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An Improved Merging Unit Model for Substation Automation System Based on IEC61850

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ABSTRACT: The implementation of the IEC61850-9-2 standard in substation automation systems requires the use of merging units for elimination of several multiple wire connections running from the switchyard to the microprocessor relays located in the control room. The conventional merging unit model collects current and voltage signals from various current and voltage transformers in the switchyard, converts them into digital form and sends the digital equivalents to the microprocessor relays via a single fiber optic cable known as the process bus. In this paper, we proposed a new merging unit model with additional features of in-built overcurrent protection and bay control functions. This new model is intended to provide local over-current protection and bay control for all equipments in the bay being monitored by a particular merging unit.

KEYWORDS: Merging Unit, Substation Automation System, IEC61850, Process Bus.

I. INTRODUCTION

A. Related Works

Several research works have been done in the area of developing digital solutions for operation of automation systems of substations. It was established in [1] that owing to the technological advancements in new communications techniques, power substations are now being transformed from hardwired configurations to networked platforms in order to achieve full automation of substations. Also, optical fiber communication technology has been identified as the choice communication technique for the implementation of IEC 61850-8-1 and 9-2 standards for substation automation [2, 3]. The fundamental concept of substation automation systems hinges on the possibility of using microprocessor-based intelligent electronic devices (IEDs) to monitor and control equipments in a substation [1]. The IEC 61850 standard combines the convenience of Ethernet communications with performance and security which are essential for modern digital substations solutions as reported in [4]. Latest research works on realization of more modern digital substations have largely been geared towards developing new process level equipments such as non-conventional instrument transformers and intelligent switchgears that can communicate directly with the bay level and station level of the substation with the merging unit working as the interfacing component between process level and the bay level.

B. Merging Unit Concept

The Merging Unit (MU) is one of the most critical elements required in the development of modern digital substations. The MU provides the suitable interface for the implementation of the process bus concept in modern substation automation systems. The IEC61850 standard specifies the communication architecture for communication systems and networks for substations [5]. The basic function of the MU in automation systems is to convert the analogue values of current and voltages measured at the process level to digital format and transmit same to the bay level of the substation where the microprocessor relays are located. In modern substations, its function is to collect multichannel digital signals output by electronic current and electronic voltage transformers synchronously and transmit these signals with the protocol of IEC 61850 to protective, measurement and control devices [6].

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II. SUBSTATION AUTOMATION USING IEC 61850 STANDARD

IEC 61850 Standard is becoming more widely used around the world wherever substation automation is to be put in place. However, most of these conventional substation automation systems only utilize the capability of IEC 61850 related the communication between the bay level and station level of the system. Examples include communication between protection relays, bay controllers, SCADA gateways and local HMIs as illustrated in figure 1. The possibility of establishing direct communication up to the process equipments and intelligent switchgears according to parts 9-2 and 8-1 respectively of the IEC 61850 has so far been implemented in only some pilot installations. Thus the destination of recent research efforts in substation automation systems is to move a step further from the state-of-the-art conventional architecture to a fully digital substation in which the entire substation activities are realized through a communication platform based on IEC61850.

A. State of the Art Substation Automation System using IEC 61850

Due to the exciting capabilities and technical benefits [4] the IEC 61850 Standard has introduced into substation automation systems; it has received quite substantial patronage. As earlier mentioned and as illustrated in figure 1, the state-of-the-art implementation of the IEC 61850 standard is limited to communication between the station level and the bay level. In the conventional approach, the automation system of a substation consists of multiple IEDs e.g. protection relays and bay control devices all connected to each other and to the substation gateway and local HMI through a communication network by means of the ***station bus***. It is called a station bus because it connects all the devices of a substation. The protocol for the communication network is defined in IEC 61850-8-1 [5].

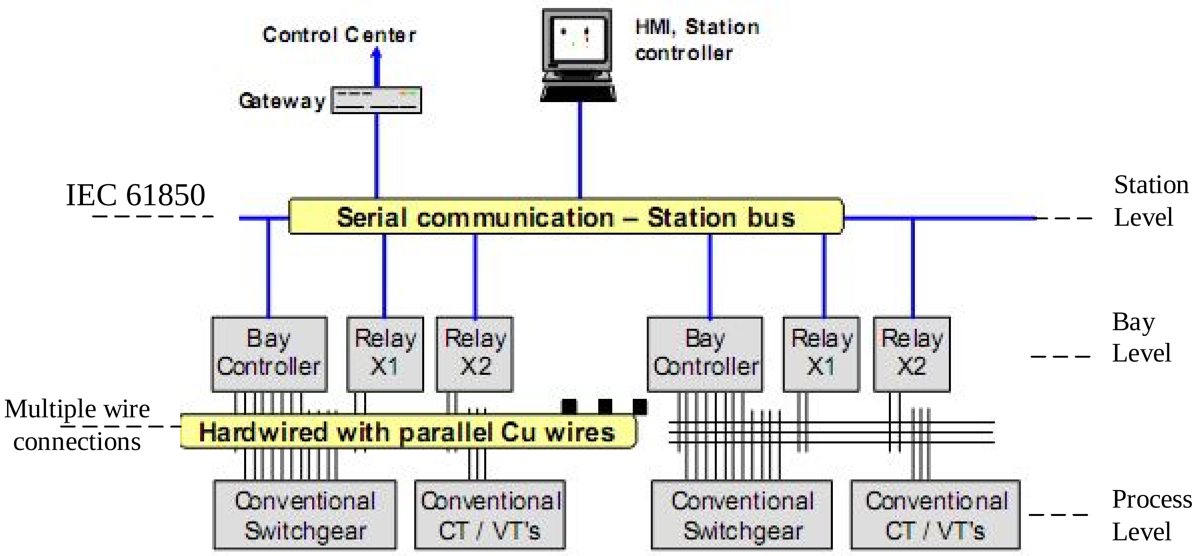

Figure 1 Architecture of conventional substation automation system

However, communication between the bay level and the process level is still achieved by hardwired connections using parallel copper wires. With this architecture, too many wired connections are required for connecting the process equipments to the bay level devices. This is simply because each of the numerous signals that emanate from the control, protection, and metering sections of the substation must be connected by a pair of copper wires which will run from the process equipment all the way to the bay level devices in the control room. Thus wiring alone attracts huge cost during installation of substations using the conventional architecture.

B. New Communication Architectures for Substation Automation using IEC 61850 Standard

The need to achieve full automation of substation operation with reduced hardwired connections has led to the extension of implementation of IEC 61850 up to the process level of substation automation. To achieve this, IEC

61850-9-2 is now being implemented at the process level such that process equipments like current transformers (CTs), voltage transformers (VTs) and switchgears can now communicate directly with the rest the devices over a fiber optic network. The automation system is realized with the introduction of another communication network known as the ***process bus***. This is illustrated in figure 2 [8]. In figure 2, the multiple hardwired connections (as in figure 1) are replaced with a single fiber optic cable forming a complete Ethernet substation LAN.
In this automation system architecture, the process equipments are made to include intelligent devices which can be directly interfaced to the communication system.

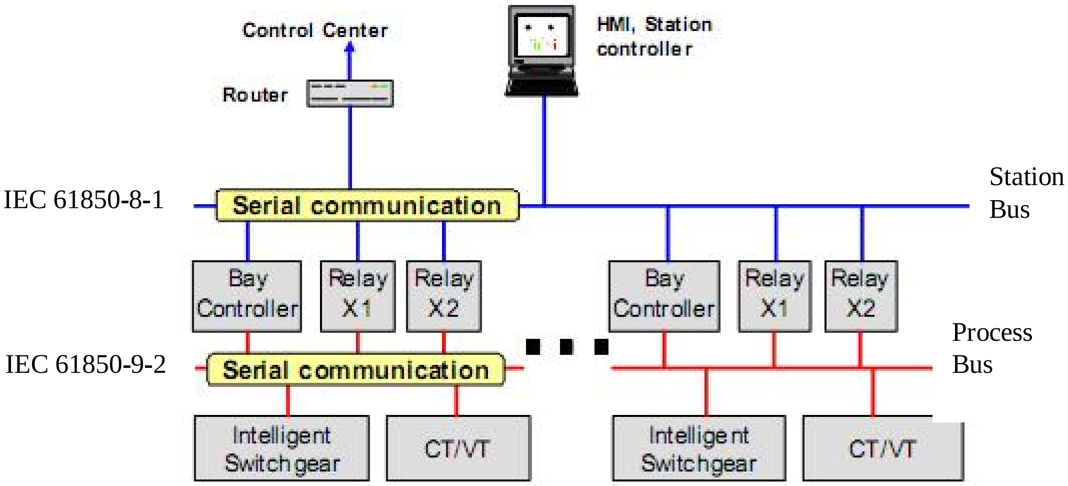

Figure 2: Substation automation communication architecture using the process bus

However the functionality of the intelligent devices depends largely on the technology of the primary equipment. The minimum specification is that each of the process equipment must include a communication interface according to the IEC 61850 Standard.

One of the techniques used is to connect the switchgears (circuit breakers and isolators) to the process bus via remote I/O devices which are directly connected to the communication network. In such implementations, each of the conventional switchgears is connected to decentralized I/O units stationed close to the switchgear. This reduces the length of copper wires used to connect to the switchgears. Thus the information captured from each of the process equipment is distributed over the communication network such that multiple IEDs can share the signals from the switchgears without the need for a marshalling box.

A more recent technique is to integrate new switchgear technology directly to the switchgear. For example, it is possible to include a communication interface to the electronics of a circuit breaker that uses servo motors for moving its contacts. Thus the communication interface can then be connected directly to **the process bus**.

There are various other architecture configurations that have been proposed for implementing this new automation system technology [7].

C. The Process Bus

Part 9-2 of the IEC 61850 standard for networks and communications in substation proposes that the current and voltage transformer outputs which are conventionally hardwired to the various devices such as relays, IEDs, meters and SCADA can be digitized and communicated to those devices using an Ethernet-based local area network (LAN) [8]. In this new system, the process bus refers to the fiber-optic based Ethernet LAN ring which carries these digitized sampled values to the bay level/station level devices. As specified by the standard, using this approach will require the instrument transformers (CTs and VTs) to have in-built analog-to-digital converters (ADC) and appropriate data formatting capability which is needed for generating sampled value (SV) messages. For conventional instrument transformers which do not have these capabilities, the same functionality can be achieved with the introduction of *merging units* located close to the instrument transformers in order to bridge the gap between the analog signals from the primary equipment and the process bus LAN. The merging unit concept is illustrated in figure 3.

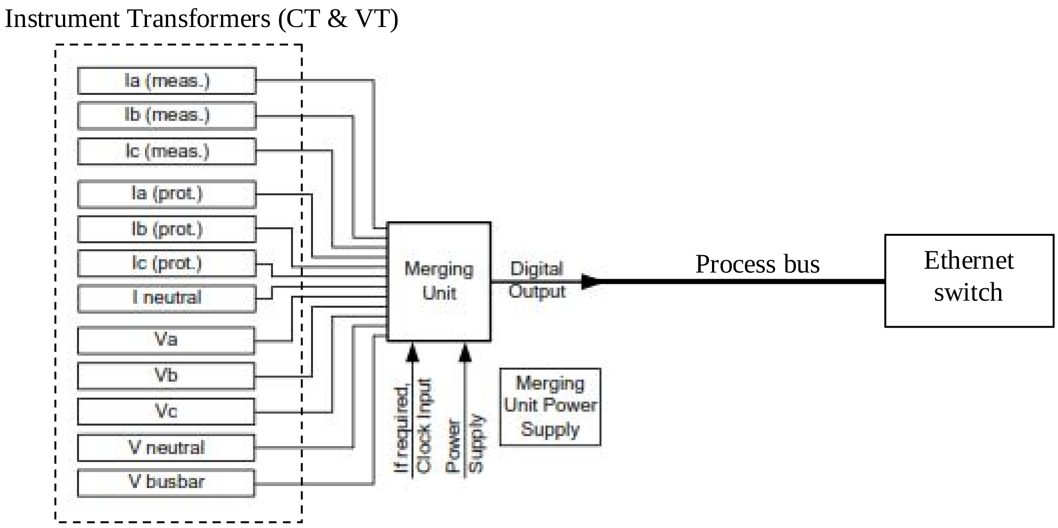

Figure 3: Merging unit showing connection to instrument transformers and process bus

The implementation of the merging unit concept in substation automation system can be better understood with the simplified block diagram of a substation using the proposed system as illustrated in figure 4 [8].

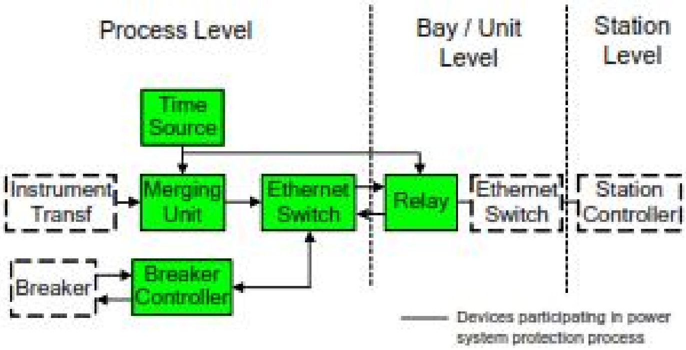

Figure 4: simplified block diagram of a substation using the IEC 61850-9-2 system [8]

III. PROPOSED AUTOMATION SYSTEM MODEL

The block diagram of the proposed automation system model is presented in figure 5. It is a modular system in which the merging units are seen as modular objects making up the system. Thus with respect to the 33kV side of a typical injection substation, there are five merging units in the model each of them representing a data merging module for each bay of the substation namely bay 1 to bay five. Note that bay 4 represents the center bay also referred to as the bus coupler.

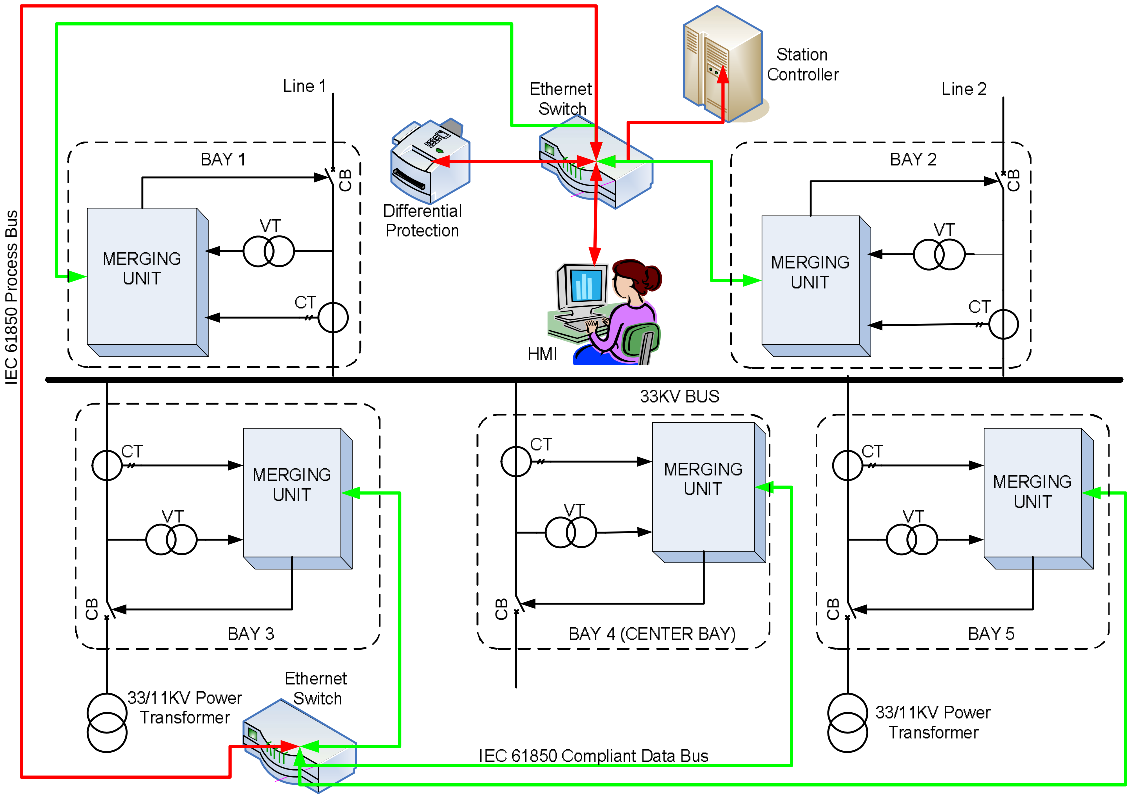

Figure 5 Modular substation automation system model based on IEC 61850 proposed for the 33 kV side of an injection substation

The modular substation automation model is an IEC61850 based system for the monitoring and control of a substation. Each bay in the substation as shown in Figure 5 is attended by a merging unit which can be linked to other devices such as the Human-Machine-Interface (HMI), station controllers, differential protections, and other bays within the substation through the IEC61850 Ethernet connection. This model focuses on the function of the merging unit as the basic substation automation component for bay monitoring and control. In this model, a merging unit serves as a unit control element with internal capabilities of real-time decision making as well as communication to other systems components for higher or alternative decision making. Hence, an IEC61850 compliant bus provides a connection between a merging unit and an Ethernet switch for data connection.

The merging unit is made to render real-time services for the control of the bay. As shown in figure 6, the bays consist of three phase supply lines with circuit breakers for control and protection purposes. The control parameters are the voltage and current sensed on each line.

Attached to each line is a voltage sensor or transducer (VT) and a current sensor or transducer (CT) which senses the voltage and current flowing through the line. The sensed voltage and current signals are then fed to a signal conditioning unit where they are amplified or attenuated, filtered, etc. This conditioning process makes the signals clean enough and in the appropriate form for the next stage to handle.

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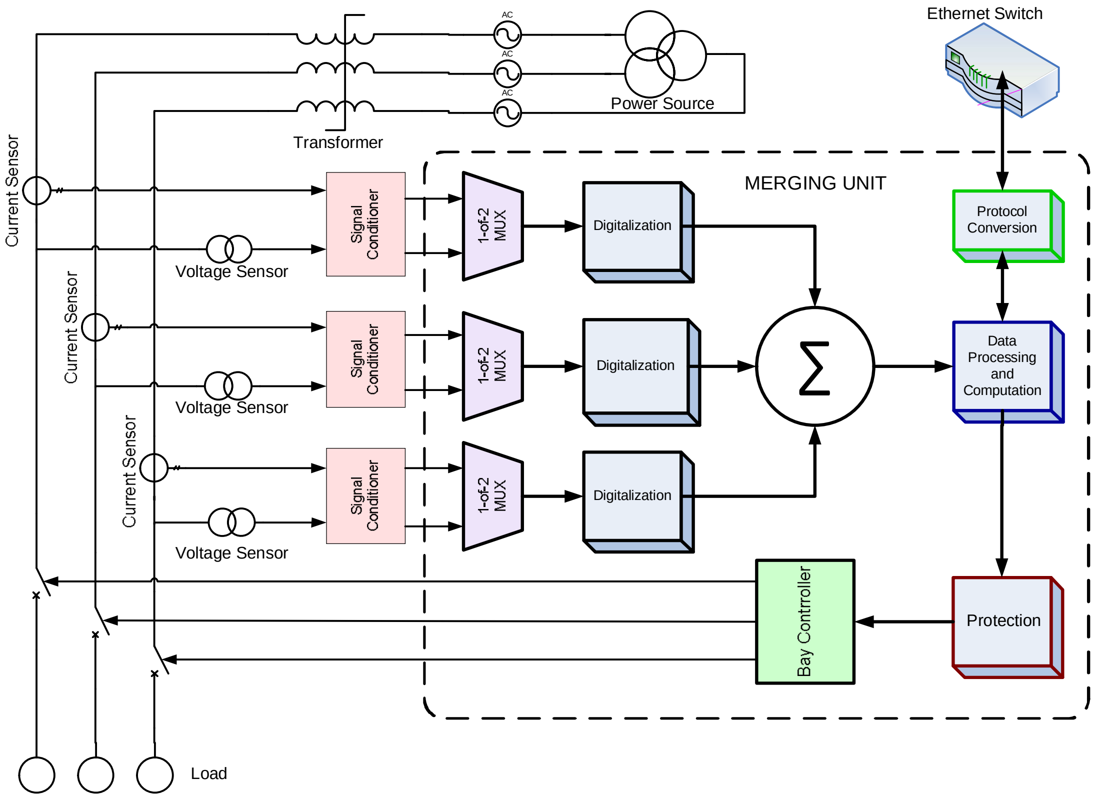

Figure 6: Modular data merging model

Further, the conditioned signals from each line are multiplexed (through a 2-line-to-1-line multiplexer) and passed into a digitization process where they are sampled and converted to their digital form. The digitized signals are then merged into a group data and passed into a data processing and computational unit for decision making.

Therefore, the basic functions required to be performed by each merging unit are summarized as follows:

- signal multiplexing, analog to digital conversion, data merging, data processing, data acquisition, protocol conversion, communication, overcurrent protection and, bay control

A Development of Mathematical Model for the System

In this subsection, we present the step by step analysis of how the mathematical model of the system was derived. The goal here is to determine the mathematical relationships between the parameters that can enable us achieve effective and reliable monitoring and control of the substation system using the proposed merging unit model. These parameters are simply currents and voltages sensed by the current and voltage sensors used in the substation whose values can be used to determine what control or protection action to be taken at any particular time.

Signal Flow Analysis

Figure 7 shows the signal flow from the lines to the processing and computational unit within the merging unit. Assuming Ø is the current output sensed by a current sensor and ϴ is the voltage output from a voltage sensor (VT), then for each line (A, B and C) the output representations are:

Line A: voltage = Θ_A and current = $\varnothing_A$ - - - - - - - (1)

Line B: voltage = Θ_B and current = $\varnothing_B$ - - - - - - - (2)
Line C: voltage = Θ_C and current = $\varnothing_C$ - - - - - - - (3)

If an amplification (or attenuation) factor of a_1 and a_2 are applied to the current and voltage signals respectively, then the measured signal values are:

Line A: current = $a_1\varnothing_A$ and voltage = $a_2\Theta_A$ - - - - - - - (4)
Line B: current = $a_1\varnothing_B$ and voltage = $a_2\Theta_B$ - - - - - - - (5)
Line C: current = $a_1\varnothing_C$ and voltage = $a_2\Theta_C$ - - - - - - - (6)

Equations (4) to (6) give the analogue weight of the voltage and current signal values. These values are then multiplexed into a single data output per line thus:

Line A: current/voltage = $a_1\varnothing_A/a_2\Theta_A$ - - - - - - - (7)
Line B: current/voltage = $a_1\varnothing_B/a_2\Theta_B$ - - - - - - - (8)
Line C: current/voltage = $a_1\varnothing_C/a_2\Theta_C$ - - - - - - - (9)

Further, the multiplexed signals are sampled and digitized with a digitization factor of $1/\eta_{ADC}$ which determines the sampling rate and the digital output size of the data. Thus,

Line A: current/voltage = $(a_1\varnothing_A/a_2\Theta_A)/\ \eta_{ADC}$ - - - - - - (10)

Line B: current/voltage = $(a_1\varnothing_B/a_2\Theta_B)/\ \eta_{ADC}$ - - - - - - - (11)

Line C: current/voltage = $(a_1\varnothing_C/a_2\Theta_C)/\ \eta_{ADC}$ - - - - - - - (12)

Equations (10) to (12) represent the digital equivalent of the analogue signal weights per line. Finally, the current and voltage data from each line are passed through a data merging process to produce an acquired sum voltage (V_{sum}) and sum current (I_{sum}) thus:

$$V_{sum} = \sum_i^N \frac{a_2}{\eta_{ADC}} \theta_i \quad - - - - - - - - - \quad (13)$$

and

$$I_{sum} = \sum_i^N \frac{a_1}{\eta_{ADC}} \emptyset_i \quad - - - - - - - - - \quad (14)$$

Where,
i = line number or identifier and N = total number of lines
Expanding equations (13) and (14) with N = 3 and i = A, B, C therefore,

$$V_{sum} = \frac{a_2}{\eta_{ADC}}(\theta_A + \theta_B + \theta_C) \quad - - - - - - - - \quad (15)$$

$$I_{sum} = \frac{a_1}{\eta_{ADC}}(\emptyset_A + \emptyset_B + \emptyset_C) \quad - - - - - - - - \quad (16)$$

These values can then be represented in their matrix form in memory as:

$$\frac{1}{\eta_{ADC}}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \cdot \begin{bmatrix} \emptyset_A & \emptyset_B & \emptyset_C \\ \theta_A & \theta_B & \theta_C \end{bmatrix} = \begin{bmatrix} I_{sum} \\ V_{sum} \end{bmatrix} \quad - - - - - - - \quad (17)$$

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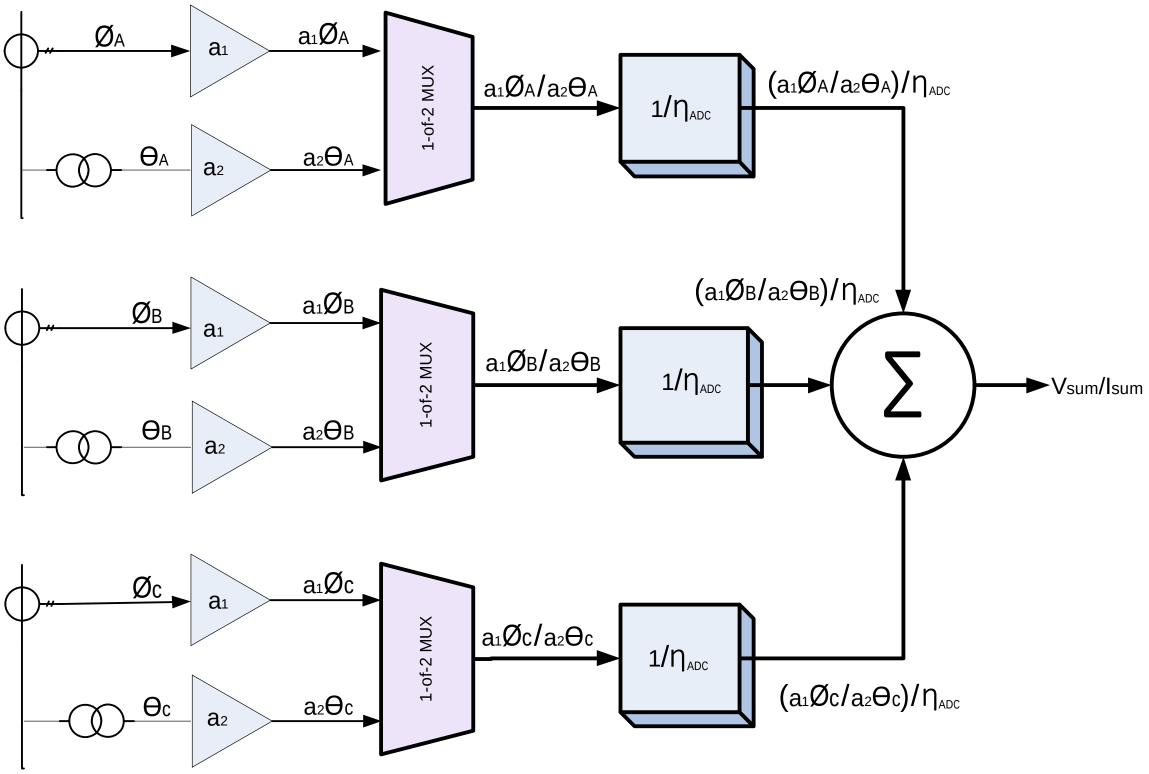

Figure 7: Data merging process modelling analysis

Equation (17) therefore represents the complete voltage and current parametric behaviour of the bay and can be used to effectively monitor, control and protect the substation at the bay level.

The value η_{ADC} depends on a factor n = number of bits of the digitizing analogue-to-digital converter (ADC) which defines the resolution of the output digital value with respect to the input signal range. In order words, the resolution defines how well the digital value equivalent accurately represents the analogue signal values. Thus η_{ADC} is determined by:

$\eta_{ADC} = 2^n - 1$ - - - - - - - - - - (18)

And the resolution is given by,

$Resolution = \frac{S_{max}}{2^n - 1}$ - - - - - - - - - (19)

Where,

S_{max} = maximum analogue input signal value.

Again, at any given time t, the current and voltages in the three lines can be expressed as:

Line A:

$\theta_A = V_A \sin(\omega t)$ - - - - - - - - - - (20)

$\emptyset_A = I_A \cos(\omega t + \psi)$ - - - - - - - - - (21)

Line B:

$\theta_A = V_A \sin(\omega t + 120^0)$ - - - - - - - - - (22)

$\emptyset_B = I_B \cos(\omega t + \psi + 120^0)$ - - - - - - - - (23)

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Line C:

$$\theta_C = V_C \sin(\omega t + 240^0) \tag{24}$$

$$\emptyset_C = I_C \cos(\omega t + \psi + 240^0) \tag{25}$$

Where,

V_A, V_B, V_C are the line voltage amplitudes, I_A, I_B, I_C are line current amplitudes, and ψ is the phase angle difference between current and voltage in a line.

Equations (20) through (25) show that the lines can be monitored for load balancing both in amplitude and phase deviations. Thus, Equation (17) can be represented in a matrix form as:

$$\begin{bmatrix} I_{sum} \\ V_{sum} \end{bmatrix} = \frac{1}{2^n - 1}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} . \begin{bmatrix} I_A\cos(\omega t + \psi) & I_B\cos(\omega t + \psi + 120^0) & I_C\cos(\omega t + \psi + 240^0) \\ V_A\sin(\omega t) & V_B\sin(\omega t + 120^0) & V_C\sin(\omega t + 240^0) \end{bmatrix} \tag{26}$$

Where a_1 = the amplification factor for current signals
a_2 = the amplification factor for voltage signals
I_A = the peak amplitude of current flowing in line A
I_B = the peak amplitude of current flowing in line B
I_C = the peak amplitude of current flowing in line C
ωt = the angular variation in radians
ψ = the phase difference between current and voltage in a line.
n = number of bits for analog to digital conversion

B Block diagram overview of the Merging Unit Design

Figure 8 shows a detailed merging process and data flow around a merging unit. First, the digitized values are passed into a data grouping unit where they are separated into current and voltage groups.

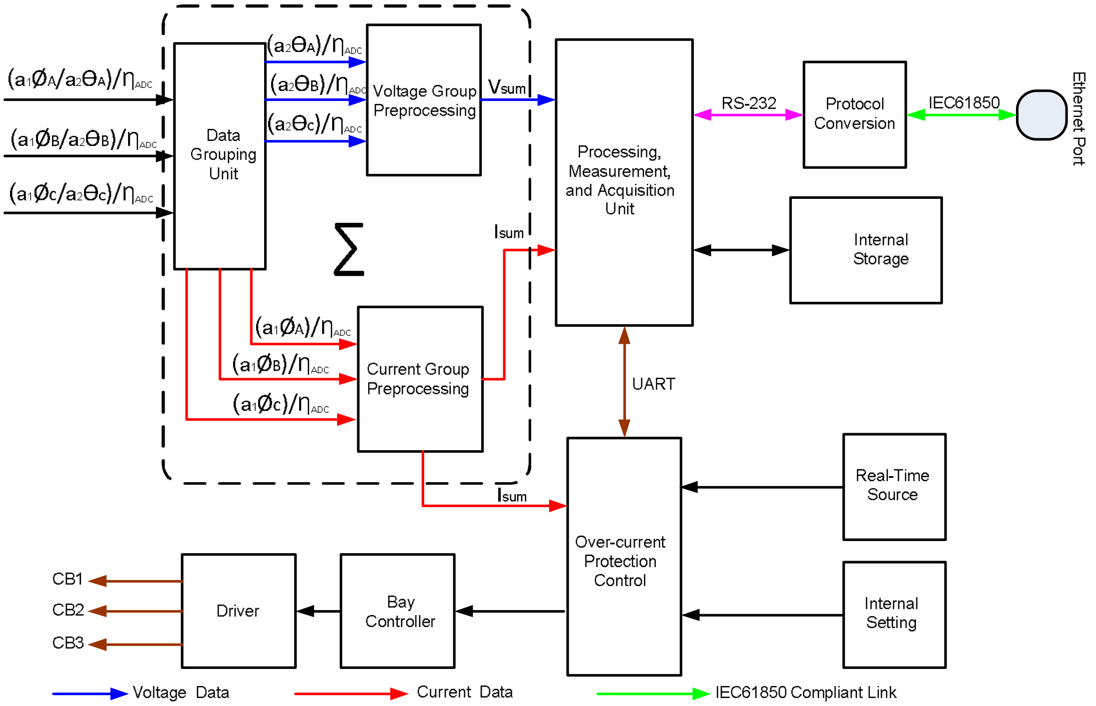

Figure 8 Detailed block diagram of the merging unit showing all the various internal function blocks involved in the merging and control process

The current and voltage data groups are pre-processed separately and passed to the processing, measurement and acquisition unit where the data are processed, measured and stored. The current data group is also directly fed to an over-current protection unit for real-time critical response as determined by preset internal settings. The over-current protection unit can equally send and receive control information to and from the measurement and processing unit for effective bay switching through the line circuit breakers (CB1, CB2, and CB3).

Finally, the merging unit communicates with the rest systems components through its IEC61850 compliant bus made possible by passing the data via a protocol converter. The conversion is necessary since most devices use other terminal technologies such as Recommended Standard (RS-232) serial bus, Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C), etc at their outputs.

IV. CONCLUSION

In this work, an overview of conventional methods of implementing merging unit design in substation automation systems was presented and an improved merging unit model having a built-in protection and control function was proposed. A mathematical model was developed for the proposed merging unit model for possible software simulation.

V. FUTURE WORK

Having theoretically developed the merging unit model, we sought for relevant simulation tools that can enable us implement the model and generate tangible and authentic results in order to validate our achievement in this work. The various software tools which we attempted to use include MATLAB and Simulink [9], ETAP 12.0.0 Demo (Students Edition), Proteus [10] etc. The major challenge we had was that none of the simulation softwares available to us could completely simulate the entire system. Thus a more robust software solution must be sought and deployed in order to simulate the entire system. Another suggestion will be to consider interfacing two or more simulation software packages and deal with the synchronization issues that may arise. However, we are currently working on a practical demonstration model as an improvised system which can be used to implement our design and generate the necessary data for evaluating our proposed substation automation system.

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