SDA)]. The device had an 8-bit quasi-bidirectional I/O port (P0–P7); including latched outputs with high current drive capability for directly driving LEDs. Each quasi-bidirectional I/O could be used as an input or output without a data-direction control signal. At power on, the I/Os are high. In this mode, only a current source to VCC was active [18].

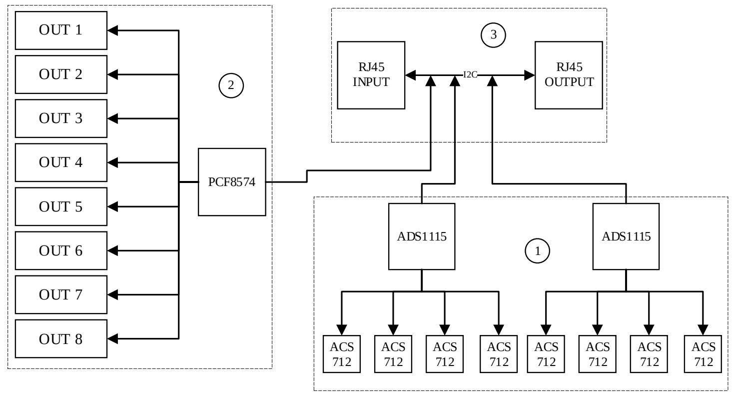


Figure 2 Block diagram of the components in the expansion circuit

2. Software Configurations

There were 2 main components were used for the software parts of the proposed load monitoring and control board: the Tasmota Firmware and MQTT protocol. The detailed structures are as follows:

2.1 Tasmota Firmware

Tasmota firmware is a free opensource firmware that operates well with the MQTT protocol. This firmware can be added to the program library directly by being added inside the Firmware itself, Tasmota can be downloaded from https://github.com/arendst/Tasmota.git. In this research, the firmware required a program library since the digital analog circuit (ADS1115) and the digital circuit (PCF8574) were not yet included in the initial program library, which could be added to the definition programming part, i.e., user_config_override.h file, by adding the following syntax lines [19]:

```
#define USE_I2C
#define USE_PCF8574
#define USE_PCF8574_SENSOR  #defineUSE_PCF8574_MQTTINPUT
#define USE_ADS1115 command
```

2.2 MQTT Protocol

The MQTT protocol connection settings could be set up by starting at the menu 'Configuration' first and then to Configure MQTT and set up by broker host, which was the address of the MQTT broker used to connect. In this research, we fix the MQTT Broker IP address at 192.168.0.104, as shown in Figure. 3. The Port MQTT was set as a channel to connect to the MQTT protocol, i.e., 1883. When the connection was successful to the console to activate MQTT using the set option command 19 = 0, when connecting successfully, the result could be observed on the Generic Loadcenter screen [19], as shown in Figure 3.

Figure 3 Setting up MQTT protocol connection in Tasmota firmware [20]

3. Experimental Test Rig

Figure 4 and Figure 5 show the prototypes of the primary circuit, the expansion circuit, and the experimental test rig of the proposed load monitoring and control board according to the explanation in Sections 2.1 and 2.2, respectively, while Figure. 6 shows the overall experimental test rig under this research. The primary and expansion circuit prototypes achieved compact and small sizes of less than 7 x 8 cm and 7.5 x 16 cm surface areas, respectively.

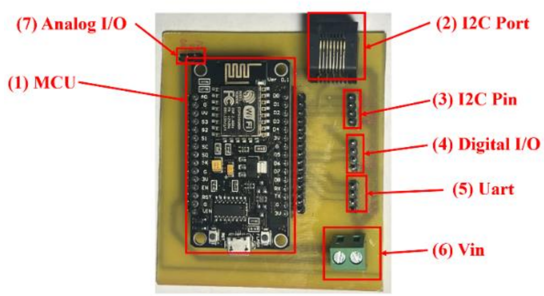


Figure 4 The main circuit prototype

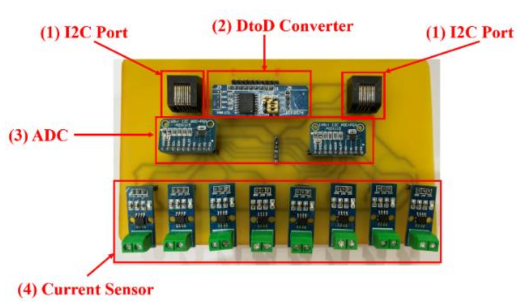


Figure 5 The expansion circuit prototype

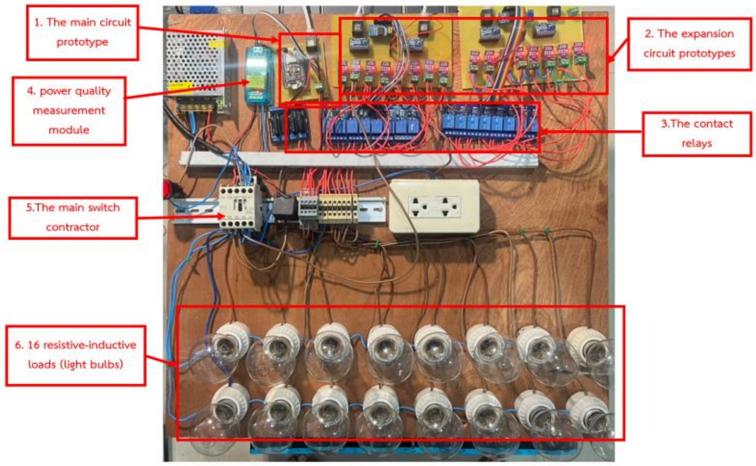


Figure 6 Experimental test-rig under this research

Results and Discussion

1. Connection and Data Transmission Test

This test was designed to test the connection and data transmission between the main and expansion circuits. The test results show no association or data transmission error during the testing with 2,000 times for 48 hours of continuous operations. Which are shown in Table 1. Figure 7 shows examples of successful data transmitted and received by the MQTT protocol via the HomeAssistant program's display screen while Table 2 shows the criteria of the commands (via the tele/loadcenter/STATE (1-17) ON/OFF) concerning the responsive loads.

Table 1 The connection test results between the expansion circuit and the main circuit

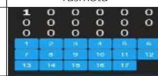
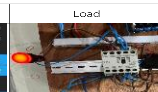
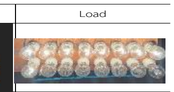
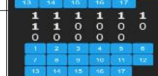
Connection Test (2,000 times)	Test results		Error (%)
	Connected	Not connected	
Expansion circuit 1	2,000	0	0.0
Expansion circuit 1 and 2	2,000	0	0.0

```
tele/tasmota_Smart_loadcenter/STATE =
{"Time":"2022-03-08T11:35:47","Uptime":"0T03:16:54","UptimeSec":11814,"Vcc":3.075,"Heap":26,"SleepMode":"Dynamic","Sleep":50,"LoadAvg":662,"MqttCount":4,
"POWER1":"OFF","POWER2":"OFF","POWER3":"OFF","POWER4":"OFF","POWER5":"OFF","POWER6":"OFF","POWER7":"OFF","POWER8":"OFF",
"POWER9":"OFF","POWER10":"OFF","POWER11":"OFF","POWER12":"OFF","POWER13":"OFF","POWER14":"OFF","POWER15":"OFF","POWER16":"OFF","POWER17":"OFF",
"Wifi":{"AP":1,"SSId":"Sarach_MAP","BSSId":"B0:A7:B9:C0:88:02","Channel":1,"Mode":"11n","RSSI":100,"Signal":-31,"LinkCount":2,"Downtime":"0T00:00:09"}}

tele/tasmota_Smart_loadcenter/SENSOR =
 {"Time":"2022-03-08T11:35:47","ENERGY":{"TotalStartTime":"2022-02-16T16:10:51","Total":0.006,"Yesterday":0.000,"Today":0.006,"Period": 0,"Power": 0,
"ApparentPower": 0,"ReactivePower": 0,"Factor":0.00,"Frequency":50,"Voltage":219,"Current":0.000},
"ADS1115-48":{"A0":13707,"A1":13650,"A2":13668,"A3":13655},"ADS1115-49":{"A0":13639,"A1":13672,"A2":13674,"A3":13674},
"ADS1115-4a":{"A0":13564,"A1":13612,"A2":13584,"A3":3766},"ADS1115-4b":{"A0":13624,"A1":13636,"A2":13614,"A3":13627},
"PCF8574-1":{"D0":1,"D1":1,"D2":1,"D3":1,"D4":1,"D5":1,"D6":1,"D7":1},"PCF8574-2":{"D0":1,"D1":1,"D2":1,"D3":1,"D4":1,"D5":1,"D6":1,"D7":1}}
```

Figure 7 Example of a message sent by the MQTT protocol

Table 2 The control scenario of the control board

No.1	Name	MQTT Message	Status		ลำดับ	ชื่อวงจร	MQTT Message	Status	
		tele/loadcenter/STATE	Tasmota	Load			tele/loadcenter/STATE	Tasmota	Load
1	Main MCB	POWE 1 ON			10	CB9	POWE 10 ON		
2	CB1	POWE 2 ON			11	CB10	POWE 11 ON		
3	CB2	POWE 3 ON			12	CB11	POWE 12 ON		
4	CB3	POWE 4 ON			13	CB12	POWE 13 ON		
5	CB4	POWE 5 ON			14	CB13	POWE 14 ON		
6	CB5	POWE 6 ON			15	CB14	POWE 15 ON		
7	CB6	POWE 7 ON			16	CB15	POWE 16 ON		
8	CB7	POWE 8 ON			17	CB16	POWE 17 ON		
9	CB8	POWE 9 ON							

2. Data Analysis Test

The proposed board was tested with some measurement devices, and the results were analyzed and evaluated. For this research, the electric power sensor PZEM004TV3 and the electric current sensor ACS712 were used for testing. The results are as follows:

2.1 Electric Power Sensor PZEM004TV3

Figure. 8 shows the % errors of the data corrected from the measured electric power sensor PZEM004TV3 compared to the standard power analyzer. It is seen that the proposed board can be collected, analyzed, and displayed correctly concerning the measured power delivered with a % error in the acceptable range of 2.77 – 5.95% compared to results obtained from the standard power analyzer.

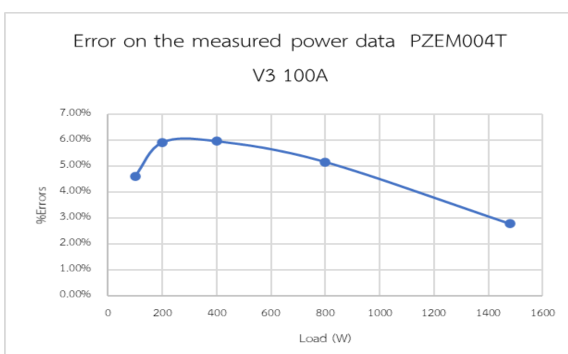


Figure 8 % error on the measured power data from sensor PZEM004TV3

2.2 Electric Current Sensor ACS712

Tables 3-5 show the experimental test results of the proposed board when used to measure the electric current via the 3 sensors with rated measurement specifications of 5A, 20A and 30A. Then the measured data were compared to the standard values obtained from the traditional power analyzer. It can be seen that low-rated current measurement sensors would provide better precision (reflected by SD.) compared to high-rated current measurement sensors.

Table 3 measured the current obtained from the ACS712, 5A sensor

Time	Standard Value (A)	Average Measured Value (A)	SD.	Error (%)
1	0	0	0.01	0
2	1.28	1.30	0.05	1.56
3	3.06	3.11	0.07	1.63
4	4.05	4.04	0.12	0.24
5	4.84	4.80	0.14	0.82

Table 4 measured the current obtained from the ACS712, 20A sensor

Time	Standard Value (A)	Average Measured Value (A)	SD.	Error (%)
1	1.29	1.31	0.08	1.5
2	2.62	2.59	0.14	1.4
3	4.32	4.28	0.26	0.92
4	5.65	5.55	0.37	1.76
5	6.53	6.37	0.37	2.45

Table 5 measured the current obtained from the ACS712, 30A sensor

Time	Standard Value (A)	Average Measured Value (A)	SD.	Error (%)
1	1.29	1.42	0.08	10.07
2	2.62	2.75	0.14	4.90
3	4.32	4.37	0.24	1.16
4	5.65	5.67	0.33	0.35
5	6.50	6.50	0.37	0.46

3. Power Consumption Test

The power consumption of the proposed board was tested in 3 conditions: (1) only the main circuit operation, (2) the main circuit with one expansion circuit, and (3) the main circuit with two expansion circuit. The average power consumption of the proposed board is shown in Table 6. This allows the user to select the most suitable option for their applications.

Table 6 Power consumption test of the proposed board.

Board	Power Consumption
The main circuit	1.1 W
The main circuit with one expansion circuit	4.8 W
The main circuit with two expansion circuits	8.5 W

4. Cost Estimation of the Components

Table 7 and Table 8 show the list of the components used for the primary circuit and the expansion circuit of the proposed board. It is seen that the estimated cost for the primary circuit and the expansion circuit are 190-400 and 322.5-531 Baht per circuit or about 412.5–931 Baht (11.26–25.41 USD) in total, which is about 2–5 times cheaper than the commercial boards.

Table 7 Estimated cost of the proposed primary circuit

The Main Circuit		
Component List	Cost (Baht)	Data resource
Tasmota Firmware	0	tasmota.github.io [14]
Node MCU Esp8266	90-100	Google shopping
Accessories	100-200	Google shopping
total cost	190-400	

Table 8 Estimated cost of the proposed expansion circuit

The Expansion Circuit		
Component List	Cost (Baht)	Data resource
ADS1115	112-215	Google shopping
PCF8475	10.5-116	Google shopping
Accessories	100-200	Google shopping
total cost	322.5 -531	

Conclusions

This paper proposes a low-cost, modular load monitoring and control board for electric parameters measurement and collections. The proposed board was designed based on the open-source software and hardware, which was driven by the Tasmota firmware and MQTT protocol. The board's hardware is composed of the main circuit and the expansion circuit with 8x2 modular input/output channels. The connection test results between the expansion circuit and the main circuit can be connected to each other effectively. The proposed board was tested with the commonly used power sensor PZEM004TV3 and current sensors ACS712, 5-20-30A. The experimental test results showed that the proposed board could operate continuously with zero data transmission error and no misconnection. The measured and collected data were well collected with data error of less than 5.95% and a low S.D. of 0.37. The estimated cost for the main and expansion circuits were 190-400 and 322.5-531 Baht, respectively, or about 412.5–931 Baht (11.26–25.41 USD), which was approximately 2–5 times less expensive than the commercial boards.

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