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Overlaying DAQ Systems on Existing Control Systems for Modernizing Power Plants to Realize Industry 4.0

S.M.K.B. Samarakoon

Abstract: In Industry 4.0, digital technologies are integrated with control systems to use enterprise applications and data analytics to improve the efficiency and productivity of industrial processes. However, power plants in Sri Lanka are yet to get such applications primarily due to lack of data acquisition capabilities, high cost of control systems supplied with data analytic applications and lack of awareness about the capabilities of such applications.

Though data analytic applications can be developed locally, obtaining data from power plants cannot be done without changing the existing control systems. This paper proposes a model to overlay a Data Acquisition System (DAQ) on top of the existing plant control system without replacing it. The acquired data can be used for Industry 4.0 applications. Due to the loose coupling of the control systems, DAQ and data analytic applications, each can be updated independently preserving each system's investment.

To demonstrate the model, an implementation of DAQ in hydropower plants in Sri Lanka in the 2000s - at a time when data analytics was not considered a part of the power plant control systems and data communication was not readily available- is discussed. Many faults were detected by these DAQs. The local development saved about Rs. 30 million for the Ceylon Electricity Board (CEB). Early fault detection would have saved billions of rupees for the CEB and Sri Lanka. This development shows the ingenuity of the engineers of the CEB at a juncture where the services and the financial operation of the CEB are questioned.

Due to the availability of Internet access and the advancement of cloud systems at present, data analytics and AI applications are within the reach of power plants in Sri Lanka. By implementing the proposed model to collect data from existing control systems, the Sri Lankan Power Utility (CEB) can consider implementing Industry 4.0 applications locally without spending an excessive amount of foreign currency.

Keywords: Data Acquisition, Supervisory Control, Industry 4.0, Programmable Logic Controllers

1. Introduction to Industry 4.0

The first industrial revolution happened in the 18th century in which, instead of the manual production of items, machines were developed to aid the production of items. During the second industrial revolution from 1870 to 1920, production lines were introduced to increase productivity. The invention of electricity accelerated the second industrial revolution. The third industrial revolution introduced computer-based control systems in the seventies.

The 4th Industrial Revolution or Industry 4.0 (I-4) was coined by the German government in 2011. In I-4, digital technologies are integrated to share information in the decision-making of production processes. Machines, devices and sensors autonomously communicate with each other as IoT (Internet of Things) devices. Due to recent developments in cloud technology, data analytics and artificial intelligence are increasingly being used in industrial automation.

Eng. (Dr.) S. M. K. B. Samarakoon, C. Eng., MIE(SL), MIET(UK), SMIEEE, B.Sc. Eng. (Hons) (Peradeniya), M.Eng. (AIT), Ph.D. (Cardiff), Senior Lecturer, Faculty of Engineering, University of Peradeniya.
Former Chief Engineer (Computer Applications), Ceylon Electricity Board
Email:kamalanath@eng.pdn.ac.lk
https://orcid.org/0000-0002-4078-9427

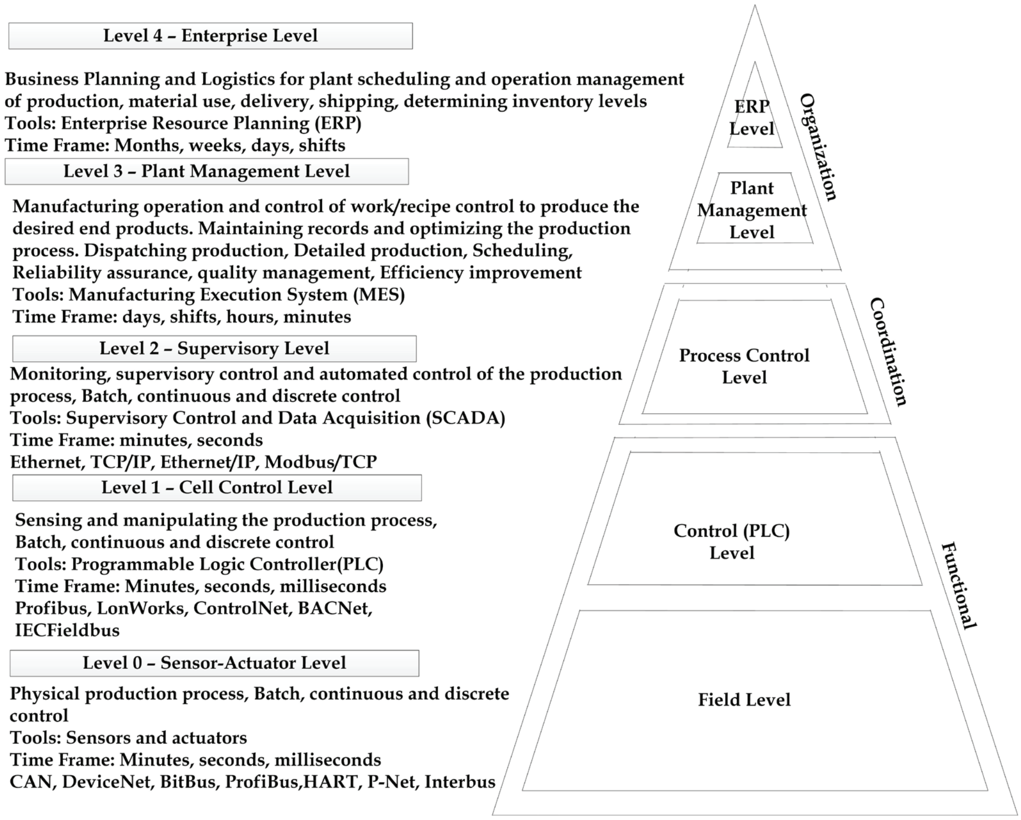

Figure 1 – Layered Enterprise Control Model Based on ISA-95 [2]

2. Computer-Based Control System Models

The early autonomous control system model called SPA (Sense-Plan-Act) has three functional systems, namely, sensing, planning and execution [1]. The sensing system or data acquisition system translates raw sensor data into a real-world model of the system. The planner takes the real-world model and generates a plan based on predefined goals. The execution system then takes the plan and generates the actions it prescribes.

The *Subsumption model* [1] proposed in the 1980s, primarily for robots, has several layers. Each layer has a set of pre-wired behaviours. Complex higher levels build upon simple lower levels and operate asynchronously. The layers are composed of networks of finite state machines (FSM). Each FSM has inputs from sensors or other FSMs. The outputs are sent to actuators or other FSMs. FSM also accepts suppression signals to override the inputs and inhibition signals to inhibit outputs.

Three layered models discussed in [1] have a reactive feedback control mechanism at the bottom, a sequencing mechanism in the middle and a slow deliberative planner on top. Unlike the *Subsumption model*, these models have layers of abstraction rather than rejecting or suppressing the results of the lower-level FSM. Higher-level layers provide inputs to the lower-level layers.

2.1 Modern Control Systems

Modern enterprise control systems follow the five-layered model [2] of the ISA-95 standard which is subsequently standardized under IEC 62264. The layers of the ISA-95 model are shown in Figure 1. Levels 0 and 1 represent the functional or controller layers. Sensors and actuators are at level 0. The controllers are at Level 1. These controllers directly control actuators based on the data received from sensors. The controllers have no or little internal states. Level 2 is the middle coordination layer or sequencer layer that controls the process and it contains memory about the past states. Levels 3 and 4 are the organization layers or deliberator layers which provide the planning functions and contains states about the future.

The layers up to Level 2 have the essential control functionality required for industrial processes. These layers are designed as highly secured systems called militarized zones because disruption to these layers will disrupt the processes. The control systems up to the

Level 2 are implemented using Programmable Logic Controllers (PLC).

Level 3 has the Manufacturing Execution Systems (MES) implemented using standard commercial networked computers and it is considered to be in a demilitarized zone. At Level 4, Enterprise Resource Planning (ERP) is being done using data collected from the plants and other external entities involved in the manufacturing process. With cloud computing, data analytics and AI applications are being added to Level 4.

Conventionally, Level 3 and Level 4 are not integrated with the mission critical layers below Level 3. With I-4, data generated below Level 3 are shared with non-mission critical Levels 3 and 4 autonomously, allowing enterprise applications to manage and optimize the entire manufacturing system.

2.2 Industry 4.0 in the Electrical Industry

I-4 concepts and technologies are being used increasingly in the electricity industry. Managing reliability-related risks, performance maximising and optimizing intervention frequency in asset management using I-4 and data analytics are discussed in [3]. The use of distribution system outage data with enterprise systems and social media is discussed in [4]. The use of IoT in smart grids is discussed in [5].

3. Power Plant Control Systems in Sri Lanka

For any automation, decision-making elements or logic devices should be used. Historically, the decision-making elements are relays. Therefore, the power plants constructed before 1990 in Kelani River (Laxapana hydropower complex) and Mahaweli River (Mahaweli Hydro Power Complex) were based on relay logic. Randenigala and Rantambe power stations commissioned in the late 1980s have computer-based systems for supervision of the control systems, but they are not controllers.

In 1992, a computer-based control system was introduced to the Samanalawewa power plant for the first time in Sri Lanka. Power plants built subsequently have PLC-based control systems. The relay-based control systems of Laxapana Hydro Power Complex were replaced with PLC-based control systems by the subsequent rehabilitation projects. However, the old Mahaweli power plants are still using relay-based control systems.

In relay-based control systems, the operating parameters are displayed on the panel meters and alarms are indicated on annunciation panels. However, there are no ways of collecting data digitally for further analysis.

PLC-based control systems collect data digitally to display on SCADA terminals. In addition, such data are stored in a database to find the history of operations but are rarely used for process optimization. According to the author's knowledge, none of the control systems in Sri Lankan power plants sends data for enterprise applications autonomously to obtain the benefits of I-4.

The PLC-based control systems can be upgraded to I-4 with an additional effort at a moderate cost as the data is available digitally. However, to obtain data from relay-based control systems, the entire power plant control system has to be replaced with a PLC-based control system. It requires replacing relays, control panels and control wiring with several PLCs connected via communication backbone and hence very expensive.

Despite the unavailability of data in a relay-based system and the high cost of a PLC-based system, the Sri Lankan power system should not delay in getting the advantages offered by I-4 because such facilities improve the operational and management efficiencies of the processes. Instead of overhauling power plants by introducing completely new, expensive advanced control systems to achieve the facilities of I-4, it is prudent to consider retrofitting the existing control systems.

This paper proposes a model that allows the implementation of I-4 in the present Sri Lankan power system. This model keeps existing mission-critical relay-based or PLC-based systems unchanged while overlaying non-mission critical Data Acquisition Systems (DAQ) and Industrial Internet of Things (IIoT).

To demonstrate the proposed model, a computer-based DAQ installed on relay-based controlled systems in major power plants in Sri Lanka in 2005 is presented. At the time of developing this DAQ, Data Analytics and AI were never heard of and even the PLC-based technologies related to the 3rd industrial revolution were not available in the Sri Lankan power sector except in the Samanalawewa power plant.

This development received the Wimalasurendra Award from the IESL and the National Science and Technology Award from the President of Sri Lanka.

As a developing country, engineers In Sri Lanka should be able to provide the most cost-effective solutions without compromising the benefits, maybe using unorthodox models, without spending an exorbitant amount of foreign currency. This development shows the ingenuity of the engineers of the CEB at a juncture where the services and the financial operation of the public power utility are questioned.

4. A Model of Overlaying DAQ on Existing Control Systems

Most of the existing relay-based power plants in Sri Lanka were constructed in the 1980s and hence the three-layered models [1] discussed in Section 2 were the state-of-the-art at that time. They have functionalities only up to Level 2 of Figure 1. Sensors and actuators are at Level 0. The unit controls are at Level 1 and the sequence control and supervisory control systems are at Level 2. Similar layers can be found in PLC-based systems as well. This layer separation allows us to overlay a computer-based DAQ on top of the existing relay-based control systems or PLC-based control systems.

At Level 0, sensors measure process parameters such as pressure, flow rate, current, voltage, etc. Motors, hydraulic pistons and breakers are examples of actuators. The unit controllers at Level 1 read sensor data and control actuators of the sub-units such as the governor, excitation system, high-pressure oil systems for the governor and main inlet valve (MIV), etc., based on the decision given by the control logic.

The sequence control system and supervisory control system are at level 2. The sequence control system is a closed-loop logic control system which coordinates the overall operation of the power plant. All unit controllers are connected to the control room. Supervisory control is done via control panels by the operators stationed in the control room. Once an operator's command is received, the sequence control system issues control commands to unit controllers step by step while monitoring the response of the unit controllers until the intended operator's command is completed.

The Instrumentation and annunciation system is the Human Machine Interface (HMI) through which the operators understand the status of the power plant given by voltages, currents, temperatures, liquid levels, pressure, flow rates, speeds, positions, etc.

The protection system of a power plant can be considered as a supervisory control at Level 2 which is automated using automatic protection relays. In a fault situation, all systems should react very fast to isolate the faults and protect the equipment as manual intervention is not fast enough. During abnormalities of subsystems, these relays initiate alarms to alert the operation staff. The alarms and status are displayed on the annunciation panels. During a fault in the system, generators, transmission lines and other subsystems may be tripped by the protection relays.

The proposed model for overlaying the DAQ system and Industry 4.0 applications on existing power plant control systems is shown in Figure 2. The grey-coloured blocks are existing control systems which are mission-critical. The remaining blocks are DAQ, plant management and enterprise applications required for I-4 and they are non-mission critical.

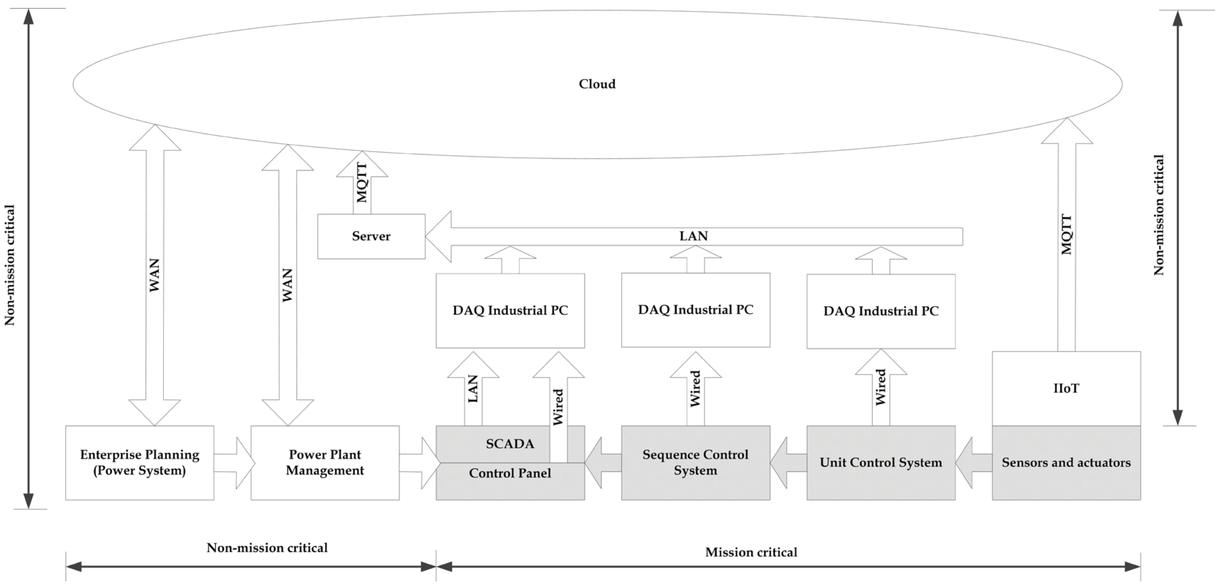

Figure 2 – Overlaying Industry 4.0 on Top of an Existing Power Plant Control System

Data Analytics and AI applications can be implemented on the cloud. In addition, the Industrial Internet of Things (IIoT) and condition monitoring systems can be installed in power plants. The proposed model allows these devices to coexist with DAQ.

Though the power plants, transmission and distribution control systems of Sri Lanka have a plethora of different technologies, the above model can be implemented irrespective of the underlying technology.

Since mission-critical and overlaid non-mission-critical systems are loosely coupled, these DAQ and data analytics applications can be installed at any time. On the other hand, existing control systems can be rehabilitated without replacing the hardware of DAQ and software, safeguarding the investment. Therefore this model is flexible, sustainable and cost-effective.

5. Example of Overlaid DAQ

Implementing such a DAQ in the 2000s is reported here as an example. At that time, all power plants in Sri Lanka were relay-based and hence did not have computer-based systems for controlling, monitoring and data acquisition. These relay-based control systems are still in operation.

In these systems, the alarms and events were recorded manually when they appeared on the control panel. The meter readings were usually recorded manually every hour. The manually collected data on paper was kept in archives and was used only for reference as analysing the data manually was an exhaustive process. Some essential parameters such as generator and bearing temperatures were recorded on paper-based continuous recorders.

When a fault occurred, tens or hundreds of alarms and events appear within a few seconds and operators were unable to comprehend the order of these events. The sequence of events and alarms and their time of occurrence are essential to identify the root cause of a fault and subsequent series of operations of the power plant equipment triggered by the initial event. Mere recording the events without time stamps has no use as the time gives the order of the events.

The accuracy of one hour for meter reading was also not sufficient as the point of change was not recorded hence unable to relate the events and the changes of measured parameters. The unavailability of sufficient data in digital form was a hindrance to power plant monitoring and fault diagnosis.

To collect data for analytics, it was decided to install automatic data acquisition systems in power plants. However, procuring commercially available systems was very expensive and also a single solution could not be given as these power plants were built using different technologies prevalent during the construction periods. Various development options were considered such as importing and in-house development. Finally, it was decided to develop a system in-house.

In this implementation, the existing relay-based control systems remained unchanged. A locally developed computer-based DAQ was overlaid onto the existing control system to collect measurements (analogue inputs) and alarms and events (digital inputs). The collected data were transmitted to a central server to store in a database. Various forms of data presentation applications were developed to facilitate the analysis.

The proposed systems were implemented at the power stations of the Mahaweli river. Five such systems were implemented in Kothmale (two units), Victoria, Rantambe and Bowatenna power stations. A picture of an installed system is shown in Figure 3.

Figure 3 – DAQ Installed in a Power Station

5.1 Hardware

The hardware of DAQ comprised six different electronic modules as shown in Figure 4. Three of them are for digital inputs and the other three are for analogue inputs. In addition, a watchdog module monitored the healthy operation of DAQ. The total number of modules installed in one power plant depends on the number of digital and analogue inputs to be captured. As a rule of thumb, one digital module (192 inputs) and one analogue module (48 inputs) per generator and one digital and one analogue module for common systems of a plant were sufficient in most cases.

These input modules are designed in such a way that in an event of a malfunction of DAQ modules, the disturbance to the existing circuits of power plants will be minimal and the power plant operation will not be affected.

5.2 Digital Inputs

The digital input circuit shown in Figure 5 comprised a locally developed 12-input *Digital Input Module*, a 48-input *Digital Isolator Module* and a commercially available low-cost digital input module (Omega *CIO-DIO 192*) which is capable of accommodating 192 digital inputs.

Digital Input Module

The Digital Input Module is the interface to the existing power plant control circuitry. The alarm and annunciation inputs and relay contacts that indicate the status of the plant were wired to the DAQ through this module.

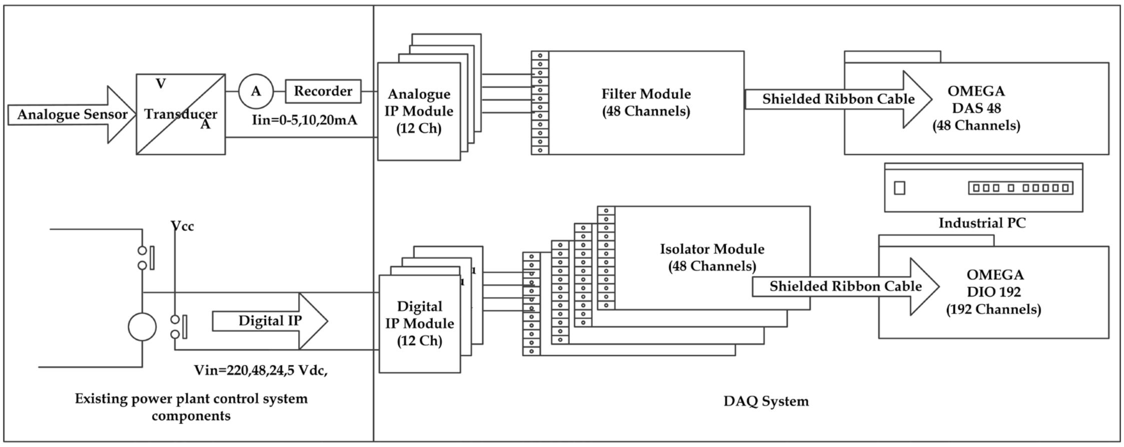

Figure 4 – Hardware of DAQ System

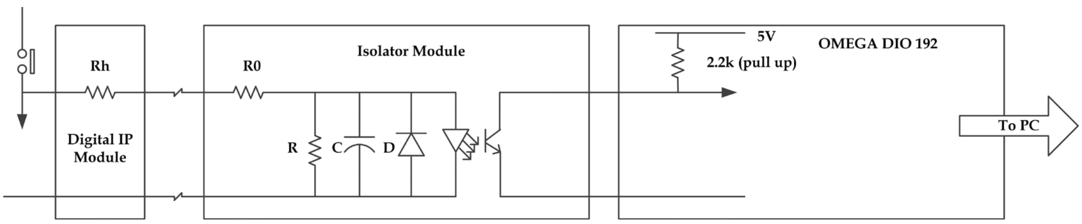

Figure 5 – Digital Input Modules

As far as possible, spare volt-free contacts of existing relays were used to minimize the impact of adding the new relays to the existing control system. These contacts were vetted by a suitable voltage available in the control systems. The modules that are suitable for 5V, 24V, 48V and 220V were developed to suit different input voltages of different control systems. If spare contacts were not available in control circuits, repeat relays were installed. Alarm and annunciation outputs that are not used for control were connected to the DAQ without repeat relays as any failure of DAQ circuits does not affect the control logic.

Each Digital Input Module has twelve resistors to connect twelve digital inputs. These resistors limit the short circuit current so that even if DAQ circuits are short-circuited, the existing control circuits will not be affected. These modules were installed close to the input source so that the new wiring was done after the modules. Shielded multi-core cables were drawn from the modules to industrial PCs. The PCs were located in the power plant considering the availability of the most input points and the distance to the DAQ PCs from the input points.

Isolator Module
The Isolator Module is a signal conditioning module which prepares the inputs. As shown in Figures 5 and 6, it has a current limiting resistor, RC low pass filter, freewheeling diode and optocoupler which does the galvanic isolation of input signals. The low pass filter removes the high magnetic interference prevalent in the power plant.

Figure 6 – Isolator Module

DIO 192 Digital Capture Module
As shown in Figure 7, DIO 192 module [6] comprises eight 82C55 CMOS Programmable Peripheral Interface circuits (PPI). PPI is a very versatile digital I/O circuit used for data acquisition since early 8086 computers. It has two 8-bit ports (A and B) and two 4-bit programmable ports (C lower and upper) (see Figure 8).

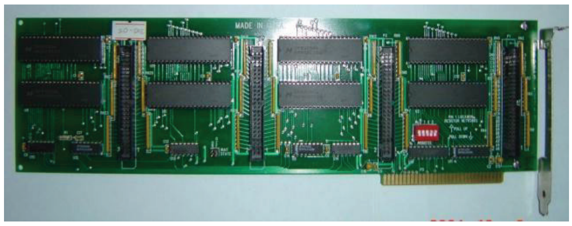

Figure 7 – DIO 192 Digital Capture Module

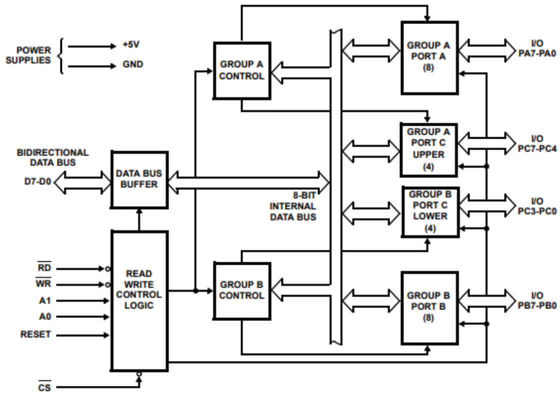

Figure 8 –Programmable Peripheral Interface

With eight PPIs, one DIO 192 can handle 192 digital I/Os. The control circuit of PPI receives the two least significant bits of the address bus and reads and writes signals from the control bus of the ISA bus (Industry Standard Architecture) of the industrial computer. By using Group A and Group B control registers, the 82C55 ports can be programmed. The 82C55 PPI has three operating modes, namely, Basic I/O, Strobed I/O and Strobed Bidirectional mode. In Basic I/O mode, all three ports can be programmed to work as independent input or output ports. In Strobe I/O mode, ports A and B can be programmed for input or outputs and port C is used for handshaking. In Strobe Bidirectional mode, Port A can be used as a bidirectional port with handshaking signals of Port C. The DIO 192 module has a DIP switch to set the address of the board.

5.3 Analogue Inputs

As shown in Figure 9, the analogue data input circuits comprised three input modules, namely, a locally developed 12-input *Analogue Input Module*, a 48-input *Filter Module* and a commercially available 48-input analogue input module (Omega *DAS 48*) [7].

Analogue Input Module
Analogue Input Modules are fixed close to the transducer outputs of a power plant. It has a Zenor diode which prevents the transducer from saturating when there is a fault in the newly installed DAQ circuitry or when the Filter Module is removed from the panel. In

such a situation the Zenor diode will break down and conduct the transducer current so that existing analogue meters will continue to display without any disturbance to the power plant operation.

Filter Module

Due to the heavy stray magnetic interference prevalent in power plants, a 50 Hz sinusoidal wave is superimposed on the DC analogue signals. As shown in Figures 9 and 10, the Filter Module has low-pass RC filters to filter out the power frequency magnetic interference. The circuitry of all Filter Modules is identical except for the ratings of the components suitable to input currents of 5 mA, 10 mA, and 20 mA.

DAS 48 Analogue Capture Module

The DAS 48 module [7] shown in Figure 11 is capable of capturing 24 differential or 48 single-ended analogue inputs. It uses six HI-508A 8-channel differential analogue multiplexers (Figure 12) and HI-574A 12-bit A/D converter IC (Figure 13). These six analogue multiplexers are capable of switching 48 single-ended or 24 differential analogue inputs to the A/D converter which does the continuous conversion of analogue inputs.

5.4 Watchdog

The *Monitor Module* shown in Figure 14 was locally developed together with software to monitor the healthy operation of the DAQ acting as a watchdog. At the prototyping stage of the DAQ, it was noticed that the system was either hung up or capturing was stopped maybe due to undue operator intervention or due to the pre-emption of the data-capturing software by the operating system. The operators were unaware that the system had stopped.

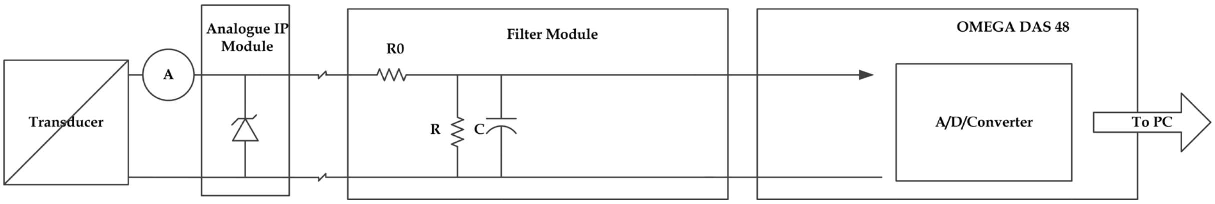

Figure 9 – Analogue Input Modules

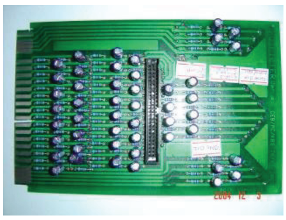

Figure 10 – Filter Module

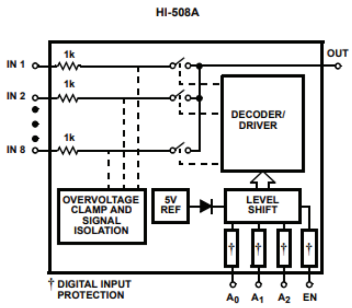

Figure 12 – HI-508A Analogue Multiplexer

Figure 11 – DAS 48 Analogue Capture Module

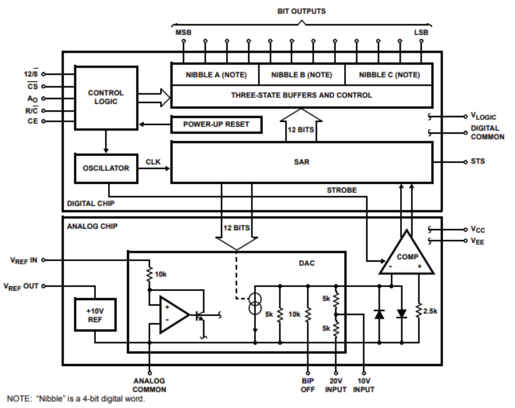

Figure 13 - HI3-574A 12-Bit A/D Converter

This Monitor Module is continuously retriggered by an input pulse given by the data-capturing software at each capturing cycle. In the absence of this pulse, the module starts to time out and sends interrupt signals to *Monitor Software* to restart the DAQ software or warm boot the operating system. If both attempts fail, it will alarm the operators through the power plant annunciation system.

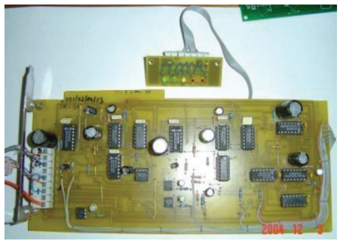

Figure 14 – Monitor Module

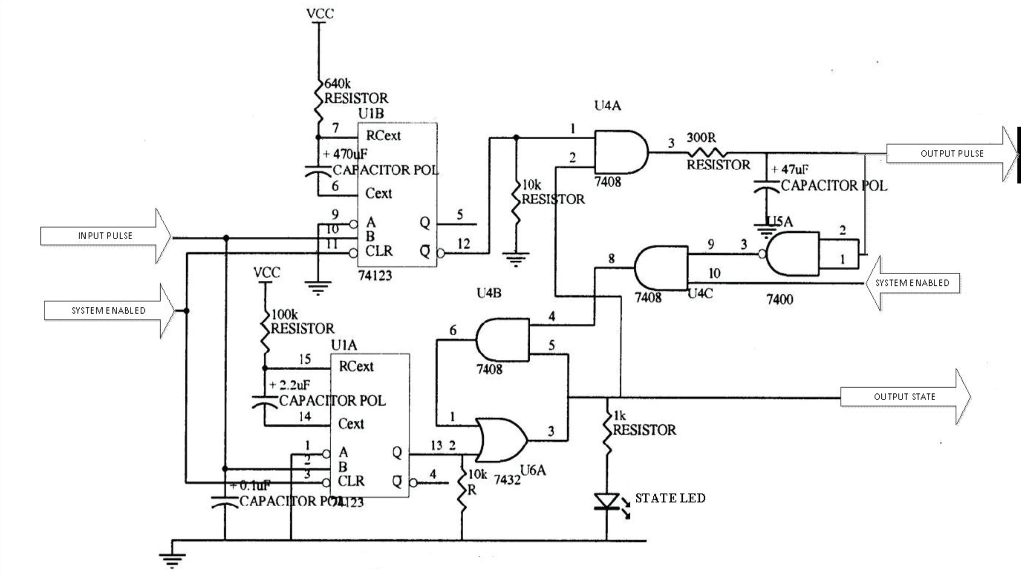

Figure 15 – One Circuit Block of Monitor

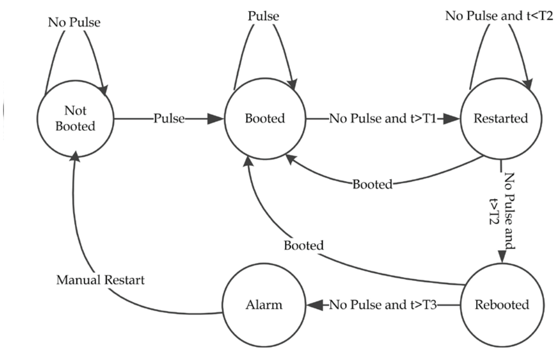

Figure 16 – State Diagram of Watchdog

The *Monitor Module* has three similar circuit blocks given in Figure 15. Each block has two re-triggerable monostable circuits. The first monostable is waiting for at least one INPUT PULSE to start the second circuit. Then, OUTPUT STATE become high indicating that the circuit is started. Once started, the second monostable is at an unstable state but the INPUT PULSE does not allow it to reach the stable state as it is re-triggered at every pulse. The second monostable is looking for an absence of a pulse for a given period to give the OUTPUT PULSE high.

The combined operation of three monitor circuit blocks is explained using the state diagram shown in Figure 16. When one pulse is received from the digital module, the monitoring system moves from the *Not Booted State* to the *Booted* state. In the absence of a pulse, the first circuit waits for T1 seconds and then sends a pulse to restart the software. This pulse triggers the second circuit and moves the system to the *Restarted* state. The second circuit waits T2 sec before giving the *Reboot* output. The output of the second circuit will move the system to the third *Rebooted* state where it waits T3 sec before alarming the operation staff through the normal power plant annunciation system. During the wait time T1, T2, and T3 if Booted Pulse is received, then the system moves back to the *Booted* state. The waiting times T1, T2, and T3 are pre-set values considering the time taken for each operation.

5.5 Software Modules

The software modules of the DAQ are time-optimized to capture digital inputs at 1 ms accuracy while doing all other operations. In addition to capturing digital inputs, DAQ captures analogue inputs, transfers captured data from memory to hard disk and performs other housekeeping activities of the PC.

The DAQ was implemented on industrial PCs with a single microprocessor as at the time of developing DAQ, multi-core processors were not available. Therefore processor-level optimization was not possible. As MS WindowsNT operating system (OS) was used, OS-level scheduling was also not possible. Therefore, application-level scheduling was used to optimize the operations of the PC. To facilitate the scheduling, instead of using one module to do all operations, nine loosely coupled modules collaborated to capture data and store them in a database. These modules were developed in-house. The details of the software are presented in reference [8].

5.6 Managing Contact Bounces of Relays

The mechanical contacts of any relay, bounce back before they settle in the final state as shown in Figure 17. The bouncing time varies from 10 ms to several hundred milliseconds depending on the size of the relay. Usually, annunciation systems of power plants suppress bouncing and indicate only alarms that persist for more than 50 ms. However, this DAQ was built as a fault diagnostic tool and hence needed to capture even a 1 ms glitch. Due to this high sampling rate, single relay operation is recorded as multiple contact-switching (10-20 numbers). Therefore, an algorithm was developed to capture even 1 ms state change and to suppress subsequent relay bounces for a given period. Typical bouncing periods of different relay types are used in the algorithm.

This algorithm gives an additional benefit by detecting the sluggish operation of relays when they are getting older. In such cases, though relay contact bounces are not present with new relays, bounces start appearing when relays are ageing. This function acts as an error forecasting system of a relay-based control system.

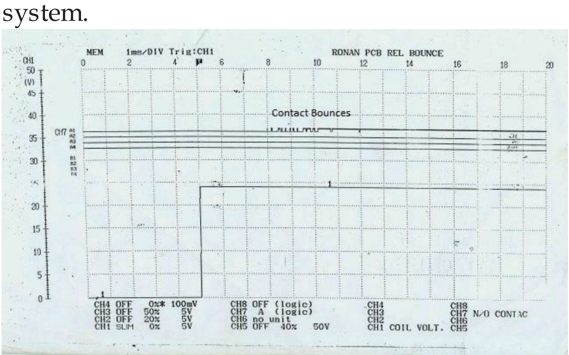

Figure 17 – Relay Bounces Recorded by High-Speed Memory Recorder

5.7 Time Synchronization

To compare the events that occurred in different power plants across the power system, the events should have the same time-base thus clocks of the DAQ PCs should be synchronized to a standard clock. To receive a standard clock signal, a GPS-based clock system [9] shown in Figure 18 was installed as a pilot at the Victoria power station. The accurate GPS clock is used to synchronize the system time of the Network Time Protocol (NTP) based time server. The clocks of all DAQs installed in a power plant are synchronized to this time server. When all DAQs use GPS clocks, the recorded events will be accurate to 1 ms of the global clock and synchronized across the power system.

Figure 18 – GPS Satellite Control Clock and GNSS Antenna

6. Use of PLCs for Developing DAQ

Compared to the 2000s, the costs of PLCs are decreasing. Therefore, recently, some power plants started installing PLC-based DAQ by replacing the locally developed DAQ reported in this paper. Though PLC-based systems can perform power plant controls as expected, the locally developed DAQ is superior for data acquisition due to many of its features.

In any control system, including PLC-based systems, relays are present. These relays are used to achieve galvanic isolation of sub-systems, to increase current handling capacity, to connect sub-systems working at different operating voltages or supplied by different vendors or to drive high-power apparatus.

As explained in Section 5.6, this DAQ has a feature to detect the ageing relays based on the bouncing time. In PLC-based DAQ, contact bounces are suppressed by using electronic anti-bouncing input circuits. Therefore, ageing relays cannot be identified and replaced at an early stage before failing. Such proactive maintenance minimizes the breakdown and improves the reliability of control systems.

Due to the low cost of the locally developed DAQ, as many axillary relays as required can be monitored. By monitoring auxiliary relays, the exact point of a failure can be found. On the other hand, the primary requirement of PLCs is to carry out control actions, and hence usually PLCs do not record a large number of inputs. Only the essential inputs required for decision-making are included due to the cost of additional inputs.

The typical scan time of a PLC control loop is in the order of 200-250 ms. However, for acquiring data for fault diagnosis, a higher sampling frequency of about 1 ms is required. PLCs can be configured to run in fast loops with scan time in the order of milliseconds. However, capturing a large number of data (e.g.,1000 digital and 200 analogue) is not possible at a consistent accuracy of 1 ms. Because the loop time of a PLC varies significantly due to the large number of inputs and processing steps of the PLC.

Distributed Control Systems (DCS) are capable of capturing large numbers of inputs with higher sampling rates. Such DCSs use separate input modules equipped with a microcontroller in each module to capture inputs and time stamped at the module itself before sending data to the central controller. Such DCS are of very high cost and hence use of them may not be justifiable for a non-mission critical DAQ.

This DAQ collected and combined transmission system data and power plant data across several grid substations and power plants such that the sequences of events can be analyzed across the plants in the event of a system failure. On the other hand, even in the present Sri Lankan power system, obtaining such a unified picture of power system events is not easy. Each power plant collects its internal data. The System Control Centre collects only data important to the transmission system. The distribution systems record their data separately. Therefore, in the case of a system failure, data should be manually combined to obtain a unified picture.

7. Data Analytics using DAQ

The worthiness of DAQ for data analytics was proved from the first date of operation. A large number of faults, which were undetected before, were found and corrected. Some of the faults were unnoticed as the existing annunciation system is incapable of capturing the events in short occurrences. Some indications were not considered faults as they appeared intermittently. The operators were under the impression that such indications were normal and hence not reported to the maintenance engineers.

By arranging the recorded events accurate to 1 ms in chronological order, the initial event and the subsequent sequence of relay operations triggered by the initial event were used to identify the faults.

Analogue data was captured at every minute. This rate is not too short to give an enormous amount of data which is incomprehensible and it is not too long to miss any measurement changes. This ability once helped to pinpoint the reason for a system failure where the operation of a breaker triggered a cascading system failure.

The trends and changes in the power plant operating parameters are used to carry out predictive maintenance by prolonging the intervals of routine maintenance. For example, trends of bearing temperatures can be used to decide the time for the next bearing overhaul.

Analogue readings are used to optimise power plant operations. Optimization of the air conditioning system by analysing the operating parameters of the chillier is one example. The energy consumption of the air conditioning system is a significant component of the auxiliary power consumption of a power plant.

This system identified weakening relays as explained in section 5.6 and avoided catastrophic events. This feature is particularly important for developing countries like Sri Lanka in which ageing control systems are not replaced as a whole due to the high cost and relays are replaced only when they are not suitable for service.

Loosening control wires due to corrosion or vibration can be detected by this system before they become disjoint completely. Signals of loosening wires appear as very short glitches in the event list but not long enough to trigger any cascading effect such as tripping of the generator.

By monitoring the deviation of operation time from the normal range, DAQ acts as an early warning system. For example, by observing the prolonged time taken to recharge a breaker, remedial actions were taken before the breaker failed.

Along with the software to analyze data of DAQ, two other enterprise applications at Level 3 namely Maintenance Management System (MMS) and Inventory Management System (IMS) were implemented.

The DAQ collects all the operation data in near-real time. MMS had information on all equipment and data on routine and breakdown maintenance. IMS managed the spares. These three systems provided a single view of the status of the power plant required for decision-making.

8. Conclusion

A model of overlaying a non-mission-critical DAQ on top of the mission-critical control system is proposed. Due to the non-mission-critical nature of the DAQ, low-cost DAQ can be locally developed and implemented while keeping the existing control system intact. Implementing such a DAQ using industrial computers and locally developed hardware and software is discussed as an example. The data collected from the DAQ identified a large number of failures and causes of power system blackouts.

The total cost of hardware per system was about Rs. 1 million. Due to local development, this system saved about Rs. 30 million for the utility. Fast fault diagnosis and early warning would have saved billions of rupees for the utility and Sri Lanka.

These DAQs were installed in Mahaweli power plants and connected to the main office in Kandy using dial-up modems. Unlike in the 2000s, all power plants now have Internet facilities and hence data can be transmitted to the cloud. Lightweight publisher-subscriber type protocols such as MQTT are being used by the industry. Data analytics and AI applications can be launched as instances on the cloud. These cloud resources can be scaled up/down in real time depending on the data volume as and when required.

The cost of computer systems and electronic components has decreased drastically over the last two decades. At the same time, the capabilities of such systems and development support increased by many folds. Therefore most of the projects that could not take off the ground due to the high cost or unavailability of technology in the past are now within the reach of local engineers. Therefore, by carefully identifying the implementation models, local engineers are now able to implement systems that are low-cost and sustainable. This is very important at this juncture when Sri Lanka is facing a financial crisis and foreign currency crisis.

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