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Practical Considerations for Controller Selection in Residential Energy Management Systems: A Review

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Abstract

A review of the wide variety of system controllers available on the market along with the practical applicability of each is discussed in this paper. The system controllers that are discussed include programmable logic controllers, microcontrollers and single board computers. These controllers are generally not competing for the same market share however, some of the capabilities of these controllers overlap with one another which makes the selection of an appropriate system controller a complex decision. The practical considerations of controller selection are discussed and reviewed in this article, a new trade off analysis is presented along with a practical example thereof. The practical example that was used to illustrate controller selection was a residential energy management system which would be installed alongside a grid-tied 2 kWp photovoltaic system. The aim of the energy management system is to ensure that all the photovoltaic generated energy is consumed locally within the residence and not fed into the distribution network. Such a system is applicable in areas where no net-metering policies are in place.

Keywords: Programmable Logic Controller, Microcontroller, Single Board Computer, Residential energy management

INTRODUCTION

The popularity of control systems and the drive towards automation is causing more system controllers to be introduced into the market [1] [2]. Over the past decade, numerous controllers apart from programmable logic controllers (PLCs) and microcontrollers (MCUs) have come to light in the form of single board computers (SBCs) [3]. Some of the most popular modern SBCs are the Raspberry Pi, Panda and Rapcon Boards which are all driven by open-source software [4], [5] , [6], [7]. These controllers form part of the SBC family which possesses processing power similar to earlier generation computers [4], [6], [8].

Although MCUs, PLCs and SBCs are generally not competing for the same market share, some of the capabilities of these controllers overlap with one another. PLCs have been the preferred controller choice for all industrial automation processes since the introduction of digital control [9]. However, both SBC and MCU manufacturers have already started exploring the opportunities in the industrial market [10]. Generally MCUs and SBCs are more popular in smaller scale and development control systems [6], [8]. Typical applications of MCUs include switch mode power supplies, inverters and other power electronic equipment [11]. SBCs have become more popular with digital signal processing (DSP) and cloud driven applications due to their superior processing power and software accessibility [12]. However, with the addition of expansion boards, any control system application can be realised by making use of one of the controllers listed in figure 1. The controllers mentioned in this figure are discussed below.

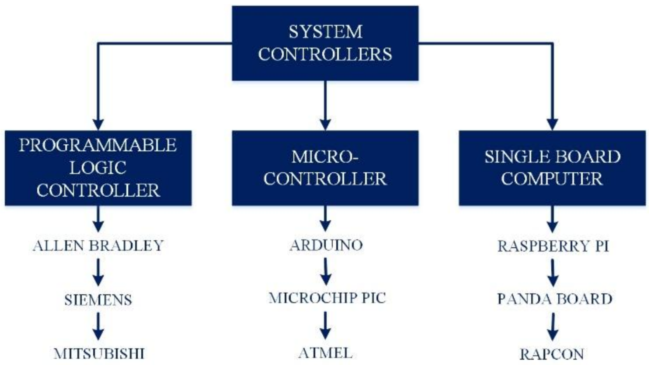

Figure 1. Summary of system controllers

MODERN CONTROLLERS

Modern controllers comes in a wide variety of capabilities ranging from basic input/output (I/O) to complex DSP [13]. This section provides a review of the controllers that are typically used in modern industrial and small scale control systems. The performance and success of a control system can be compromised by selecting an unsuitable controller. The controllers discussed in this section include A) PLCs B) MCUs and C) SBCs.

A. Programmable Logic Controllers

A PLC is a solid-state digital computer used to control and automate electromechanical processes such as production lines in factories, building energy management systems and heating, ventilation and air conditioning (HVAC) systems [14] [15]. PLCs are renowned for their robustness and capability to withstand harsh environments such as excessive temperatures, dusty/smoke conditions and vibration. Apart from the robustness and reliability under extreme conditions, the simple programming techniques that is used to set the PLC's parameter makes this a favourable controller in all applications [16] , [17].

The programming techniques associated with a PLC are based on logical structure such as AND, OR, NOT, XOR etc. [14]. This structure of programming permits the use of logical gates and basic truth tables to control the PLC in a desirable manner. These logical structures are also presented in graphical forms to ensure a user friendly programming environment; the most widely used graphical environments include ladder and functional block diagrams. Another notable advantage of PLCs are the simplified redesign of established circuits [18]. Alterations to the circuit are easily done without rewiring the entire circuit, only logical program code alterations need to be made. This ensures a time-efficient solution to rectify a fault or alteration to an established circuit [14]. These devices have a built-in non-volatile memory bank hosting an independent operating system which makes standalone and real-time automation possible [19]. Automation through these devices is made possible by the fact that inputs can be obtained from sensors, calculations can be performed in real-time and the appropriate outputs can be activated [14]. The architecture of a PLC controlled system is shown in figure 2 [14], [20].

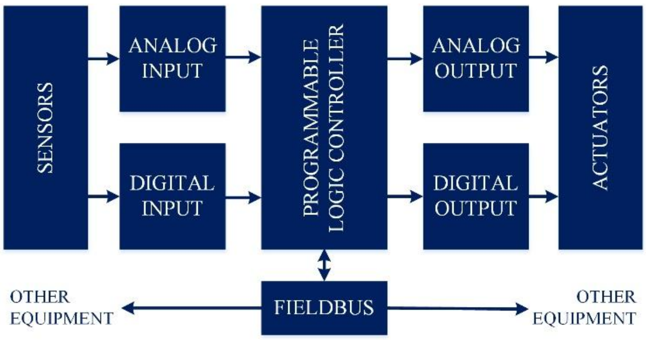

Figure 2. PLC application architecture [11], [14]

A summary of the practical advantages and disadvantages associated with PLCs are summarised in table 1. The table highlights benefits and shortcoming that are commonly found in industry and experimental control systems.

Table 1. Advantages and disadvantages of PLCs [21] [22]

Advantages	Disadvantages
Rugged and tested in harsh conditions	Lots of wiring makes fault investigations timely
Simple integration of modules i.e. I/O, Comms.	Expensive to set-up control system
Simple programming language	Integration issues between manufacturers' PLCs
Small controllers can control multiple machines	Semiconductors are temperature dependent
Real-time simulation prior to commissioning	
Reliable industrial controller	

Industry and development applications of PLCs

In a study by Yilmaz, a home automation system implementing a PLC was designed and constructed [23]. The main purpose of this system was to automatically control the lighting, wall outlets, gas and water system of a home to optimise energy consumption. The control of the wall outlets came from connecting several of the outlets onto the relays controlled by the PLC. In a similar manner, the distribution panel lighting switches were also connected to the PLC's relays; however, the control of these lighting switches was performed using a single keypad as input device. The keypad was strategically placed within the home which allowed centralised lighting control. With a low pressure gas system present in the home, Yilmaz decided to implement a gas safety system into the home which shuts down the gas inflow in case of a leakage [23].

In a study presented by Balasevicius *et al.*, a small building energy management system consisting of renewable energy sources and a diesel generator were developed [24]. Solar PV and wind power plants of up to 5~kW was considered alongside a 10~kW diesel generator. The aim of the project was to minimise energy consumption from the national grid and expend all the locally generated energy. According to Balasevicius *et al*., the small building was divided into ten sections of electric loads, each connected to a triac-bank which is connected to the sources of energy [24]. The control system consisted of a power meter connected at each load section. The control strategy that was followed was to first connect the building to the utility company's grid and determine the power required by each section. Once this was established, the available energy from the wind, solar and diesel generator was determined. Based on these measurements, the PLC determined and controlled which load sections could be connected to the sources of energy.

A study presents a building energy management system that offers distributed control of the indoor comfort level whilst reducing the energy consumption. According to Kolokotsa *et al*., the system used a smart card unit, controlled by a user, to adjust the indoor illuminance and HVAC settings according to the user's smart card [25]. In cases where a smart card was not presented, the system assumed no-one was present and switched off all the lights and HVAC. A PLC performed fuzzy logic algorithms to determine the sensor inputs, actuator outputs and to send data across a communication network. There were several illuminance and temperature sensors connected to the control system which determined the comfort level according to the user's inputs. In addition, the PLC collected data from various users' smart cards and stored the data to adapt the control strategy.

B. Microcontrollers

Microcontrollers are comparable to a small computers since similarities in architectural design exist. Similar to a computer, an MCU has a reduced instruction set computer (RISC) processor, variable random access memory (RAM) and input/output (I/O) peripherals [26]. A MCU also contains an instructions set which hosts the program code embedded by the programmer. These devices contain numerous features which make these embedded devices very attractive when considering simplified control systems.

Some of the main features of MCUs are reduced size, weight and cost compared to other controllers consisting of a separate processor, memory module and I/O devices. The reduction to a single integrated circuit (IC) permits the implementation of cost effective embedded systems. The downside to MCUs is that in cases where high processing power is required, the MCU may fall short of the expected demand. Another shortcoming associated with MCUs is the low-level programming language knowledge that is required to set the parameters of these devices. However, advances made in the field of MCUs have seen the development of MCUs, such as Arduino, that are programmable with high-level programming languages. These languages are not as efficient and requires more memory as their low-level language counterparts.

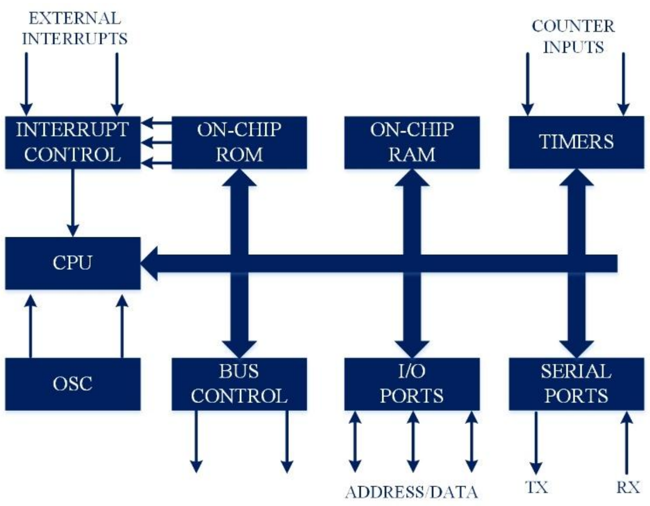

Figure 3. MCU generic architecture [27]

A summary of the practical advantages and disadvantages associated with MCUs are summarised in table 2.

Table 2. Advantages and disadvantages of MCUs [28] [29]

Advantages	Disadvantages
Real-time simulation prior to commissioning	Requires custom built printed circuit board (PCB)
Permits numerous peripherals	Complex programming language
No unnecessary components on the PCB	Not fit for harsh conditions such as high temperatures
Small controllers can control multiple devices	Time intensive to debug
Cost effective	Limited to control signals (no on-board relays)

Industry and development applications of microcontrollers

MCUs are conventionally not used in heavy current applications as the control unit [30]; however, there are exceptions which are discussed below.

In a case study, Belvedere *et al.*, presented an energy management system that consisted of a battery storage system, fuel cells and solar PV emulator [31]. The system was interconnected in such a way that a small distributed network of 4.5 kW was formed which was not connected to the utility grid but rather formed its own 230 V AC bus. The two networks were isolated from one another and is never connected simultaneously. A 5 kW load emulator was connected to the bus to emulate various loads connected to the network. The main objective of the control strategy for the MCU system was to connect and disconnect the fuel cells and solar PV emulator to optimise the charging of the battery bank. Based on the battery bank state-of-charge, the MCU decided which source of energy, battery or utility grid, should supply the loads [20].

In another case study, Ghodki presented a study which contained a distribution system consisting of solar PV power and the utility grid [32]. A monitoring system employing smart metering was used to measure the amount of electrical energy consumed by the load and based on these measurements, the MCU controlled the power flow. The control of the power flow was established by using relays to connect the solar PV system and the utility grid in a parallel connection to the load [21]. The MCU measured the power consumed by the load and based on the capacity of the solar PV system, a decision was made regarding which source of energy, solar PV or utility, was used to power the load [21].

In a case study presented by Pisica *et al.*, a prototype home energy management system was designed and implemented [33]. The main objective of this study was to make use of dynamic tariff monitoring and scheduling home appliances operation according to those tariffs. This way loads was shifted to a time frame where more generation capacity and a lower tariff was avaislable. In this manner, electricity savings was increased by a scheduling pattern. The system also consisted of a web page that hosted all the scheduling, time frames and connected appliances. According to Pisica *et al.*, the additional distributeds generation was advised to further increase electricity savings [22].

C. Single Board Computers

Single Board Computers are fast becoming popular as embedded computer controllers due to their compact size and high processing [34] [35]. Similarly to conventional computers, SBCs also consist of an embedded processor, memory module and I/O ports. Although these are low-end 8/16 bit processors, basic dynamic RAM and a limited number of I/O peripherals, these devices still offer competitive computation power at a fraction of the cost and size of conventional computers [36]. The majority of SBCs are driven by Linux based operating systems; some these operating systems include Ubuntu, Android and Angstrom.

SBCs are similar to microcontrollers in the sense that the need for expansion boards are much higher than with PLCs. SBCs and microcontrollers are both only capable to produce low power control signals. Additional actuator expansion boards are required to control any real-world system. However, SBCs have a distinct advantage over all other compact controllers when comparing the number of connectible peripherals, communication protocols and processing power.

Table 3. Advantages and disadvantages of SBCs [37] [38]

Advantages	Disadvantages
Real-time simulation prior to commissioning	Limited to control signals (no on-board relays)
Permits numerous peripherals	Complex programming language
Capable of handling complex control systems	Not fit for harsh conditions such as high temperatures
Small controllers can control multiple devices	Time intensive to debug
Cost effective	Fairly new technology with little reliability tests
Multiple communication protocols	

Industry and development applications of SBCs

There is a shortfall of energy management studies using SBCs which is due to the fact that SBCs are fairly new on the market and studies have not yet been conducted in this manner. However, there is a home automation system powered by SBCs which is discussed below.

In the study presented by Ramses *et al.*, a home automation system was implemented to control various loads by using a mobile device [39]. A Raspberry Pi SBC was used as a server to connect the home onto the internet. The user was then able to access the server through the mobile device's internet connection and control several of the loads from a centralised point. The main actuator was controlled through wireless network communication received from the SBC and relays were used to connect and disconnect the loads [24].

In the study presented by Raja *et al.*, a secured smart home energy monitoring system using a Raspberry PI was designed [40]. The system included a home automation system that was controlled by a mobile device through a web-application. The loads that were controlled included a television and microwave. Furthermore, the system controlled the residence's video security system which was activated when motion control sensors were triggered.

PRACTICAL CONSIDERATIONS

Development and industrial controllers usually come in the form of a base model with very basic features and capabilities. However, expansion modules are always available from manufactures to enhance and improve the features of the base model. It is therefore considered a complex procedure when performing a trade-off analysis when selecting an appropriate controller for a specific application. The most important practical consideration regarding the controller that should be kept in mind are listed below.

a) Supply Voltage

(i) Alternating (AC) or direct current (DC)

(ii) Voltage level and range (i.e. 85-264 VAC)

b) Input Ports

(i) Digital inputs

- Number of inputs
- Maximum permissible voltage
- High and low threshold values
- Isolated or non-isolated

(ii) Analog inputs

- Number of inputs
- Acceptable input type and range (i.e. 0-10 V or 4-20 mA)
- Resolution (i.e. 13 bits)
- Sampling rate
- Differential inputs

c) Output Ports

(i) Digital outputs

- Number of outputs
- Type of outputs (i.e. transistor or relay)
- Output protection (i.e. short circuit)
- Output current capability
- Switching frequency
- Operating cycles

(ii) Analog outputs

- Number of outputs
- Output ranges (i.e. 0-10 V or 4-20 mA)
- Resolution (i.e. 10 bits)
- Differential outputs

d) Communication

(i) Protocol (i.e. serial, ethernet, bluetooth etc.)

(ii) Data transfer rate

(iii) Architecture (i.e. client-server)

e) Environmental

(i) Degree of Protection (i.e. ingress protection (IP) 54)

(ii) Operating temperature

(iii) Vibration

f) Processor Capability

(i) Work memory

(ii) Load memory (i.e. internal and expandable)

(iii) Processing times (i.e. cycle, operation, calculation etc.)

(iv) Number of timers, counters, flags etc.

EXPERIMENTAL SYSTEM CONTROLLER SELECTION

A system controller for a residential energy management system (EMS) needs to be selected. The EMS will be installed along with a residential grid-tied photovoltaic (PV) system and will aim to ensure that all the locally generated energy is absorbed in the residence. This is applicable in areas where no net-metering policies are present and all energy that is fed into the utility network is essentially lost. The loads will be controlled by energising relay contacts which will ultimately supply the loads. The loads that need to be controlled is the electric geyser, refrigerator, dishwasher, washing machine, tumble dryer and swimming pool pump. Details regarding the loads are illustrated in table 4.

Table 4. Load power levels

Load	Power Rating	Voltage Rating	Current Draw
Geyser	3 kW	220 V	13.6 A
Swimming Pool	0.55 kW	220V	2.5 A
Washing Machine and Tumble Dryer	0.55 kW 2.2 kW	220 V	2.5 A 10 A
Dishwasher	1.8 kW	220V	8.1 A
Refrigerator	0.25 kW	220 V	1.2 A

The solar PV system will have an installed capacity of 2 kWp. The PV modules will be connected to a Kaco Powador 2002 grid-tie inverter (GTI) which uses the RS-232 protocol to communicate the incoming and outgoing power, current and voltage. This information will be used to optimise local energy consumption by switching on/off the loads according to the incoming solar PV profile. The loads' power consumption will be measured by making use of current transformers (CTs) and feeding the load currents back to the controller. This way it can be ensured that the total load current exceeds the incoming generation current.

The home-owner should be able to switch off/on the EMS with a push-button and also isolate the loads from the PV system in case of emergency. Based on the discussion in the previous section, the practical considerations and specifications will be set out accordingly.

a) Supply Voltage

(i) An AC voltage is readily available without the need for any converters; however a DC voltage can be easily obtained by installing a AC-DC converter.

(ii) The nominal voltage readily available in the residence is at 220 VAC; however with an ACDC converter any DC voltage can be obtained. It is decided that the controller will be supplied by 24 VDC as this will also be used to power the control circuitry.

b) Input Ports

(i) Digital inputs

- The system requires a total of two digital inputs. One for the switch off/on button and also one for the emergency stop button.
- The control circuitry voltage is supplied from the AC-DC converter that supplies the controller and hence will be 24 VDC.
- The threshold values of each controller varies; however there seem to be a trend that the low threshold seems to be at 45% of the rated control voltage. For a 24 VDC system this translates to approximately 10.8 VDC.
- Isolated inputs are required when higher than the rated input voltage are present near the controller and the possibility exists that the controller may be exposed to that voltage level. In this case, the controller may be exposed to 220 VAC which will cause permanent damage to the controller if there are no isolated inputs.

(ii) Analog inputs

- The number of inputs is directly linked to the number of CTs that will be used to measure the load currents; therefore a total of five analog inputs are required.
- The CTs will be terminated by a burden resistor and hence the analog input type needs to be voltage. The CTs output a low current (in the order of mA) that will be run through the burden resistor to generate a voltage of less than 10 V. Therefore, an analog input module permitting a voltage swing of between -10 and 10 V would be adequate.
- Since the accuracy of the measurements will be determined by the CTs (less than 2%), the resolution of the analog input module will not be the limiting factor. Adequate resolution for the measurements will be 8 bits.
- Sampling rate
- Differential inputs

c) Output Ports

Table 5: Controllers trade-off analysis

1 - Poor … … 5 – Very Good	**Cost**	**Robustness**	**Life Expectancy**	**Ease of Implementation**	**After Sales Support**	**Software Ease of Use**	**Size**	**Score**
	0.15	**0.05**	**0.2**	**0.2**	**0.1**	**0.1**	**0.2**	**1**
PLC	2	5	5	5	5	2	2	**4.4**
MCU	5	3	4	5	5	2	5	**4.1**
SBC	4	3	3	4	2	2	5	**3.05**

(i) Digital outputs

- The number of outputs is determined by the number of loads that need to be controlled. The total number of loads that must be controlled is six and therefore six outputs is required.
- Continuous current draw applications is best controlled by making use of relay outputs.
- External short circuit protection is needed at the relay outputs.
- Based on the data presented in table 4, the current draw of the loads determines the continuous current capability rating of the outputs.
- Relay outputs cannot be switched at high frequencies due to the mechanical design; however the loads do not require switching at high frequencies.
- The mechanical design of the relays is designed and built for numerous switching operations; however the switching on loads will not require a great deal of switching throughout the day.

(ii) Analog outputs

- No analog outputs are required

d) Communication

(i) The communication protocols required between the controller and other equipment is established through RS-232 communication.

(ii) The transfer rate of the GTI is set at 9600 baud (9.6 kbps).

(iii) The network topology will be client-server.

e) Environmental

(i) The controller will be installed in an enclosure indoors and hence does not require an IP rating that is rated for excessive vibration, humidity and temperature.

Each of the controllers mentioned in the preceding sections deemed adequate with the addition of expansion boards. A practical evaluation was performed to determine the correct controller for the application and is shown in table 5. From table 5 it was evident that the PLC is the best suited system controller for the given application. The decision is mainly driven by the fact that the reliability and after sales support of the PLC are superior compared to the MCU and SBC. The selection of the PLC requires an additional analog input module to be added to meet the number of required analog input ports. Furthermore, a serial communication board is also required to permit communication in the system.

CONCLUSION

This paper provided a review and analysis on the three families of modern system controllers used in industry and development control systems. The three controllers that were discussed included PLCs, MCUs and SBCs. PLCs are still considered to be the favourite in industrial control systems. The development of open-source hardware and software at reasonable prices has opened the possibilities for SBCs and MCUs to enter the industrial market. However, the lack of after sales support of open-source products is a limiting factor in the absorption in industrial control systems.

The paper further discussed the practical considerations that need to be considered when selecting a controller for a control system. Factors that primarily influence controller selection are the supply voltage, number of I/O ports, I/O type (analog/digital/relay), communication protocols and environmental conditions. Within the primary influencing factors, detailed secondary factors need to be taken into account. A new method of trade off analysis for selecting the best possible controller was presented and an example of a residential EMS was used to practically illustrate the design considerations that need to be taken into account. The system controller had to control the various residential loads and the communication between the equipment to ensure that the EMS efficiently managed the system. It was found that for the residential EMS that performed load shifting, a PLC was best suited as it had the necessary specifications to control the EMS. Some of these specifications included a 220 VAC supply, 6 relay outputs, 8 digital inputs, 8 analog inputs an additional RS-232 communication module.

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