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A review on the applications of programmable logic controllers (PLCs)

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ABSTRACT

As the need of automation increases significantly, a control system needs to be easily programmable, flexible, reliable, robust and cost effective. In this paper a review on the application of programmable logic controller (PLC) in our current market is discussed. Investigations on the applications of PLCs in energy research, engineering studies, industrial control applications and monitoring of plants are reviewed in this paper. PLCs do have its own limitations, but findings indicate that PLCs have more advantages than limitations. This paper concludes that PLCs can be used for any applications whether it is of simple or complicated control system.

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1. Introduction

Programmable logic controllers [PLC] are computer-based, solid-state, single processor devices that emulate the behavior of an electric ladder diagram [1] capable of controlling many types of industrial equipment and entire automated systems [2]. PLCs are usually a main part of automatic systems in industry [3]. They are very efficient and reliable in applications involving sequential control and the synchronization of processes and auxiliary elements in the manufacturing, chemical and process industries [4,5]. Besides having technological advantages of using PLC, it also decreases the prices in the advanced level and complex control system [5–7]. Nowadays, most of the control elements used to execute the logic of the system was substituted by the PLCs [8].

The term logic is used because the programming is primarily concerned with implementing logic and switching operations. Input devices such as switches, and output devices such as motors, being controlled are connected to the PLC and then the controller monitors the inputs and outputs according to the machine or process [9]. Originally PLCs were designed as a replacement for hard-wired relay and timer logic control systems. (*Hard-wiring* means that all of the components were manually connected by wires). PLC consists of two parts i.e. the PLC hardware and programming. Details on the hardware and programming will be discussed in the Sections 3 and 4, respectively.

PLCs were first used by the automotive industry in the late 1960s [2,10–13], its automated equipment was primarily controlled by discrete inflexible circuits consisting of electromechanical relays and coils hardwired on panels. General Motors developed the specifications for a programmable controller that could replace the hard-wired relay circuits [2,11,12]. The most radical idea, was the implementation of a programming language based on a relay schematic diagram, with inputs (from limit switches, pushbuttons, etc.) represented by relay contact, and outputs (to solenoids, motor starters, lamps, etc.) represented by relay coils [12]. Fig. 1(a) shows a simple hydraulic cylinder which can be extended or retracted by pushbuttons. Its stroke is set by limit switches which open at the end of travel, and the solenoids can only be operated if the hydraulic pump is running. This would be controlled by the computer program of Fig. 1(b) which is identical to the relay circuit needed to control the cylinder. These programs look like the rungs on a ladder, and were consequently called ‘Ladder Diagrams.’

In the mid-1960s, Hydramatic, a division of General Motors Corporation, envisioned that a computer could be used to perform the logic functions then performed by relays [2]. The engineering team wrote a list of features of the proposed computing device. GM initiated the development of the computing device by specifying certain design criteria, including:

- The device must be durable so that it can operate in the harsh environments (dirty air, humidity, vibration, electrical noise, etc.) encountered in a factory
- It must provide flexibility by implementing circuit modifications quickly and easily through software changes.
- It must be designed to use a programming language in ladder diagram form already familiar to technicians and electricians.
- It must allow field wiring to be terminated on input/output terminals of the controller.

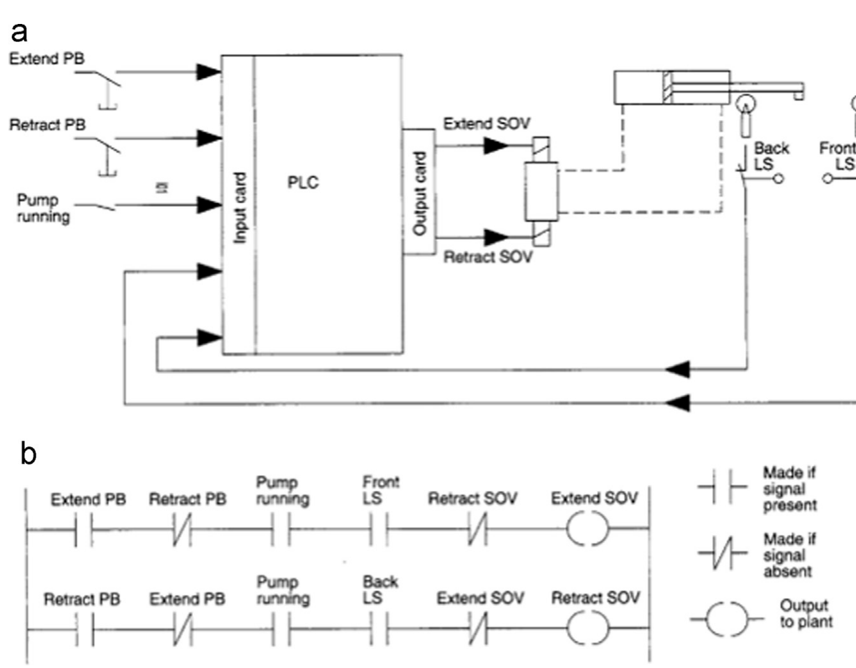

Fig. 1. A simple PLC application: (a) a hydraulic cylinder controlled by a PLC; (b) the ‘Ladder Diagram’ program used to control the cylinder [12].

GM used this list of specifications when it solicited interested companies to develop a device that met its design requirements. Dick Morley conceived the first programmable controller on January 1, 1968 [14]. When his company, Gould Modicon Company developed the first PLC [2,11,14], the first model 084 PLC was installed at the Oldsmobile Division of General Motors Corporation and the Landis Company in Landis, Pennsylvania. The first PLC was large and expensive. They were capable of On-Off control only, which limited their applications to operations that required repetitive movements.

Innovations and improvements in microprocessor technology and software programming techniques have added more features and capabilities to the PLC. This enhancements enable the PLC to perform more complex motion and process control applications, and with greater speed.

Presently, more than a dozen manufacturers produce PLCs, Table 1. Most of these companies make several models that vary in size, cost and sophistication to meet the needs of specific applications.

Table 1
List of PLC manufacturers in the global market.

No	Manufacturer	No	Manufacturer
1	Siemens	9	Panasonic
2	ABB	10	Idec
3	Schneider (Modicon)	11	Keyence
4	Rockwell (Allen-Bradley)	12	Toshiba
5	Mitsubishi	13	Fuji
6	GE-Fanuc	14	Beckhoff
7	Omron	15	Bosch Rexroth
8	Koyo	16	Rockwell/Allen-Bradley

2. Personal Computer (PC) versus PLC

The original design for the programmable logic controller was called a programmable controller, or PC [14]. The abbreviation caused no confusion until the personal computer became widely used and also adopted the PC abbreviation. To avoid confusion, the programmable controller industry added the word logic in the title, producing the new term programmable logic controller, of PLC.

A modern PLC is a computer-based device designed to control a process [1,15]. It relates information coming from sensors that monitor the state of a process, with the status of some actuators that are capable of changing it. Although PLC and Personal Computers (PC) are both computers, there are some significant differences [10,14,16].

Let us look at the similarities. The architecture of the PC and PLC systems are similar, with both featuring a motherboard, processor, memory, and expansion slots [14].

The differences are that PLCs processor has a microprocessor chip linked to memory and I/O (input/output) chips through parallel address, data, and control buses. Generally, PLCs do not have removable or fixed storage media such as floppy and hard disk drives, but they do have solid-state memory to store programs. PLCs do not have a monitor, but a human machine interface (HMI) flat screen display is often used to show process or production machine status. They also come equipped with terminals for input and output field devices as well as communications port. PCs in the other hand do many jobs in homes, offices, and are complex computing machines capable of executing several programs or tasks simultaneously and in any order but PLCs perform only one task in an orderly and sequential fashion form first to last

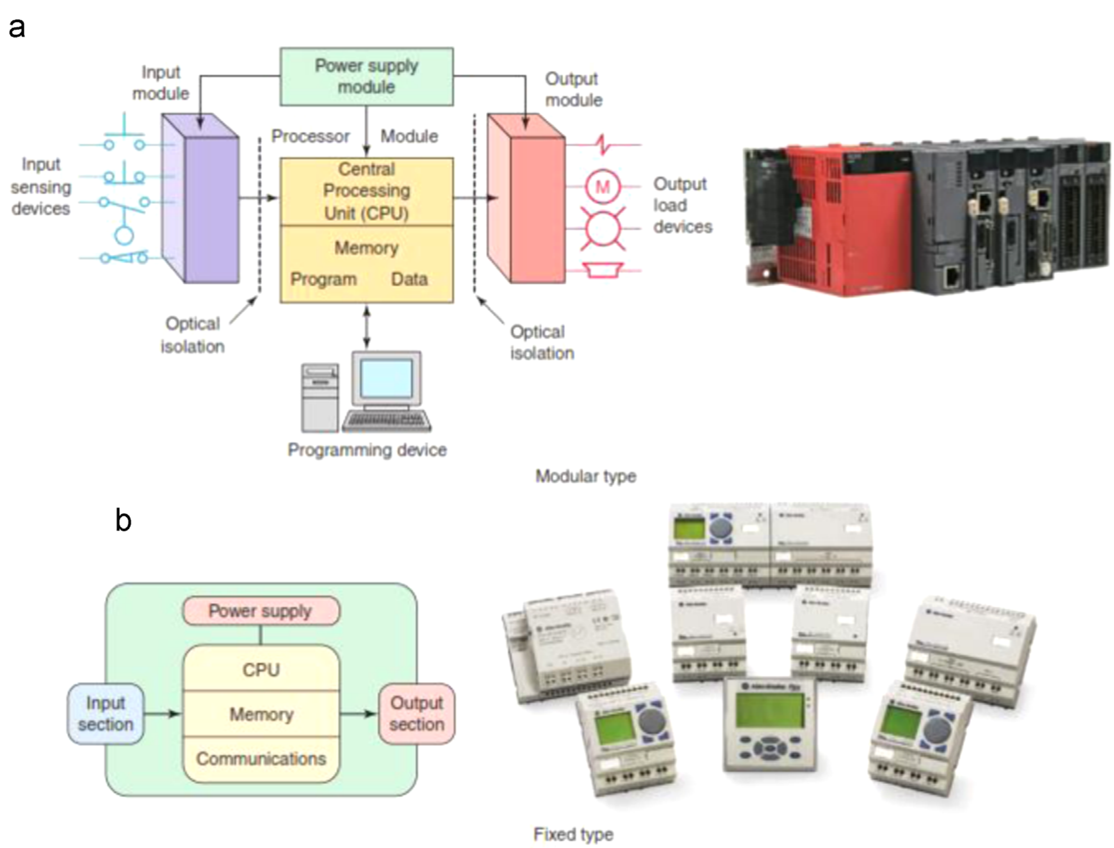

Fig. 2. Typical parts of a programmable controller. (a) Mitsubishi Automation (b) Rockwell Automation, Inc. [16].

Fig. 3. CJ1 Type PLC, Omron [18].

instruction, the control of manufacturing machines and processes. Any computer that is intended for industrial use must be able to withstand extremes of temperature and humidity [14,16]: ignore voltage spikes and drops on the power line; survive in an atmosphere that often contains corrosive vapors, oil, and dirt; and withstand shock and vibration.

PLC control systems have been designed to be easily installed and maintained. Troubleshooting is simplified by the use of fault indicators and messaging displayed on the programmer screen. Input/output modules for connecting the field devices are easily connected and replaced [16].

PLCs are designed to be programmed with schematic or ladder diagrams instead of common computer languages [1,10,14,16,17]. The PLC comes with its program language built into its memory (Figs. 2–5).

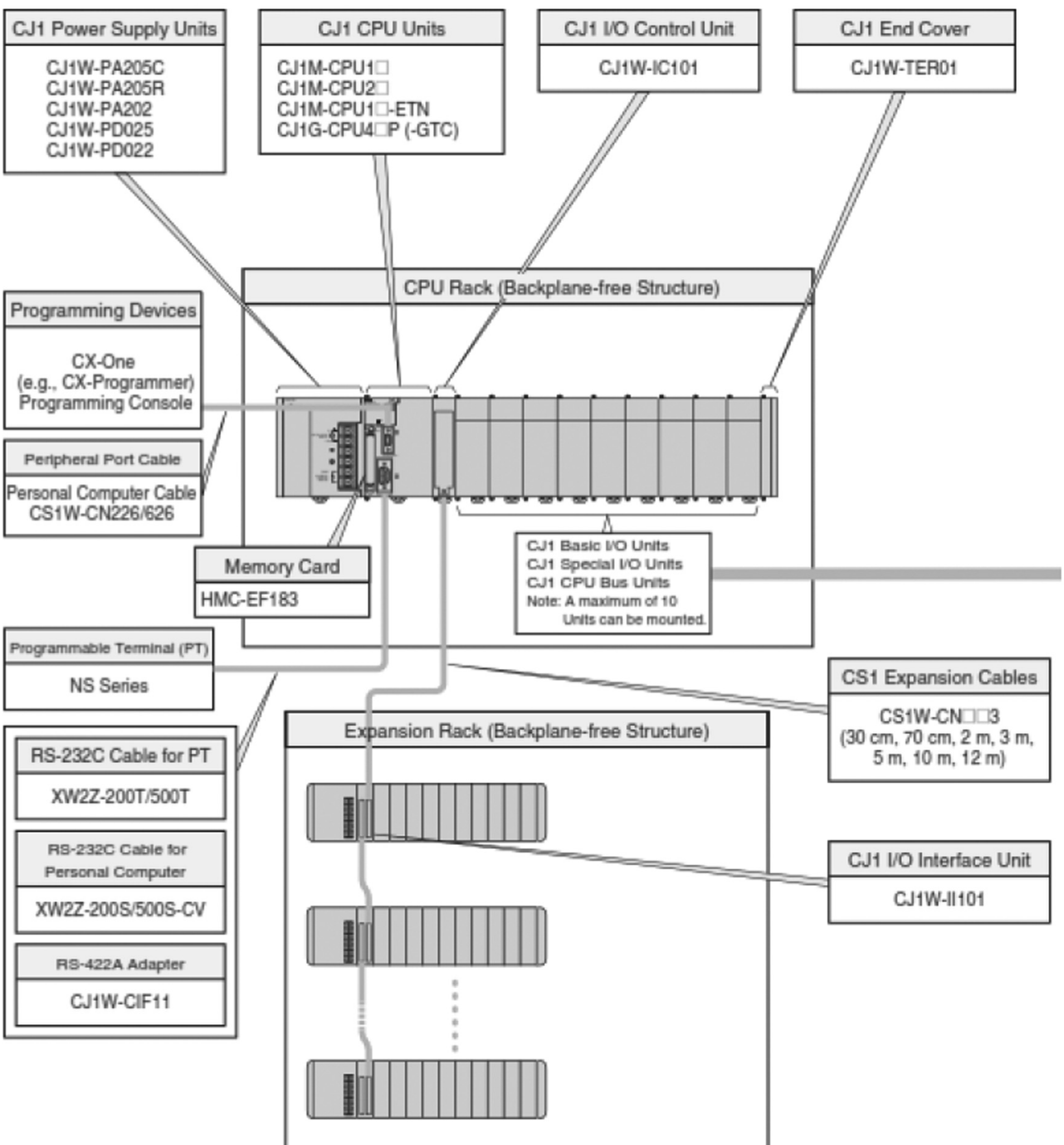

Fig. 4. CJ1 PLC System Configuration, Omron [18].

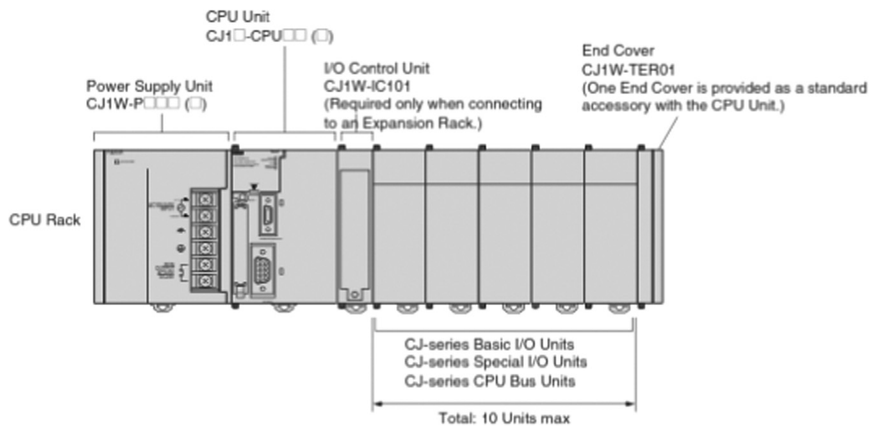

Fig. 5. A CJ-series CPU Rack consists of a CPU Unit, Power Supply Unit, Configuration Units (Basic I/O Units, Special I/O Units, and CPU BusUnits), and an End Cover. [18].

3. PLC Hardware

The modern version of the ladder logic system is the programmable controller. All PLC systems are comprised of the same basic building blocks that detect incoming data, process it, and control various outputs [2]. The basic blocks are;

- Rack Assembly
- Power Supply
- Programming Device
- Input/Output Section
- Central Processing Unit (CPU)

3.1. Rack Assembly

Most programmable controllers that have a large number of input and output terminals are constructed by using a variety of modules. These modules include the power supply, processor unit, and input/output modules [2]. Allen-Bradley controllers make a distinction between a PLC chassis and rack [16]. The hardware assembly that houses Input/Output (I/O) modules, processor modules, and power supplies is referred to as the chassis. The modules are installed in a rack. The PLC rack serves several functions. It physically holds the modules in place, and it also provides electrical connections between the modules by using a printed circuit board at the back or the rack assembly [2,14,16].

The modules are easily inserted into channels on the rack. They fit into sockets mounted on the motherboard to make electrical contact with the other circuitry. The ability to plug modules into the rack allows maintenance personnel to replace defective units quickly.

3.2. Power supply

The power supply supplies direct current (DC) power to other modules that plug into the rack, Fig. 6. With larger systems, power to field devices is provided by external alternating current (AC) or DC supplies. For some small micro PLC systems, the power supply may be used to power field devices [2,16].

3.3. Programming Unit/Device/Terminal

The programming terminal or loading terminal is used to program the CPU [2,10,14,16]. The type of terminal used depends on the manufacturer and often the preference of the customer. Some are small handheld devices that use a liquid crystal display or light-emitting diodes to show the program. Some of these small units will display one line of the program at a time and other required the program to be entered in a language called Boolean (Fig. 7).

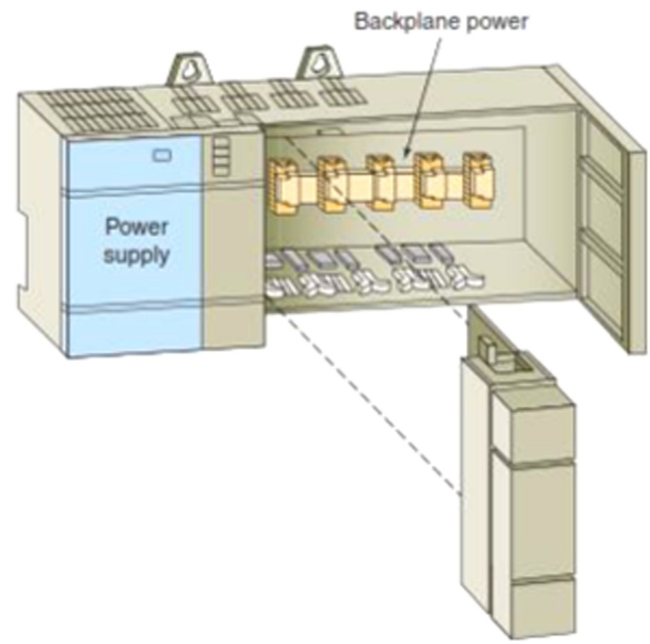

Fig. 6. Modules receive their voltage and current from the backplane [16].

Another type of programming terminal contains a display and keyboard, Fig. 8. This type of terminal generally displays several lines of the program at a time and can be used to observe the operation of the circuit as it is operating [19].

Many industries prefer to use a notebook or laptop computer [20] for programming, Fig. 9. An interface that permits the computer to be connected to the input of the PLC and software program is generally available form the manufacturer of the PLC [10].

3.4. Input/Output section

The I/O section of a PLC is the section to which all field devices are connected and provides the interface between them and the CPU. Input/output arrangements are built into a fixed PLC while modular types use External I/O modules that plug into the PLC [16].

The I/O interface used in PLCs can take two forms: *fixed* and *modular* [14]. The fixed type is associated with the small or micro PLC system where all of the features are integrated into a single unit. The number of I/O ports is fixed within each model and cannot be changed. The modular types use a rack to hold the I/O modules so the number and type of I/O modules can be varied.

Fig. 7. Typical hand-held programming device [16].

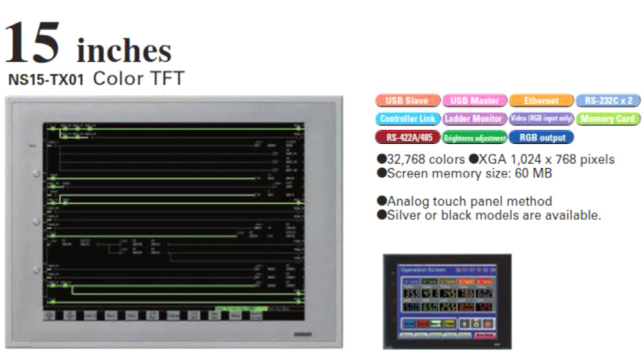

Fig. 8. Omron Programming Terminal, NS15-TX01 [19].

Fig. 9. A Dell notebook computer, Dell Companies [20].

Input interface modules accept signals from the machine or process devices and convert them into signals that can be used by the controller [16]. Output interface modules convert controller signals into external signals used to control the machine or process. The I/O system provides an interface between the hardwired components in the field and the CPU. The input interface allows status information regarding processes to be communicated to the CPU, and thus allows the CPU to communicate operating signals through the output interface to the process devices under its control.

3.4.1. Input module

Internally a computer usually operates at 5 V d.c. the external devices (solenoids, motor starters, limit switches, etc.) operate at voltages up to 110 V a.c. [12]. The mixing of these two voltages will cause irreparable damage to the PLC electronics. The central processing unit of a programmable logic controller is extremely sensitive to voltage spikes and electrical noise. [10]. For this reason, the I/O uses opto-isolation to electrically separate the incoming signal form the CPU [10,12,14,16].

3.4.2. Output module

The output module is used to connect the central processing unit to the load. Output modules provide the line isolation between the CPU and the external circuit. Isolation is generally provided in one of two ways. The most popular is with the optical isolation very similar to that used for the input modules. In this case, the CPU controls a light-emitting diode [10]. The LED is used to signal a solid-state device to connect the load to the line. If the load is operated by direct current, a power phototransistor is used to connect the load to the line. If the load is an alternating current device, a triac is used to connect the load to the line. No voltage spikes or electrical noise can be transmitted to the CPU (Figs. 10–14).

3.4.3. Discrete I/O modules

The most common type of I/O interface module is the discrete type, Fig. 15. This type of interface connects field input devices of the ON/OFF nature such as selector switch, pushbuttons, and limit switches [16]. Likewise, output control is limited to devices such as lights, relays, solenoids, and motor starters that require simple ON/OFF switching.

3.4.4. Analog I/O modules

Earlier PLCs were limited to discrete or digital I/O interfaces, which allowed only on/off-type devices to be connected. This limitation meant that the PLC could have only partial control of many process applications. Today analog interfaces are available that will allow controllers to be applied to practically any type of

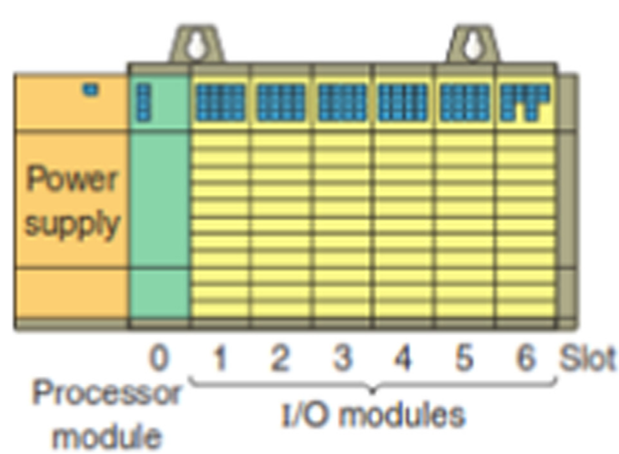

Fig. 10. Rack based I/O Section [16].

control process [16]. Fig. 15 illustrates how PLC analog input and output modules are used in measuring and displaying the level of fluid in a tank.

Common physical quantities measured by a PLC analog module include temperature, speed, level, flow, weight, pressure, and position.

3.4.5. Special I/O modules

Many different types of I/O modules have been developed to meet special needs. These includes [16]:

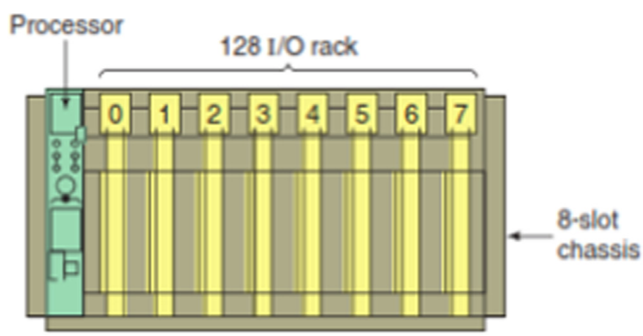

Fig. 11. Allen-Bradley chassis and rack [16].

i. High-Speed Counter Module
ii. Thumbwheel Module
iii. Encoder-Counter Module
iv. Basic or ASCII Module
v. Stepper-Motor Module
vi. BCD-Output Module
vii. PID Module
viii. Motion and Position Control Module
ix. Communication Module

3.5. Central processing unit (CPU)

The CPU coordinates and controls the operation of the entire programmable controller system. A processor module is usually located at one side of the rack assembly. It contains integrated circuit chips that include one and more microprocessors, memory chips, and circuits that enable data to be stored into and retrieved from memory [2].

The processor is composed of three main sections: the *central processing unit* (CPU), the *arithmetic logic unit* (ALU) and the *memory*.

The central processing unit is the brain of the PLC. The principle function of the CPU is to interpret and execute computer-based programs that are permanently stored in the processor's memory. These programs are written by the PLC manufacturer to enable the

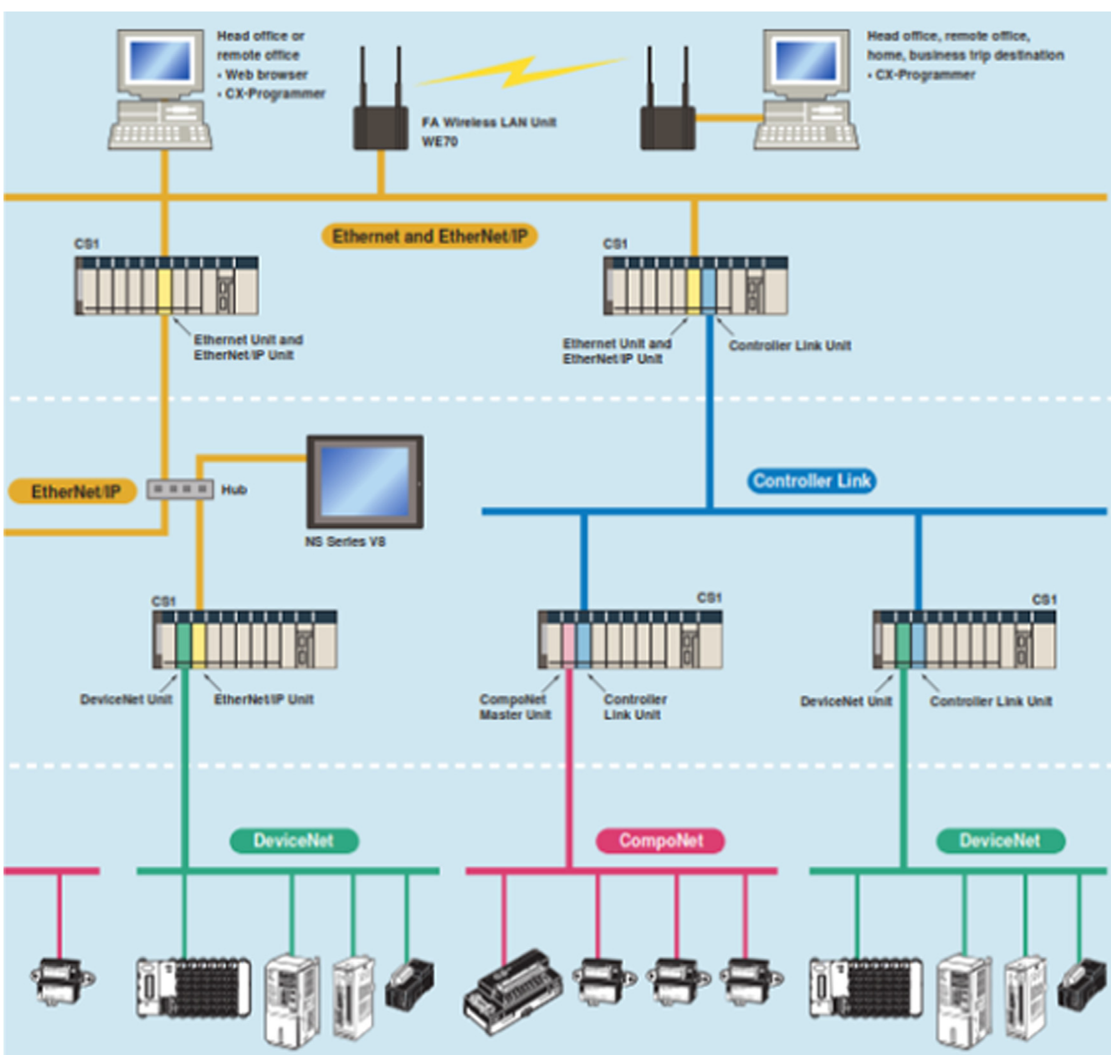

Fig. 12. Seamless networks increase for CS1 production site transparency [21].

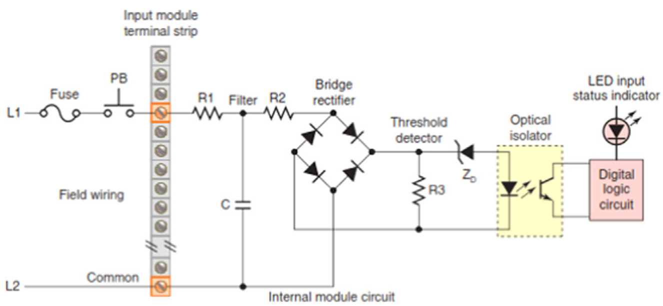

Fig. 13. Simplified diagram for a single input of a discrete AC input module [16].

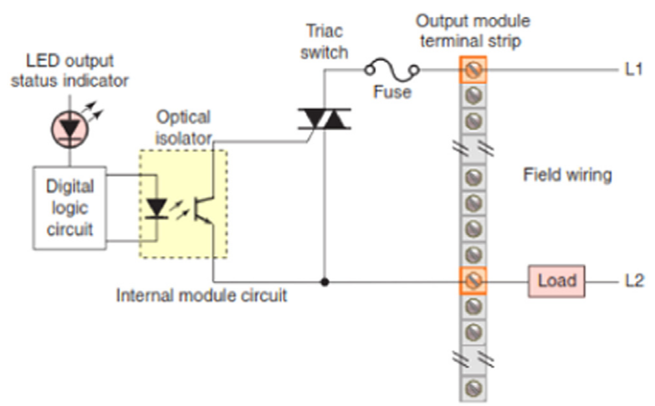

Fig. 14. Simplified diagram for a single output of a discrete AC output module [16].

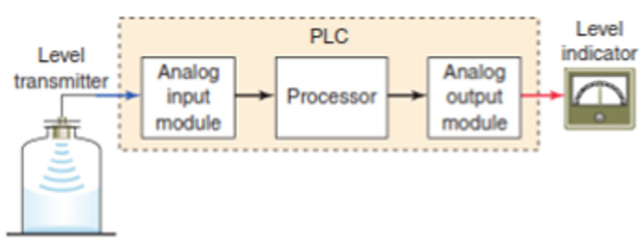

Fig. 15. Analog input and output to a PLC [16].

PLC to perform ladder logic instead of other programming languages. The CPU coordinates the operation of the ALU and the memory [2]. For example, based on the software program, the CPU determines what should be done in the ALU and the memory, and when it should be done. The CPU also performs other functions, such as self-diagnostic routines to determine whether the PLC is operating properly and communication with peripheral devices and other processors.

The function of the ALU is to perform mathematical calculations and make logic functions.

The memory function of the processor stores programs and data that the CPU needs to perform various operations. The memory is organized into several sections according to the function they perform.

The executive is a collection of system programs permanently stored in ROM memory devices. These programs enable the CPU to understand the commands if receives form the program instructions written by the operator.

As the CPU performs various operations such as logic analysis, data manipulation, or mathematical functions, it is necessary to temporarily hold data as calculations are performed or decisions are made. The work area used to temporarily store the binary information used by the processor is the scratch pad. RAM-type memory chips are used to perform scratch pad operations. RAM memory is volatile, which means that if power supplied to these chips is removed, the contents will be lost.

4. PLC programming

PLCs are widely used in automation control. They drive assembly lines, robots, and whole chemical plants. Networking system can be well incorporated with PLC application for various functions [21]. The standard IEC 61131-3 defines a number of programming languages for PLCs [22]. These languages range form high-level, graphical ones with powerful structuring possibilities to low level languages close to circuit design or machine language.

The most common way to program a PLC is to design the desired control circuit in the form of a relay logic ladder diagram and then enter this ladder diagram into a programming terminal [11]. The programming terminal is capable of converting the ladder diagram into digital codes and then sending this program to the PLC where it is stored in memory. There are also other ways to program a PLC beside ladder diagram (Fig. 16).

Below, Figs. 17 and 18 are examples of ladder diagram programming by using CX-One Programmer Software developed by Omron.

5. Other Programmable Devices

The controller is an element of the closed-loop system that processes information to perform the decision-making function. The controller can be considered the brain that enables automated system to operate without human intervention [2]. In a closed-

Fig. 16. Discrete input and output devices [16].

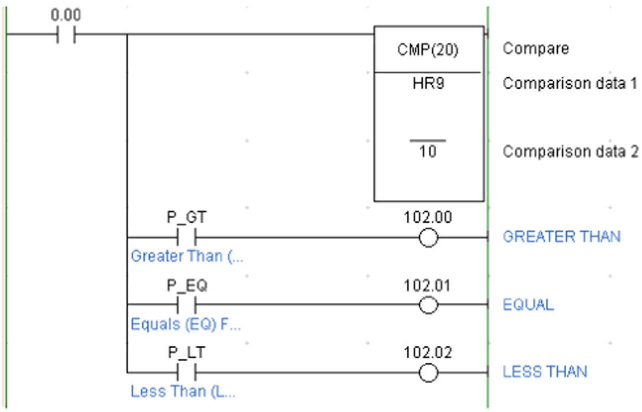

Fig. 17. Ladder diagram for Compare Instruction [23].

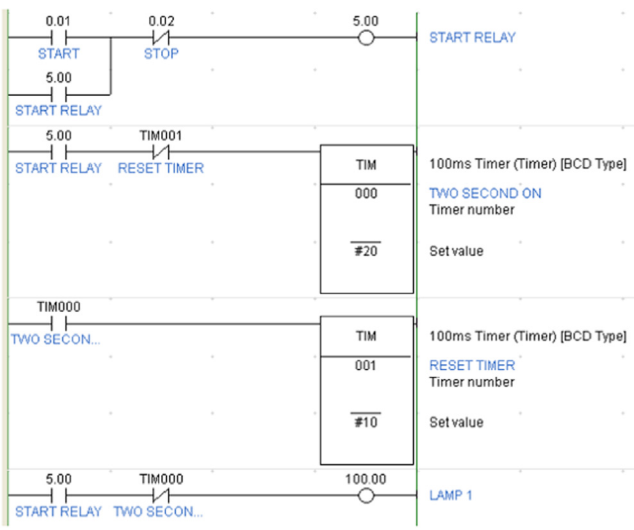

Fig. 18. Blinking light operation using CQM1H PLC. The program was written using CX-Programmer [23].

loop control system, a controller is used to compare continuously the output of a system with the required condition and convert the error into a control action designed to reduce the error. The error might arise as a result of some change in the conditions being controlled or because the set value is changed, e.g. there is a step input to the system to change the set value to a new value [9].

Then there are microcontrollers, the tools of choice for learning about electronics and programming as well as providing the capabilities needed to create sophisticated applications cheaply and easily [24].

5.1. Control modes

There are a number of ways by which a control unit can react to an error signal and supply an output for correction elements [9]:

i. The *two-step* or on-off control mode in which the controller is essentially just a switch which is activated by the error signal and supplies just an o/off correcting signal
ii. The *proportional mode* (P) which produces a control action that is proportional to the error. The correcting signal thus becomes bigger, the bigger the error. Thus as the error is reduced the amount of correction is reduced and the correcting process slows down.
iii. The *derivative mode* (D) which produces a control action that is proportional to the rate at which the error is changing. When there is a sudden change in the error signal the controller gives a large correcting signal; when there is a gradual change only a small correcting signal is produced. Derivative control can be considered to be a form of anticipatory control in that the existing rate of change of error is measured, a coming larger error is anticipated and correction is applied before the larger error has arrived. Derivative control is not used alone but always in conjunction with proportional control and, often, integral control.
iv. The *integral mode* (I) which produces a control action that is proportional to the integral of the error with time. Thus a constant error signal will produce an increasing correcting signal. The correction continues to increase as long as the error persists. The integral controller can be considered to be 'looking back', summing all the errors and thus responding to changes that have occurred.
v. *Combinations of modes*: proportional plus derivative (PD) modes, proportional plus integral (PI) modes, proportional plus integral plus derivative (PID) modes. The term three-term is used for PID control.

5.2. Programmable Devices

In this section we will briefly discuss the various types of programmable devices available in the industries.

i. PID controller-a proportional-integral-derivative controller which can be either analog or digital [11].
ii. Adaptive controller – a controller that is capable to monitor their own output and make minor changes in the gain constants ($K_P K_I$ and K_D) [9,11].
iii. PIP controller – A Proportional+Integral+Preview (PIP) controller is a system that incorporates information of the future path in its current output [11]. Many systems have this information available – either the entire path is stored in memory or the system is equipped with a preview sensor.
iv. Fuzzy logic controller – Fuzzy logic is a form of artificial intelligence that enables a computer to simulate human reasoning [2,9,11]. Reasoning is the process of going from what is known to what is not known. An example of *deterministic reasoning* is to use the 'if-then' rule. *Non-deterministic reasoning* allows us to make predictions based on probability. Fuzzy logic was proposed by L.A. Zadeh working at Berkeley in 1965.
v. Peripheral Interface Controller (PIC) microcontroller (MCU) – PIC MCU for creating any applications easily and effectively. A PIC MCU can be programmed using Assembly language, BASIC, and C [24].
vi. Programmable Logic Arrays (PLAs) – Based on the idea that logic functions can be realized in sum-of-products form, a PLA comprises a collection and AND gates that feeds a set of OR gates [25–27]
vii. Programmable Array Logic (PAL) – in a PLA both the AND and OR plans are programmable. Historically, the programmable switches presented two difficulties for manufacturers of these devices: they were hard to fabricate correctly, and they reduced the speed-performance of circuits implemented in the PLAs. These drawbacks led to the development of a similar device in which the AND plane is programmable, but the OR plane is fixed [25].
viii. Complex Programmable Logic Devices (CPLDs) – for implementations of circuits that require more inputs and outputs a CPLD, can be used. A CPLD comprises multiple circuit blocks on a single chip, with internal wiring resources to connect the circuit blocks.
ix. Field-Programmable Gate Array (FPGA) – is a programmable logic device that supports implementation of relatively large

logic circuits. FPGAs do not contain AND and OR planes. Instead, FPGAs provide logic blocks for implementation of the required functions.

6. PLC applications

PLCs have been widely used for many applications, e.g. pumping systems, motor control, energy research, system monitoring and etc. Some specific applications are discussed in the subsequent section.

6.1. Water and wastewater management control

Bayindir & Cetinceviz (2011) [3] describes a water pumping control system that is designed for production plants and implemented in an experimental setup in laboratory, Fig. 19. These plants contain harsh environments in which chemicals, vibrations or moving parts exist that could potentially damage the cabling or wires that are parts of the control system. Furthermore, the data has to be transferred over paths that are accessible to the public. The control systems that it uses are a PLC and industrial wireless local area network (IWLAN) technologies. It is implemented by a PLC, a communication processor (CP), two IWLAN modules, and a distributed input/output (I/O) module, as well as the water pump and sensors. The system communication is based on an Industrial Ethernet and uses the standard Transport Control Protocol/Internet Protocol for parameterisation, configuration and diagnostics. The main function of the PLC is to send a digital signal to the water pump to turn it on or off, based on the tank level, using a pressure transmitter and inputs from limit switches that indicate the level of the water in the tank.

Ramos et al. (2010) [28] developed an improvement of photovoltaic pumping systems [PVPS] based on standard frequency converters [SFCs] by using a PLC. PVPS based on SFCs are currently experiencing a growing interest in pumping programs implemented in remote areas because of their high performance in terms of component reliability, low cost, high power range and good availability of components virtually anywhere in the world. However, in practical applications there have appeared a number of problems related to the adaptation of the SFCs to the requirements of the PVPS. Another disadvantage of dedicated PVPS is the difficulty in implementing maximum power point tracking [MPPT]. Based on the testing being done, a PLC can solve the problems. The PLC does not increase the cost and complexity of the system, but improves the adaptation of the SFC to the photovoltaic pumping system, and increases the overall performance of the system.

Punal et al. (1999) [29] made a study on industrial pilot scale anaerobic wastewater treatment (AWT) using an advanced combination of PLC-PC system to monitor and control the operation of an industrial pilot plant. The system proved to be flexible and reliable. The PLC has its own setting point, which facilitates control of the plant even when the control unit in the PC is out of order. The software, developed and implemented in the PC allowed a proper signal acquisition, filtered in order to avoid noise, and stored to retrieve the information.

Manesis, Sapidis and King (1998) [30] studied an intelligent control system for wastewater treatment plants whereby their study consists of fuzzy system combined with a PLC. Their findings indicate that they usage of a PLC with a fuzzy controller was favourable and the potential was limitless.

Fantozzi et al. (2014) [31] researched the implementation of ICT Solutions for Efficient Water Resources (ICeWater) Management in Europe. The management addressed the areas of sensors, monitoring, automation and control. PLCs controls pumps that are fitted with variable frequency drive (VFD), the VFD varies the frequency that's driving the pump in order to regulate or vary the output of the pump.

A water recording system for large user of water supply network based on PLC control system was developed by Jie et al

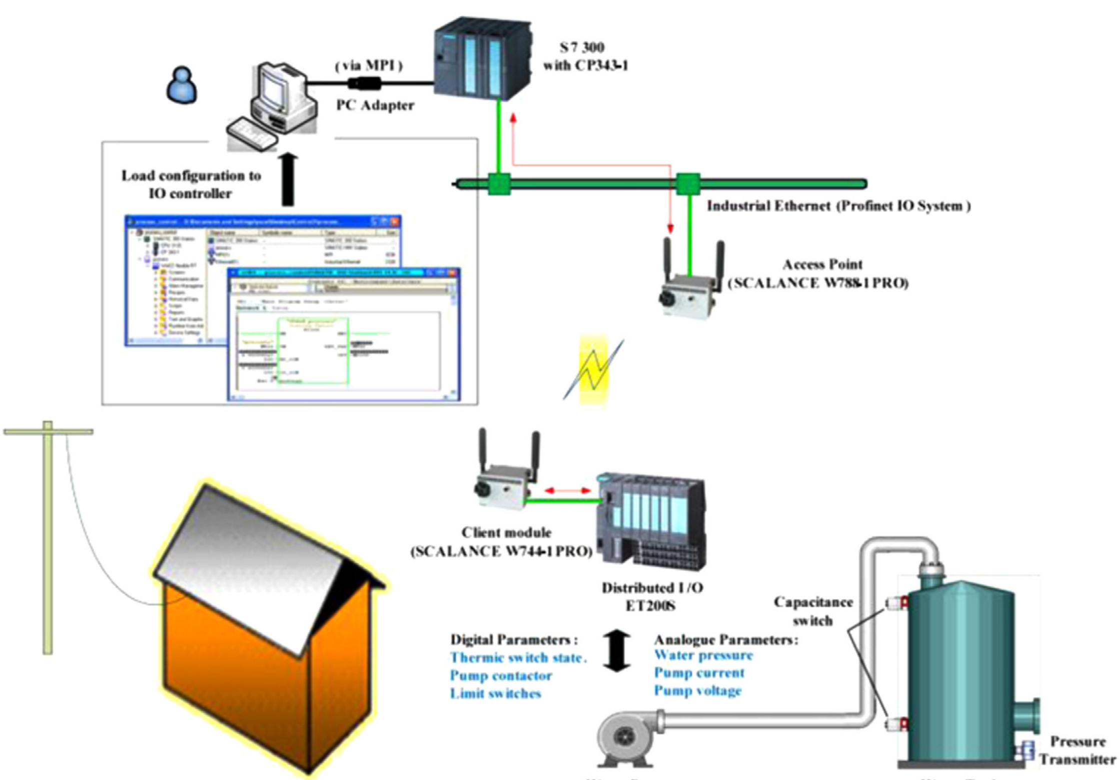

Fig. 19. System configuration diagram [3].

(2011) [32]. The research was mainly describes a simple designed transformation from gear rotation to a practical on/off pulse signal which is collected and stored by a PLC. All date can be read form the PLC by a computer after a sampling period, such as 10 days or less.

Smith et al. (2005) [33] design a generic control system for optimizing back flush durations in a submerged membrane hybrid reactor. A PLC controls the implementation of the system. Smith et al. (2006) [34] also design a new approach to backwash initiation in a membrane system.

6.2. Energy research

Renewable energy research has been going on for decades. Nowadays, with the high reliance on fossil fuel energy and the major cause of ozone layer depletion, other types of renewable energy has been researched and implemented. Highly developed industry has already spent extremely large energy in the past and also caused very serious environmental pollution. Greenhouse effect has also continuously destroyed the atmospheric ozone layer [35]. In this paper we will discuss some other types of energy research that uses PLC as the main control or joint control with other control systems.

6.2.1. Sun-tracking system

Ahmad et. al (2013) [36] carried test on the generated power and the power consumption of an open-loop time and date based sun positioning solar collector system under three weather conditions: sunny and clear day, cloudy day and heavy overcast and rainy day under Malaysian tropical climate at location E100°11', N6°26'. The two-axes tracking system used a PLC to maneuver a photovoltaic solar module based on 10° altitude angle tracking and 10 azimuth angle tracking.

Sungur (2009) [37], developed a multi-axes sun-tracking system with PLC control for photovoltaic panels in Turkey. In his study, the azimuth and solar altitude angles of the of the sun were calculated for a period of 1 year at 37.6 latitude in the Northern hemisphere, where Turkey is located, and according to these angles, an electromechanical system which tracks the sun on both axes and which is controlled via a PLC and an analog module was designed and implemented.

Al-Soud et al. (2010) [38], developed a parabolic solar cooker with automatic two axes sun tracking system for overcoming the need for frequent tracking and standing in the sun, facing all concentrating solar cooker with manual tracking, and a PLC was used to control the motion of the solar cooker. As a result from the test, the water temperature inside the cooker's tube reached 90 °C in summer days, when the maximum registered ambient temperature was 36 °C.

Al-Mohamad (2004) [39] developed a moving photo-voltaic (PV) module sun-tracking system using a PLC unit. The PLC units were employed to control and monitor the mechanical movement of the PV module and to collect and store data related to the Sun's radiation. The author found that the daily output power of the PV was increased by more than 20% in comparison with that of a fixed module.

Mousazadeh et al. (2009) [40] review on different types of sun-tracking system also confirms that PLCs are applied on these trackers.

Abu-Khader et al. (2008) [41] evaluate a multi-axes sun-tracking system at different modes of operation in Jordan. In [41] the author developed two systems based on vertical control and slope control.

6.2.2. Wind energy

Ting et al. (2011) [35] developed a wind chiller integrated with wind generator. A PLC is applied in this forced dual system to select the wind chiller or the wind generator separately in terms of the rotational speed of the wind machine.

Galardo-Calles et al. (2013) [42] researched the implementation of wind farm in Spain. Their findings indicates that monitoring and control of wind turbines are by using PLCs and SCADA that are directly connected in the local network system.

6.2.3. Photovoltaic applications

Manolakos et al. (2004) [43] developed a stand-alone photovoltaic power system for a village in Donoussa Island in the Aegean Sea Greece, using pumped water energy storage. During the day, the load is satisfied directly from the photovoltaic generator through the inverter, while any energy surplus is directed to the pump for pumping water from the low level reservoir, to the high level reservoir. During the night, water is turbined to the low level reservoir providing energy to the load. The whole system is controlled using a Siemens S5 115-U PLC.

Lamont and Chaar (2011) [44] developed a stand-alone surface cleaning system for photovoltaic panels using PLC and PIC based cleaning mechanisms. Their systems were proven to be efficient in cost and performance as well as having capability to be scalable.

Zaki, Eskander and Elewa (1994) [45] developed PV generator to generate energy for water pumping energy for irrigation, household purposes and the energy needs. The system used a PLC control system.

6.2.4. Heating, ventilating and air-conditioning (HVAC) control

Soyguder and Alli (2010) [46] designed a heating, ventilating and air-conditioning (HVAC) system with two different damper gap rates (actuators position) of a HVAC system. A PLC using a PID control algorithm was utilized to control the air flow on the entrance ducts for the indoor.

6.3. Research, training and education

Dhanabalan & Selvi, 2015 [47] did a study on how to improve the speed of scan time of PLC multiple analog to digital converter by using a field programmable gate array (FPGA). The simulation result shows that the scan time of multichannel analog to digital (ACD) can be improved. His finding indicates that conversion time is 13.17 μs.

Po et al. (2011) [48] design a fuzzy controller for air conditioning system using PLC as the controller. His result manage to change the different load of the compressor at any different levels.

Besada Portas et al. (2013) [49] develop a remote laboratory for systems engineering and automation control courses, based on the combined use of TwinCAT, a laboratory Java server application, and Easy Java Simulations (EJS). The TwinCAT system is used to close the control loop for the selected plants by means of PLCs in PCs.

Kulisz et al. (2015) [50], researched the Arithmetic and Logic Unit (ALU) of a prototype PLC, implemented in an FPGA device. The ALU can execute 32 operations, which include the basic logic operations, comparators, and the four basic arithmetic operations. The migration of Hardware Description Language (HDL) can be easily ported to FPGA architectures or to an Application Specific Integrated Circuit (ASIC) technologies.

Mokhtarname et al (2015) [51] study the design and implementation of an Industrial Generalized Predictive Controller with the aid of artificial neural networks (ANNs) for multivariable processes via industrial PLCs. His results indicates that advanced techniques can be implemented on PLCs with normal computational power without bearing the high cost of upgrading the PLCs.

Kabalan et al. (2015) [52] design an electrical load controller for rural micro-hydroelectric using a PLC. The controller was experimentally tested in a lab using a micro-hydroelectric emulator. Base on the data collected, a PLC can be used as a viable load control system.

Tsukamoto and Takahashi (2014) [53] researched on the method to model elevator control logic using Mark Flow Graph (MFG), and translate the MFG model into PLC programming language.

Guler and Ata (2013) [54] developed a training mechanical ventilator set for clinicians and students. Mechanical ventilator is widely used in anesthesia and intensive care units. The patients are usually connected with the ventilator through an endotracheal tube (ETT). Oxygen, which is the most important gas for keeping human alive is moved into patients lungs by the use of ventilators according to setting of clinicians. Clinicians have to determine the best treatment for patients because of the fact that ventilators generally work as open loop controlled. Thus, a training mechanical ventilator set was designed and implemented. PLC was used to control the system. It controls inspiration/expiration valves and evaluates pressure info received from pressure sensors. Inspiration/expiration time and operation mode can be easily changed on screen. The designed and implemented set is cheaper than ventilator used in an intensive care units.

Bayrak and Cebeci (2012) [55], developed an automaton platform for electrical and electronics students. The authors introduced an application study for education of electrical and electronic students about programming, connecting and designing PLC and Supervisory Control and Data Acquisition [SCADA] systems and understanding automation system.

Engin (2013) [56] design a PID control algorithm for a level control system that was implemented using a PLC for the purpose of educational training in school. Result of the experiments indicates that auto-tuning mode of the PID control system was stable. Samin et al. (2011) [57] also use a PID control system implemented by a PLC for a heating tank in a mini automation plant. Base on the result, the controller was able to handle system.

Katrancioglu and Yilmaz (2011) [58], developed a distance control tool laboratory experiment set. The control experiment can be done internally in the laboratory but also anywhere as long as there is internet connectivity. The set consists of an electronic control card connected to a computer, a server and client applications runs the system with requests and confirmation. Yilmaz and Katrancioglu (2011) [6] also developed a PLC experiment set with internal experiment block for education.

Chen and Gao (2012) [59] designed and implemented a remote PLC laboratory. In [59] the authors describes that the development of computer and the internet have made distance learning for remote laboratory designed to be used in PLC practical work to be easier and faster. The programming exercises were able to be done at different location and time.

Callahan et al. (2005) [60] developed a computational methods for planning and developing flexible manufacturing systems.

Ozdemir and Orhan (2012) [61] designed an experimental micro hydro power plant prototype system for the use of education. A PLC system was chosen as the main controller.

6.4. Manufacturing

Buhrer et al. (2015) [62] design a manufacturing automation system using an Orchestration Engine which allow flexibility in changes in PLCs. The Orchestration Engine even able to adapt to physical changes of production environment.

Hong (2011) [63] developed an automatic turnover device in automatic production line using a PLC based control system. By using the PLC control hydraulic system, the system's stability, reliability, security and automation level was greatly improved.

Tay et al. (2005) [64] developed a flexible and programmable vibratory bowl feeding system which is suitable for use in a flexible manufacturing system [FMS]. Controlled by computer and driven by electro-pneumatic cylinders and stepper motor, this feeding system is capable of identifying the orientations of non-rotational parts and actively re-orientating them into the desired orientation. The feeding system was controlled by a PLC system.

Chua (2007) [65] developed an active feeder, controlled and driven by a PLC and electro-pneumatics. Swider et al. [8] also developed a system using a PLC to control electro-pneumatic systems.

Saad and Arrofiq (2012) [4] developed and design a PLC-based modified controller for PWM-driven to control speed of an induction motor and implementing a constant V/Hz ratio control. The plant consists of a PWM inverter, an induction motor and a load. The PWM inverter functions as an interface between the PLC and the induction motor. The personal computer (PC) acts as a terminal for developing and downloading the program including the fuzzy logic routines to PLC and human–machine-interface (HMI) design to HMI.

Jang et al. (1997) [66] design a manufacturing cell consists of a PLC, two industrial robots, tow machine stations (for grinding and washing), and a conveyor. The cell has proven effective in achieving the efficiency and reliability advantages of multirobotic operations.

Piggin (2004) [67] describe safety-related fieldbus is now being employed in many varied applications. The combination of predefined diagnostics and visualization for some safety controllers enable timely detection and display of diagnostics. Status and safety diagnostics from the programmable safety controller can be easily integrated into PLC/PC-based systems, using a conventional (non-safe) fieldbus. The programmable safety controller enables the continuous monitoring of safety, whilst providing the auditing

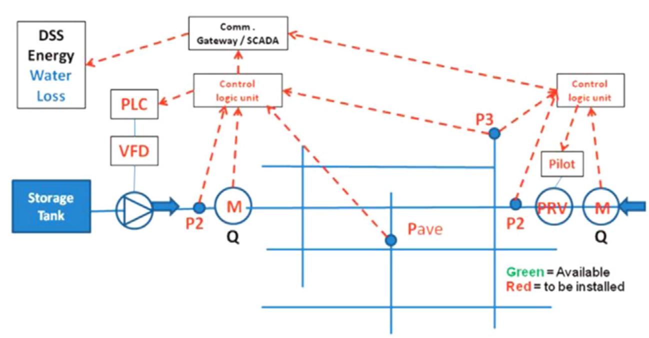

Fig. 20. Pressure Optimisation in Abbiategrasso PMZ in Milan [31].

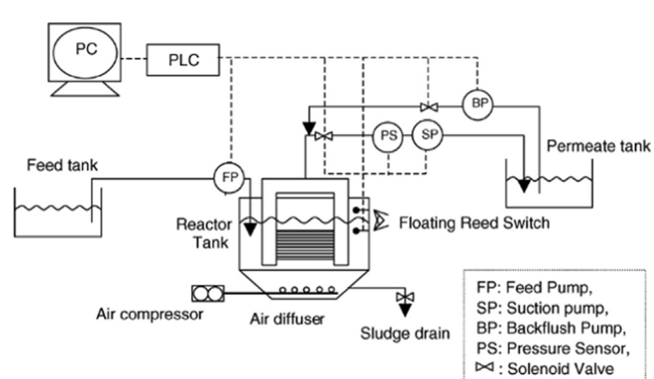

Fig. 21. Experimental set-up of the SMFAHS [33,34].

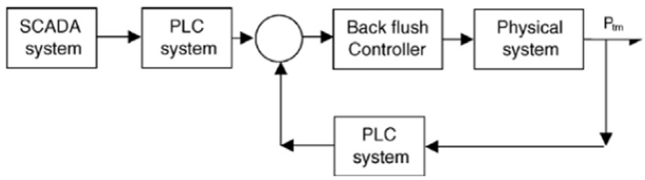

Fig. 22. Control system block diagram [33].

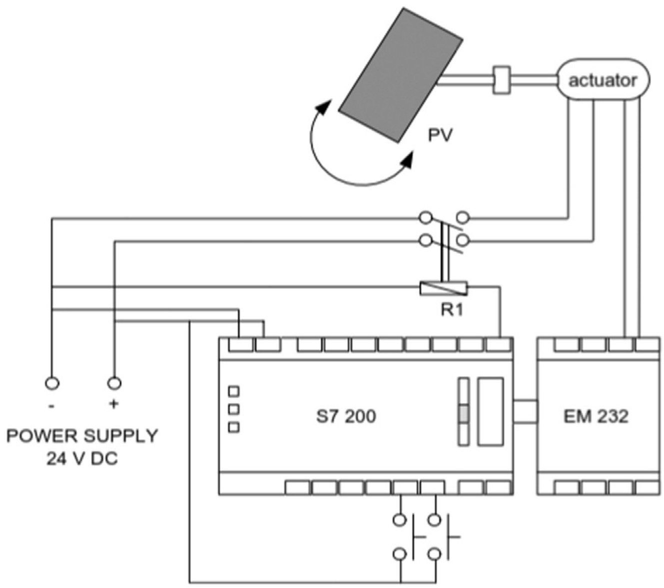

Fig. 23. The electromechanical connection diagram which provides the movement of the system on the vertical axis [37].

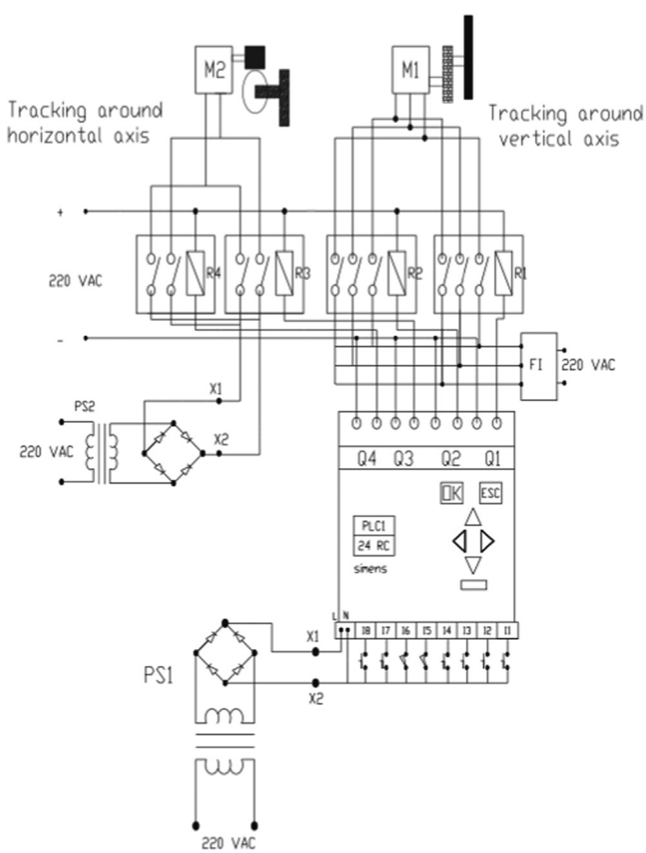

Fig. 24. The electromechanical circuit for driving the two motors of proposed parabolic solar cooker [38].

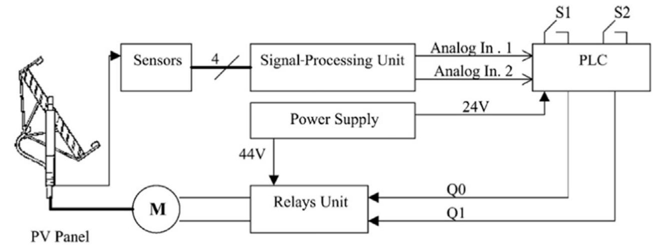

Fig. 25. The whole system block-diagram [39].

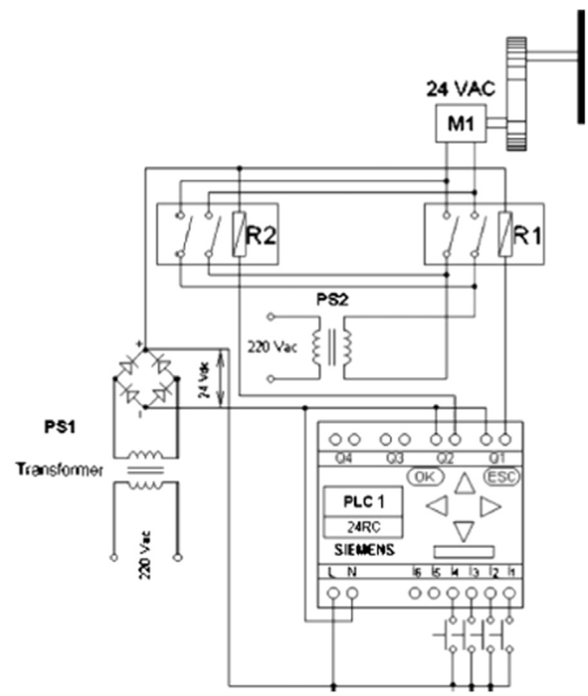

Fig. 26. The electromechanical circuit for vertical control [41].

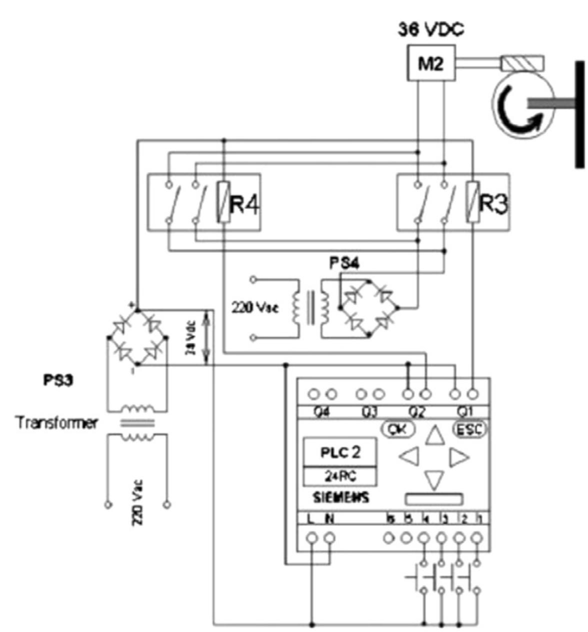

Fig. 27. The electromechanical circuit for slope control [41].

safety functionality, ensuring safety system testing at regular intervals (e.g. at the beginning of each day or shift).

Ren et al. (2007) [68] developed a closed-loop tension control system with the PLC with function modules as its control kernel, the alternating current (AC) servo motor as the execute element and the radius–following device to accomplish the real-time radius compensation.

Hajarnavis and Young (2008) [69] investigates PLC software design techniques in the automotive industry throughout Germany, UK and the USA. The author targeted the survey at a specific production line called body-in-white shops, the part of the assembly process in which panels are joined together to form a car body. This is the most heavily automated part of the car manufacturing process, with devices such as robots, weld controllers, clamps, drives and transfer facilities all requiring control by a PLC coordinating all of the operations taking place in a manufacturing cell.

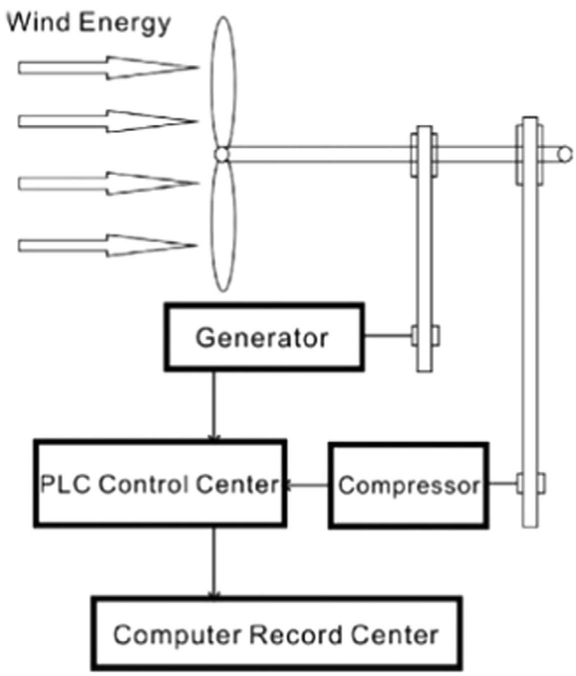

Fig. 28. Schema of the wind forced dual system in connection with the PLC controller [35].

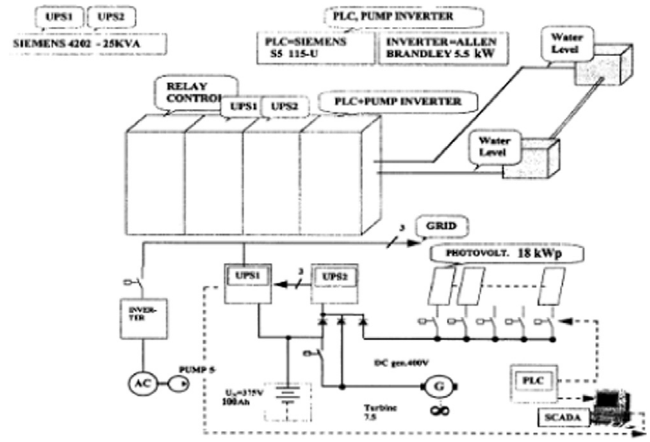

Fig. 30. Schematic diagram of the installed system [43].

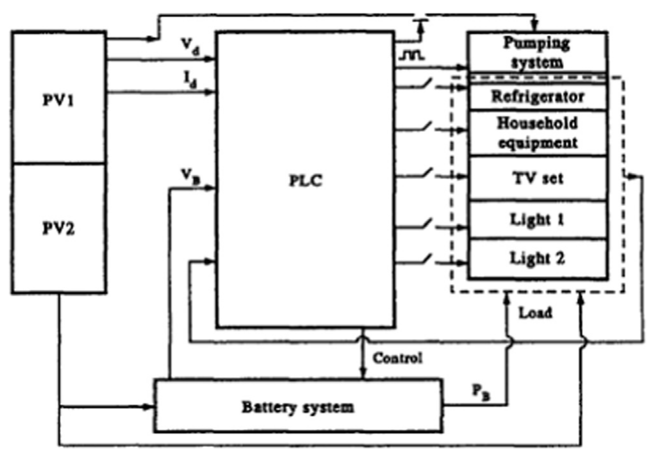

Fig. 31. System block diagram [45].

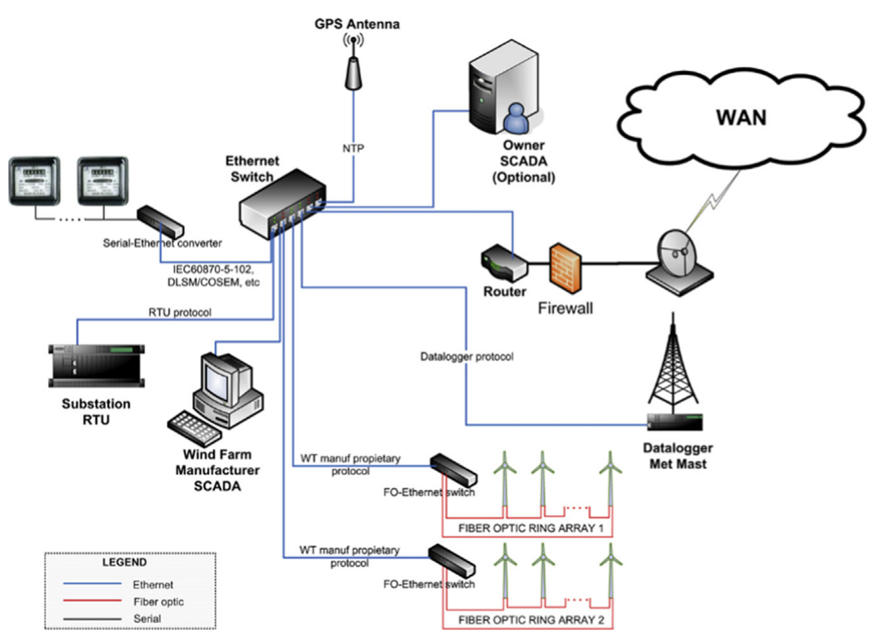

Fig. 29. Typical control architecture of a wind farm [42].

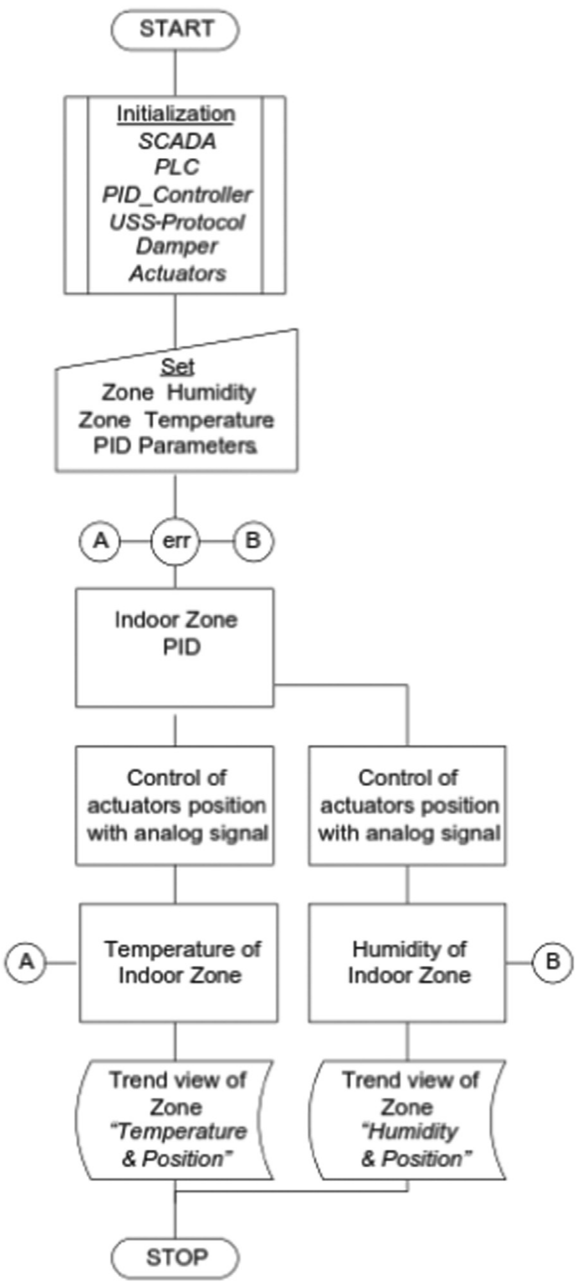

Fig. 32. The flowchart of the PLC program [46].

Hu et al. (1999) [70] developed two generic diagnostic models based on the logical function chart and sequential control process of a PLC. The author presented models of a typical flexible manufacturing system for diagnostics.

Alper Selver et al. (2011) [71] developed an automated industrial conveyor belt system using image processing and hierarchical clustering for classifying marble slabs. A PLC was used as the controller.

6.5. Control and monitoring of plants and other applications

Ardi et al. (2013) [72] design a control system for a machining process of piston using PLC. Their study indicates an improvement of 30% of cycle time from 40 sec per piece to 28 second per piece.

Honda et al. (2008) [73] replaced a control system of the cryogenic facility in the JT-60 NBI system with employing the PLC and SCADA system. The system used function block diagram (FBD) to optimize the control. At present, the replaced system has worked well.

Zhang et al. (2009) [74] studied the effect of flue gas impurities on CO^2 capture performance from flue gas at coal-fired power stations by vacuum swing adsorption. A fully programmable logic controller (PLC) automated three-column pilot plant was built to perform the study with real-time control and data acquisition conducted through Human Machine Interface/Supervisory Control and Data Acquisition (HMI/SCADA) system.

Kazagic and Smajevic (2007) [75] did an experimental research into the ash behavior of different Bosnian coal types and biomass fired in electrically heated entrained pulverized fuel flow experimental reactor. The temperature of the reaction zone is controlled by a programmable logic controller (PLC) with thyristor units for each of the heating zones, allowing the process temperature to be varied at will across the range from ambient to 1560 °C.

Sastry and Seekumar (2012) [76] developed an automatic operations and real time monitoring and controlling of a marine loading arm. The system uses industry standard position sensors, PLC systems, interactive human machine interface (HMI) and integrates fail-safe operation and emergency shutdown procedures.

Guasch et al. (2000) [77] developed approaches for improving the fault diagnosis of gas turbine. The approach consists of the automatic development of a troubleshooting system which can be automatically built using the deterministic knowledge embedded within the Programmable Logic Controller (PLC). This system tries to overcome diagnosis deficiencies present especially in older gas turbines PLC controllers.

Kolokotsa et al. (2002) [78] implemented a genetic algorithms optimized fuzzy controller for the indoor environmental

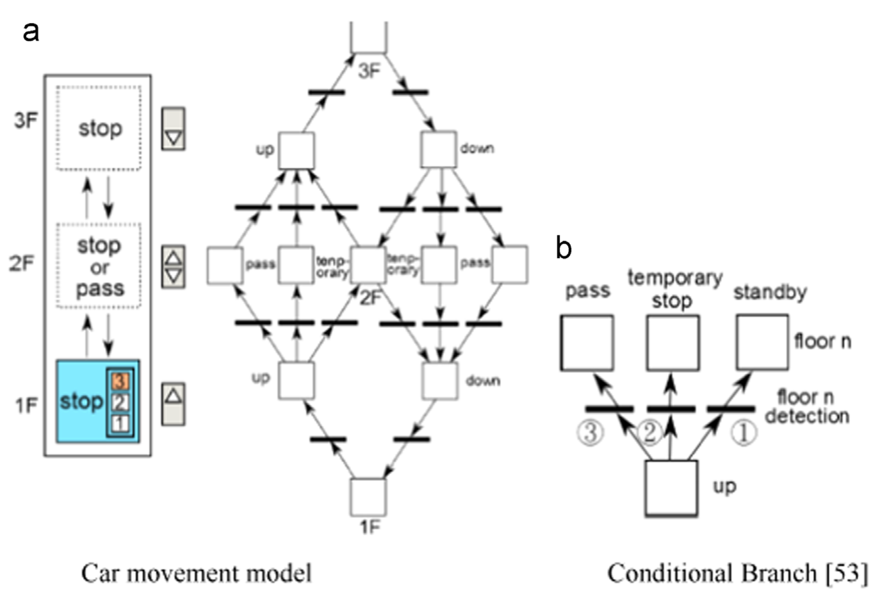

Fig. 33. (a) Car movement model (b) Conditional Branch [53].

management in the building of the Laboratory of Electronics of the Technical University of Crete. The PLC or local operating network (LON) module runs the optimized fuzzy controller that retains indoor thermal comfort, visual comfort and indoor air quality.

Aydogmus and Talu (2012) [5] developed a vision-based measurement installation using a PLC powered via Object Linking and Embedding for Process Control (OPC) technology. The system consists of a PLC, webcam and a SCADA PC.

Yu and Wen-qing (2011) [79] developed a gas distributing device using a PLC with Human Machine Interface (HMI) device to control the output of mass flow, gas output mixture and proportion of the flammable gas continuously.

Xin et al (2012) [80] design a system that can precisely regulate the moisture and the concentration of potassium (K) in the soil in plant ecological park by using a PLC. The system used a PLC controller and at the same time a control algorithm used to analyze the moisture and concentration of K.

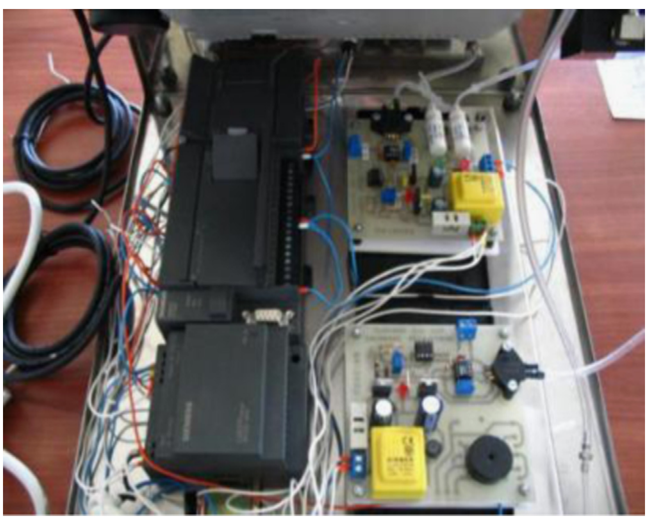

Fig. 34. Electronic circuits of developed mechanical ventilator training set [54].

Jing et al. (2012) [81] researched on the implementation of intelligent control system of stack-boiler. The system combines a self-learning and self-optimizing fuzzy control system with a PLC. The fuzzy system controls the ratio of air/coal for achieving the best and optimized combustion, while the PLC accelerates the speed of response to the boiler.

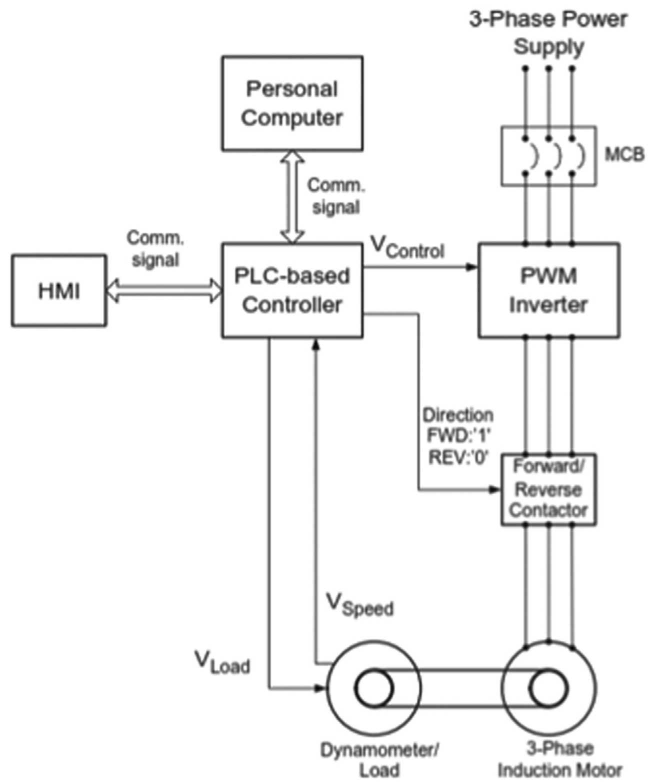

Fig. 36. Physical system layout with HMI, PLC, PWM inverter, induction motor and load [4].

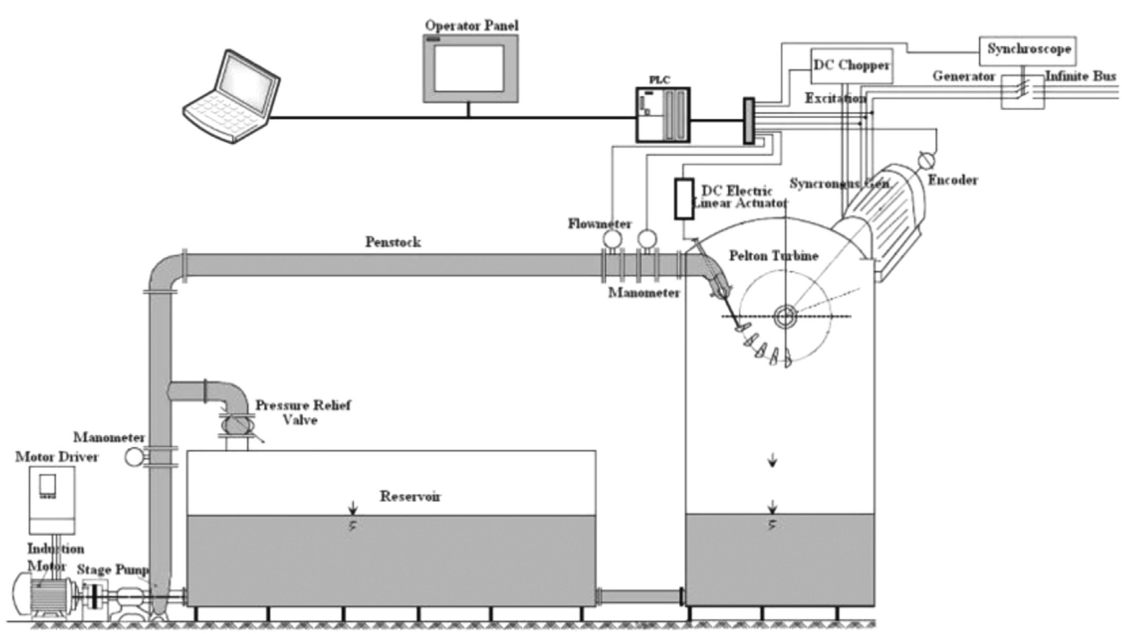

Fig. 35. Scheme of the Micro Hydro Power Plant Prototype [61].

A comparative study of single-loop and cascade control of third-order object for water tanks was done by Zhong and Luo (2011) [82]. The system was controlled by Siemens PLC.

Two independent sodium loops under common name INSOT facilities were constructed in Fast Reactor Technology Group, IGCAR for conducting material testing of Prototype Fast Breeder Reactor (PFBR) components in dynamic sodium, Shanmugal et al. [83]. A versatile PLC based instrumentation system was successfully implemented for the monitoring and control of the process parameters.

Experimental Advanced Superconducting Tokamak (EAST) is the first whole superconducting tokamak with divertor configuration in the world, Chen et al (2012) [84]. A stable and reliable control system for vacuum operation is required essentially during the plasma discharges. PLCs hardware control system is applied on the basic level.

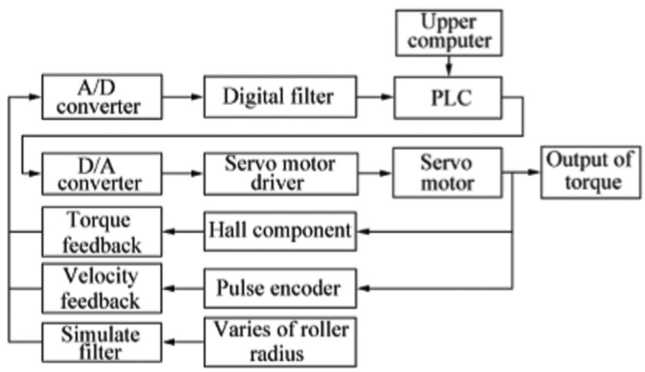

Fig. 37. Principle of tension control system [68].

Randolf and Moore (2006) [85], developed a testing system for proton exchange membrane (PEM) using the integration of real time target (which runs the simulation), the test stand PC(that controls the operation of the test stand) and the PLC, for safety and low-level control tasks (Figs. 20–45).

7. Advantages and limitations of PLC

Complete automation assembly is a high-production tool. It is expensive and will involve a degree of investment risk [86]. Here a PLC can help in expanding the system to a semi or even a fully automated system, but it does come with its own limitations.

In this section we will discuss some of the advantages and limitations that a PLC have.

7.1. Advantages of a PLC

Although PLCs are similar to 'conventional' computers in terms of hardware architecture, they have advantages suited for industrial control [87]. Listed below are some of the advantages of a PLC;

i. It is more rugged and has noise immune capability
ii. modular approach in construction, allowing easy replacement/addition of units (e.g. I/O)
iii. standard I/O connections and signal levels

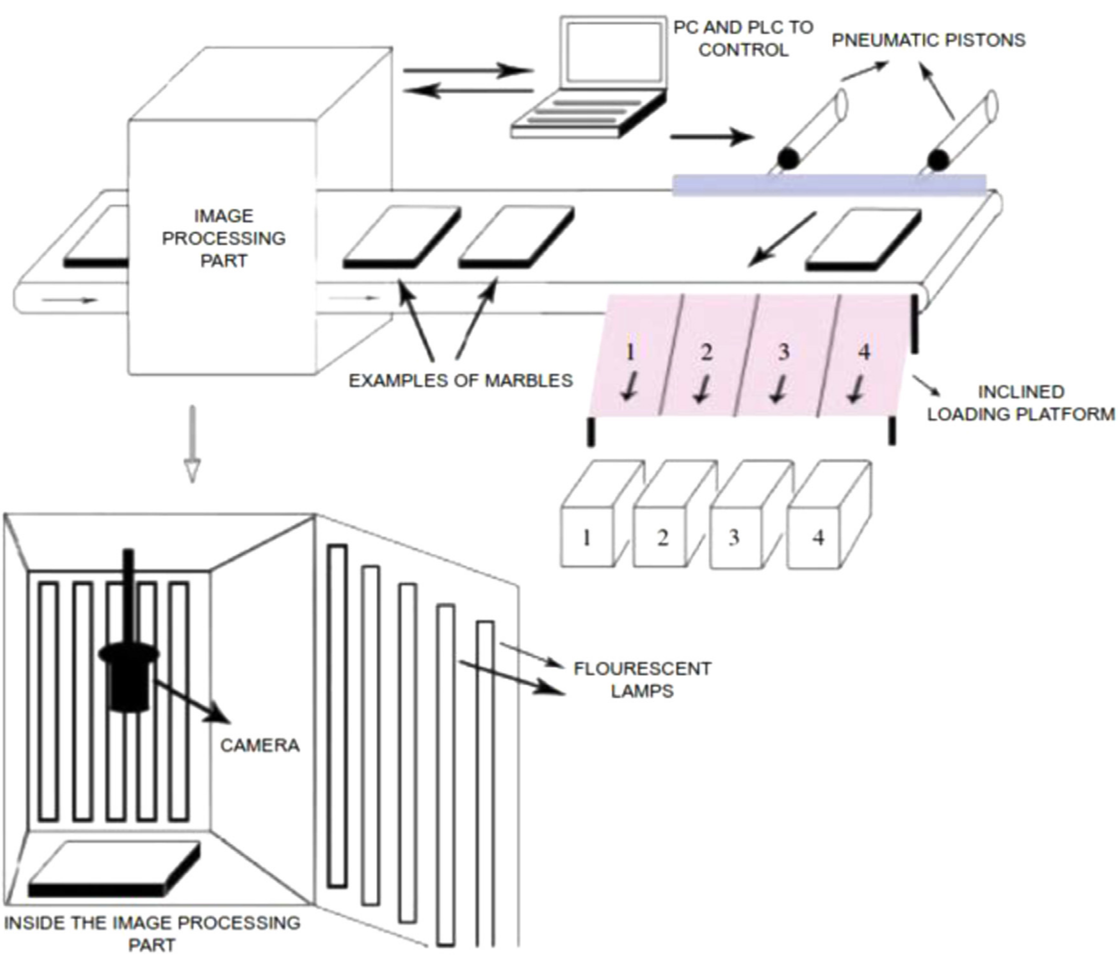

Fig. 38. Block diagram of the electro-mechanical conveyor belt system for marble classification [71].

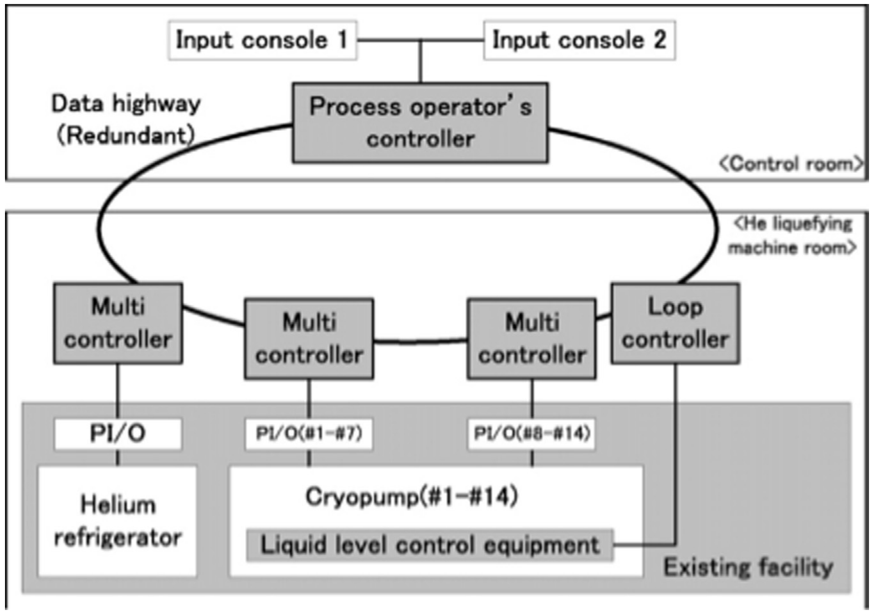

Fig. 39. Original control system with Distributed Control System (DCS) [73].

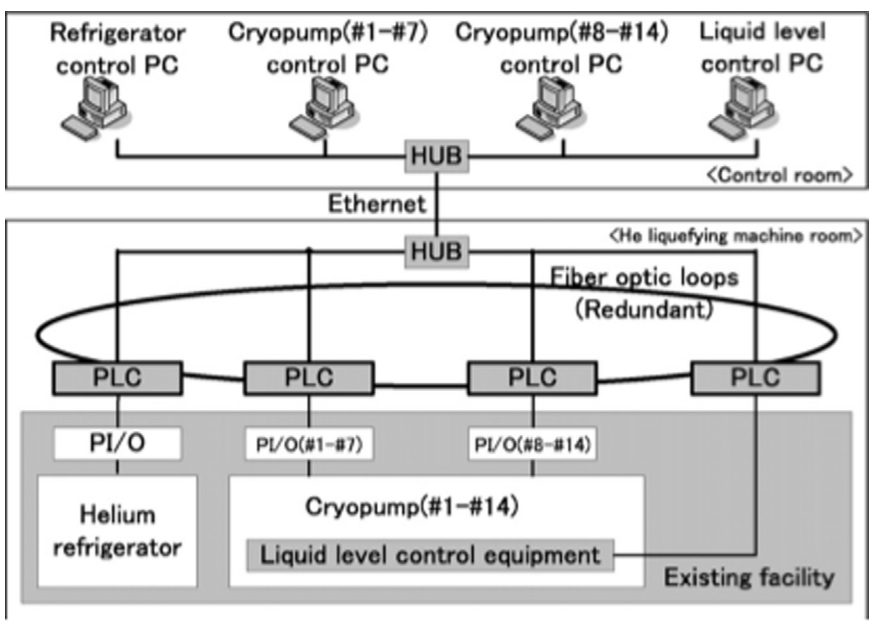

Fig. 40. PLC based control system [73].

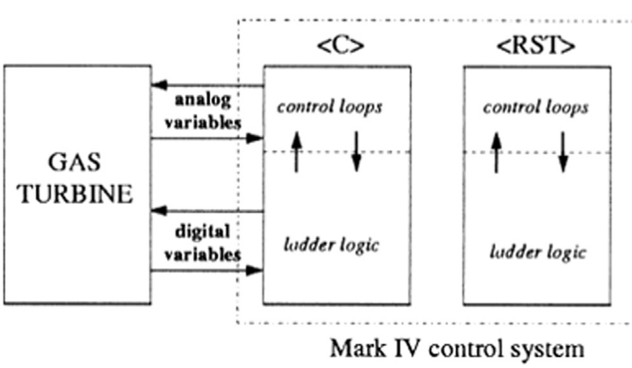

Fig. 41. Basic block diagram of Speedtronic Mark IV control system [77].

iv. More reliable compare to relays since electro-mechanical devices, and physical wear in relay logic controls occurs every time the devices are turned on.
v. Easy to understand, program and reprogram (e.g. ladder diagram): Off-line programming: programming software allows PLC program development on the PC to be tested with emulator software to find problems before the software is used in the control system. On-line programming allows the programmer to edit ladder logic rungs while the PLC is executing a production program [14].
vi. Broad application base: PLC software supports a broad range of discrete and analog applications in numerous industries.
vii. Low cost and small footprints: the cost and size of PLCs have dropped significantly in the last 10 years [14]. A micro PLC

which could fit in the palm of your hand, offer powerful machine control for less than US300.

viii. High-end control grows exponentially: although cost and size are dropping on the low end, the capabilities of large PLC systems expand as well. The ability to network and distribute the control using numerous proprietary and international network standards permits PLCs to take control of entire manufacturing systems and production plants [14].

Aprea and Maiorino (2009) [88] did an experimental investigation on working optimization for a "split-system" to cool air in residential application by varying the heat rejection proposed of the use of a PLC to improve the control of an electronic back pressure valve because of the flexibility of the control system.

7.2. Limitations of a PLC

In this section, we will discuss the limitations of PLC against a PC programming since, nowadays automation are mostly PC based system and high level programming language that are able to execute automated system. Listed below are the limitations of a PLC against a PC.

i. PCs improve at a rapid pace, cheaper and have more power than a PLC [1]

ii. Pentium systems widely available today outperform even the fastest PLC

iii. A new generation of PCs becomes available every six to nine months

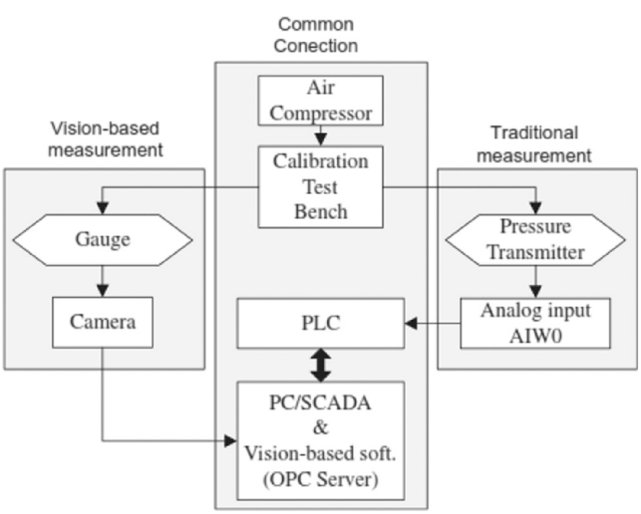

Fig. 42. Experimental setup for comparison of the proposed and traditional connection [5].

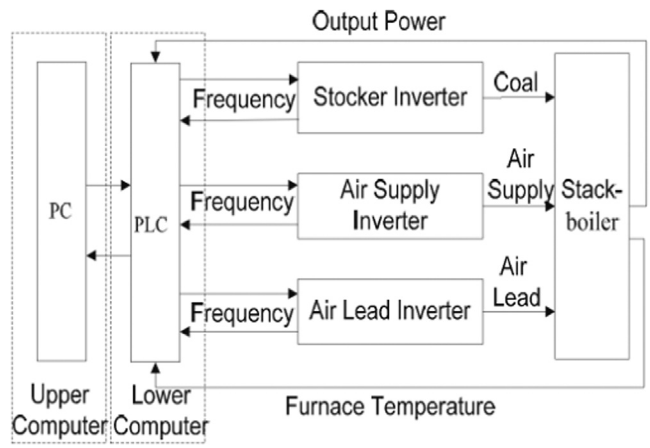

Fig. 44. Structure diagram of stack-boiler system [81].

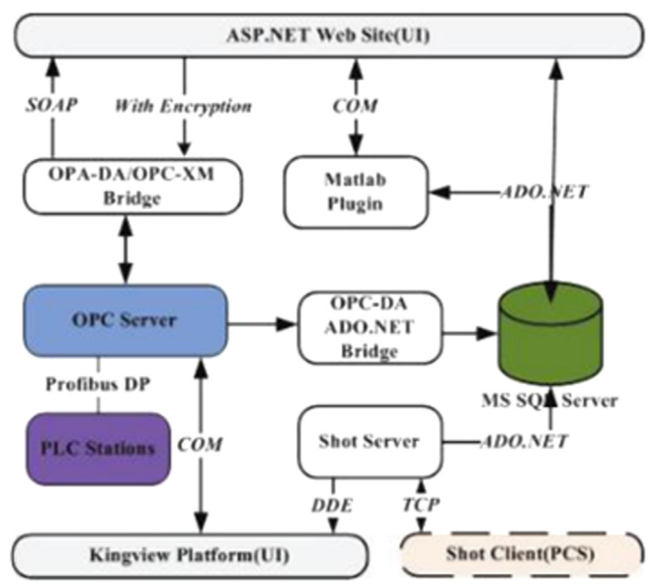

Fig. 45. Software architecture and data transmission [84].

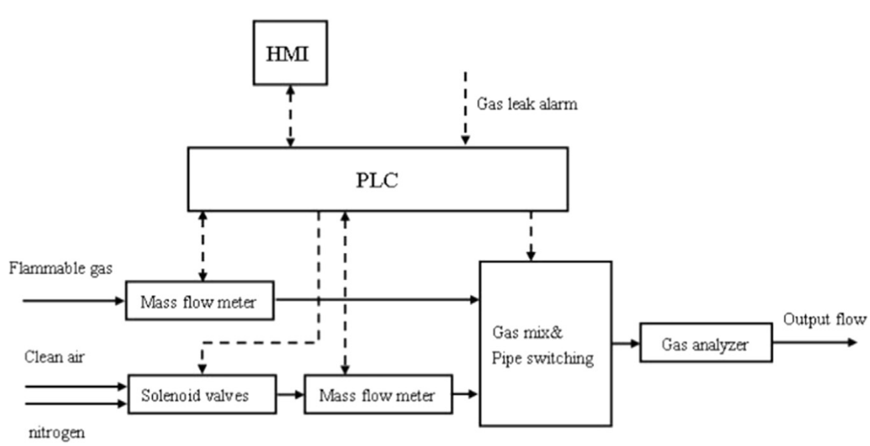

Fig. 43. Block diagram of structure [79].

iv. PCs memories have exceeded 1 Terabyte while PLCs are still within Mbyte or even still kbyte.
v. PC is available worldwide, on short notice, from many vendors.
vi. PC developers are continuously advancing the functionality and ease of use of PC-*compatible* hardware and software.
vii. PC can provide a totally integrated solution that incorporates the functions of the PLC, Human Machine Interface (HMI), and the programming terminal [1]. Softlogic software allows the PC to simulate the actions of a PLC [14]. Soft PLC is available and are being applied on pipeline welding, Luo et al. (2011) [89].

Studies on certain systems also indicates that not all PLC applications are needed to improve a system, ie. A few examples stated below.

A study done by DeBedictis et al. (2013) [90] on the operational energy-efficiency improvement of municipal water pumping in California, found that a PLC did not improve the efficiency of a water pumping system, but it could actually harm the pumping system's overall energy efficiency.

Ahshan et al. (2008) [91] developed a small induction-generator based wind-turbine using a micro-controller. In [91] the author stated that they were considering of using a PLC for the control system however, it was not a cost effective option for a low-cost small wind-turbine. Their system requires a very low computing-power and therefore a single board computer is unnecessary.

8. Conclusions

PLC was first conceived in late 60's and now has become a major player in automation system. Generally from the review that has been done, PLCs can be fully adaptable for any research, industry applications, control of simple or advanced system, monitoring and even joint control with any other controller in the market such as PID, PIC MCU, PLA, PAL and fuzzy controller to name a few.

As more advancement of PLCs in the current market, either if its in the hardware of software application, we can see that more people are coming to terms in using PLCs as their main controller in their applications. Programming system using ladder diagram comparing with other type of programming languages are very much beneficial since even an electrician with limited knowledge of programming would be able to understand and program a PLC base on his knowledge of electrical system. Programming is no more for programmers but simple layman can involve in programming machines.

In the near future, we can see that researchers will tend to use PLCs as their main controller for any field of research even though there are other controllers out there in the market. We can conclude that PLCs can be applied to any system, whether it is a simple or complicated control system.

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