ELECTRICAL ENGINEERING

Wireless sensing of substation parameters for remote monitoring and analysis

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Abstract This paper aimed to monitor the different bus parameters in a substation from a centralized control room with the help of Zigbee enabled wireless sensor network (WSN). The parameters such as magnitude and phase angles of voltage and current, frequency, rate-of-change-of-frequency (ROCOF), active and reactive powers are measured using a state-of-the-art customized Zigbee enabled phasor measurement unit (ZPMU). The data from different ZPMUs at different bus nodes are acquired with the help of WSN system in order to have a centralized monitoring of different equipments load status. The coordination among different parameters for different buses and/or equipment is done from a centralized control room within the substation or plant with the help of substation management software and Zigbee networking. The data thus collected are utilized to study the power flow status of the different buses on real time basis and are stored within a server based database for future analysis purposes.

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1. Introduction

The electrical substation is an important part of an electrical system. With the advent of deregulation of the power industry, the importance of substation automation has further increased to become a necessity for the next generation modern power grid. Substation automation is also of great interest as an emerging issue to the researchers and scientists all over the globe because of proper operation, maintenance and load flow analysis purposes of the modern power industry.

The information about the existing conditions of different equipments in a substation provides a clear picture of the state of its components. Further, the information about the direction of flow of electricity will help the electricity utility provider to have a better control over that substation [1]. Although it is possible to monitor the status of the equipments in a substation manually, human error and system response speed become the crucial factors in building up a successful monitoring system. To reduce these limitations and with the improvement in communication and computer technology, the condition based maintenance of substation is becoming possible through online measuring instruments. Thus the measured information regarding the operational voltage level,
magnitudes of current flow and the direction of power flow at different nodes of bus bars, supply frequency, etc. is needed to be transmitted and stored to a central location in order to have their remote monitoring and analysis. Moreover, trend analysis is performed with the above stored data for better planning and expansion of the substation. The load flow analysis helps in realizing the healthiness of the nodes and any faulty node, if occurs, can be isolated from the circuit in order to maintain uninterrupted supply at the healthy zone(s) [2–4].

The present day substation utilizes a three layered structure, comprising of the Process Level, Bay Level and Station Level for the monitoring of its equipments [5]. In this context, the phasor measurement unit (PMU) is one of the most important and promising technologies in building a modern power system. The application of PMUs has been increasing constantly as one of the new tools to improve substation monitoring and performance. PMUs are high speed power system devices that provide synchronized measurements of real-time phasors of voltages and currents. The information from a PMU is used to estimate different electrical parameters including phasor measurement as mentioned above. Time synchronization of PMUs is achieved by same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) satellite. A PMU usually runs of its own sampling time which is synchronized to the common time reference frame with a PLL system. Synchronized phasor measurements evaluate the standards of power system monitoring, control, and protection to a new level [6–8]. By referring the phase angle to a global reference time, it is possible to capture the wide area snap shot of the power system. The data obtained from a PMU can be further used for justifying as well as avoiding blackouts and learning the real time behavior of the power system [6,9]. Since the behavior of a network depends upon the bus voltage magnitude and angle, their real time measurement is a powerful tool for operating a network [6,7,10–12].

The communication among the PMUs, control equipments, actuators and with the centralized control room is achieved by using wired, such as RS 232 and RS485, or wireless, such as Bluetooth, UWB, Wi-Fi and Zigbee communication protocols. The importance of Wireless technologies in different industrial applications is further enhanced nowadays due to their safe and reliable operations. It is desirable that the sensors used in a Wireless Sensor Network (WSN) be provided with long battery lives. Although a lot of standards are available with high data rates, they are unable to meet the unique needs of sensors and control devices. This is because the sensors and controls need low latency and very low energy consumption for longer battery lives and for larger device arrays. Zigbee is a specification for a suite of high level communication protocols. It uses tiny, low-power digital radios based on an IEEE 802 standard for personal area networks (PAN). Zigbee is a low-cost, low-power, wireless mesh network standard. The low cost allows the technology to be widely deployed in wireless control and monitoring applications. Low power usage allows longer life with low capacity batteries. Mesh networking provides high reliability and more extensive range. Zigbee has a defined rate of 250 kbps best suited for periodic or intermittent data or a single signal transmission from a sensor or input device [13–16].

It is also worthwhile to mention that in a substation the electromagnetic emissions created by large motors, heavy equipment, high power generation and usage, and other typical industrial machinery creates extremely high levels of noise that can interfere with the communication of the wireless equipments. In such environments, transmitters and remote nodes are unable to hear each other, resulting in frequent data loss. In such conditions, the robust Zigbee wireless technology is quite efficient in transmitting the data to the destination node by utilizing its hopping feature [17].

The authors in [13] propose Zigbee wireless network as an emerging technology for the development of the on-line monitoring of different parameters in a substation. This standard is the most popular protocol for a Wireless Public Area Network (WPAN) due to its low power consumption, high flexibility, self-healing, feasibility of formation of mesh networking, low cost, etc.

Thus, remote monitoring of electrical parameters for different nodes of a substation is becoming important and research works have been started since the last three decades in order to make their operation automatic. IEC 61850 standard is evolved and the monitoring devices are being made following this standard. The adoption of background Ethernet and GOOSE communication, which is migrated from mere serial communication, has increased the system efficiency by reducing the latency to a great extent [18,19].

In this proposed work, the authors have tried to develop a monitoring system with a microcontroller based state-of-the-art customized Zigbee enabled PMU (ZPMU), Zigbee enabled Intelligent Electronic Device (ZIED) and a MATLAB based GUI. The main objective of this work was to establish a Wireless Sensor Networking (WSN) among the different ZPMUs. This is achieved by incorporating a zigbee module in each of the own developed PMUs. The ZPMUs are to be installed at different bus nodes of substation to monitor the various parameters in a synchronized time reference frame such that the power flows at different buses can be estimated at any instant of time. Moreover, the data acquired by the ZPMUs from different nodes can be also used for fault diagnosis purpose. In each ZPMU, besides all parameters’ measurement following IEEE C37.118, the active and reactive power are measured using a newly introduced Sample Shifting Technique (SST) [10] with an added feature of detecting the direction of power flow in order to detect import or export of power. The data from different ZPMUs are acquired in a centralized PC with the help of Zigbee based wireless networking and a ZIED to monitor the different equipments’ load status installed at different bus nodes. A MATLAB based front end graphical user interface (GUI) is developed to acquire these data using the PC’s USB port. The microcontroller in the ZIED communicates with the PC using MODBUS protocol and hence an IEC61850 to MODBUS converter hub is used. The software and ZIED coordinate all the time synchronization measurement from the ZPMUs and maintain a sequential routing for the data collection from them. The system performance is tested with three sensing modules in Real Time Digital Simulation (RTDS) based system. The accuracy of the ZPMU data is checked with one single module in a 400 kV ac transmission line simulator.
2. System overview

2.1. Zigbee based system

The schematic diagram of the proposed system is shown in Fig. 1. As shown, the state-of-the-art ZPMU is customized with the use of current transformer (CT) and potential transformer (PT) as basic sensors of electrical parameters, GPS receiver to provide time synchronized reference clock pulses and Zigbee module with a data rate of 500 kbps to provide wireless networking facility.

In its second part, a wireless networking is constituted with several ZPMUs within the coverage range of Zigbee modules with the state-of-the-art central ZIED. The ZIED communicates with PCs at the control station through IEC61850 based station bus as well as all the ZPMUs in a time reference frame of GPS.

In the final part, a MATLAB based GUI is developed for the wireless acquisition of parameters of different bus nodes through ZIED.

2.2. Development of state-of-the-art ZPMU

The concept of PMU technology provides real time phasor information of voltage and current signals by acquiring their samples in a time synchronized reference frame [8,20]. The synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from a common time reference frame, such as the Global Positioning System (GPS) time.

Fig. 2 shows the schematic diagram of the customized ZPMU block. The voltage and current signals at a node are stepped down using potential and current transformers respectively before their conversion by the ADCs of the ZPMUs. For three phase measurement, six numbers of ADCs have been used to measure all the three phase voltages and the respective phase currents. The clock pulses from the phase locked loop (PLL) are fed to all the ADCs for their simultaneous conversions of the analog inputs in synchronization with the GPS reference time frame.

The microcontroller in the ZPMU generates a reference clock pulse on receipt of the synchronizing pulse from the GPS unit. As shown in Fig. 3, \( T_{GPS} \) denotes the period between the successive synchronizing pulses of 1pps generated by GPS, which is fed to the microcontroller that generates a reference clock pulse \( T_{ref} \). This \( T_{ref} \) is fed to the PLL in order to get the clock frequency of the ADCs, the period of which is shown by \( T_{ADC} \) in Fig. 4. The ADC conversion time is \( \approx 70 \) clock cycles. However, the ADCs’ outputs are sampled by the microcontroller at the desired sampling frequency \( T_{sample} \) (here, it is considered as 1 kHz). The acquisition is achieved by generating six read strobe signals one after another and since the same clock pulse is fed their conversion is made independent of sample acquisition.

The microcontroller in the customized ZPMU computes and stores the rms values, phase angles, frequency, rate of
change of frequency (ROCOF), active and reactive power for one complete cycle of the input signal waveform using its samples only. These data are sent to the PC through a ZIED in the central monitoring location for their storage and display in the PC using Zigbee protocol.

2.3. ZIED and synchronization

The ZIED is constituted with a microcontroller, GPS receiver, Zigbee module, bus converter and a UART to USB hub as shown in Fig. 4. The basic purpose of the ZIED is to establish coordination among the different ZPMUs installed at different locations using Zigbee protocol and the PC. The microcontroller in the ZIED communicates with the PC through its USB based virtual COM port using RS232 protocol. ZIED sends a “data request” packet of five bytes to the ZPMU, mentioning the ZPMU ID number within the packet, in order to acquire the data. The ZPMU responds to this request, by transmitting a “data frame” of 31 bytes to the ZIED only when its ID number is matched. This “data frame” consists of a 2-byte SYNC word followed by a 2-byte ID code to indicate the ZPMU number, a time stamp consisting of a 4-byte SOC, a 22-byte data and finally a CHECK word of 1 byte which is “CHECK SUM”. The 22-byte data consist of rms values of voltage (3 byte) and current (3 byte) signals, active power (4 byte), reactive power (4 byte), phase angle of voltage signal (3 byte), phase angle of current signal (3 byte), frequency (1 byte) and ROCOF (1 byte) of the signals measured by the ZPMU at a particular bus end. However, in order to increase the battery life during power shut down mode, the Zigbee module sends only 4 bytes instead of the normal 31 bytes. The 4 byte consists of a one byte indicating no power and the SYNC and CHECKSUM bytes.

The next ZPMU data will be acquired in a similar technique by changing the ID number in the “data request” packet, only when the previous one is completed. On the other hand, the ZIED modifies this received data packet to another packet format excluding the time stamping, SYNC word and CHECK word and sends it to the PC using serial communication. This protocol conversion is done to reduce the length of data bytes by 7 bytes for successive ZPMU data. The ZIED to PC data packet is thus another SYNC (2-byte), STARTING TIME (4-byte), ZPMU ID number, parameter data, next ZPMU ID, parameter data and so on. In this way, all ZPMU data are collected by the ZIED within one complete line cycle period. The 50 fps pulse is generated by the ZPMU microcontroller in synchronization with GPS real time clock. In its each frame of 50 fps time, the ZIED sends and collects the required data packet to and from all the ZPMUs one after another and in this way the time synchronization is achieved.

The PC stores the data of all the ZPMUs as well as this time information in a server such that the power system parameters from different nodes can be monitored with respect to the real time clock. In order to detect the healthiness as well as the presence of any abnormal working conditions in the system, a fault detection algorithm based on sequence components is used.

2.4. Sample Shifting Technique

The line power flows can be easily calculated by utilizing the voltage and current samples of a bus end, as measured by the ZPMU. This method is known as the Sample Shifting Technique. Hence, it is possible to measure the active as well as the reactive powers consumed at a node of the substation. The most important advantage of this state-of-the-art method is that it does not require the computation of power factor angle between the voltage and the current signals [10].

(i) Calculation of active power ($P$)

If the voltage and current signals be represented as

\[ v(t) = V_m \sin \omega t \]
\[ I(t) = I_m \sin(\omega t - \phi) \]

then, the active power, $P$, will be represented as,
where $v_n$ and $i_n$ are the samples of the instantaneous values of the voltage and current signals at the nth instant respectively and $N$ is the total number of samples over a full line cycle. Thus, it can be interpreted that the $\cos \Phi$ is inherently associated with their product and average.

(ii) Calculation of reactive power ($Q$)

The reactive power, $Q$, can be expressed as,

$$Q = VI \sin \phi = VI \cos(90 - \phi)$$

In order to keep parity with Eq. (1), a similar equation can be generated for the reactive power as follows,

$$Q = \frac{1}{N} \sum_{n=1}^{N} v_n i_{n-90}$$

where $v_n$ and $i_{n-90}$ are the sample values of voltage and $90^\circ$ shifted current signals respectively and $N$ is the total number of samples over a full cycle. The samples of $i_{n-90}$ are generated by applying Sample Shifting Technique to $i_n$ as described in [10].

2.5. Zigbee based modified substation

The proposed system is actually a part of modern substation monitoring system. The typical schematic diagram of the modified substation (SS) is shown in Fig. 5 where the entire SS is divided into a three layered structure.

The first or the bottom layer is the process layer which is interfaced with the field equipments for data acquisition and the functioning of the protection equipments. The other side of this layer communicates with the Bay Level equipments for their measurement values, indications, control parameter, state estimation, etc. The final layer is responsible for the HMI and WAN connectivity with respect to GPS time reference frame.

The proposed system’s objective is to adopt the advantages of Zigbee Wireless Communication in between the Process level and Bay Level equipments by utilizing ZPMUs and centralized ZIED.

3. Customization of ZPMU

3.1. Sensing of power flow direction

Although the conventional electric power industry is a regulated one, the latest Electricity Act has opened up huge opportunities for import and export of electricity. The determination of export or import of power can be easily done by sensing of direction of power flow from the sample values of the voltage and current signals only as described in the forthcoming sections.

Fig. 6 shows the phasors of voltage and current signals for four different conditions with the voltage phasor as the reference phasor i.e. $V \angle 0^\circ$. When the current phasor is at any angle within $-90^\circ < \theta < 90^\circ$, the power flow direction is considered as the forward direction i.e. from power grid to the load with either lagging or leading load angle. Similarly, for reverse direction of power flow, the current phasor will be within $90^\circ < \theta < -90^\circ$ w.r.t. the same voltage phasor. Fig. 7 further illustrates this fact with the help of voltage and current waveforms.

The determination of lagging or leading states of the signals is done from the positive slope of the waveforms only. For positive power flow direction, the zero crossing instant of current waveform lies within $0^\circ < \theta < 90^\circ$ of voltage waveform for lagging load angle within $-90^\circ < \theta < 0^\circ$. Similarly, for leading load angle within $0^\circ < \theta < 90^\circ$ the zero crossing instant of current waveform falls within $270^\circ < \theta < 360^\circ$ for the same measuring condition. This is illustrated in Table 1.

Similarly, for reverse power flow, the zero crossing instant of current waveform falls within $180^\circ < \theta < 270^\circ$ for lagging
load angle within $-90^\circ < \theta < 180^\circ$ and for leading load angle within $-180^\circ < \theta < -90^\circ$ the zero crossing instant of current waveform falls within $90^\circ < \theta < 180^\circ$ [7].

### 3.2. Wireless sensing of parameters using Zigbee modules

The ZPMUs are installed at different bus nodes in a substation to facilitate private area monitoring (PAM) of power system parameters. The Zigbee Reduced Functional Device (ZRFD) module, interfaced with the ZPMU, provides for the wireless sensing facility. A Zigbee Basic Service Set (ZBSS) is constituted with a Zigbee Full Functional Device (ZFFD) module as a central node.

### 4. Networking of meters within Zigbee basic service set (ZBSS)

Coordination of these ZPMUs to build up a Zigbee Basic Service Set (ZBSS) based networking is done with the help of a Zigbee Coordinator (ZC) as shown in Fig. 8.

ZC communicates with ZPMUs in unicast mode of communication i.e. if a data packet is required from a particular ZPMU, ZIED sends the request through ZC to all the ZPMUs along with the Medium Access Control (MAC) address of the intended ZPMU in the request packet. The intended ZPMU, whose MAC matches, will respond only on that request by sending the required data packet.

### 5. Result and discussion

#### 5.1. Real Time Digital Simulation (RTDS) unit

The performance of the system is studied with the help of RTDS [from Manitoba University, Canada] unit and three ZPMUs. A transmission system is simulated, as shown in Fig. 9, in the RTDS and the voltage and current signals at the incoming and outgoing bus ends are sampled during the

<table>
<thead>
<tr>
<th>Power flow direction</th>
<th>Load angle range</th>
<th>Positive slope zero crossing angles</th>
<th>Quadrant (w.r.t. zero crossing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>$0^\circ &lt; \theta &lt; -90^\circ$ (lag)</td>
<td>$0^\circ &lt; \theta &lt; 90^\circ$</td>
<td>First</td>
</tr>
<tr>
<td>Forward</td>
<td>$0^\circ &lt; \theta &lt; 90^\circ$ (lead)</td>
<td>$270^\circ &lt; \theta &lt; 360^\circ$</td>
<td>Fourth</td>
</tr>
<tr>
<td>Reverse</td>
<td>$90^\circ &lt; \theta &lt; 180^\circ$ (lag)</td>
<td>$180^\circ &lt; \theta &lt; 270^\circ$</td>
<td>Third</td>
</tr>
<tr>
<td>Reverse</td>
<td>$-180^\circ &lt; \theta &lt; -90^\circ$ (lead)</td>
<td>$90^\circ &lt; \theta &lt; 180^\circ$</td>
<td>Second</td>
</tr>
</tbody>
</table>
running condition. The data containing information about magnitudes and phases of voltage and current signals, active power, reactive power, frequency and ROCOF at the respective bus ends are acquired by the ZPMUs. In addition, different types of faults such as, line-to-line and line-to-ground are also created with the help of the RTDS unit and the corresponding data are acquired with the help of the ZPMUs.

The RTDS hardware is capable to handle input and output in digital as well as in analog domain. With the help of the user interface, various processors can be assigned for this input and output purpose. In this case the analog outputs for voltage and current signals are obtained from processor 'A' of 3PC card [21].

5.2. ZPMU data collection and communication bandwidth

The parameter information of the ZPMU is transferred to the ZIED through Zigbee module. These data from the ZIED are transmitted to the PC using serial communication@115.2 kbps. The data are displayed in the PC using a MATLAB based GUI. The MATLAB program has the inbuilt capability to detect any preliminary abnormal conditions by using the fault detection algorithm based on sequence components. If necessary, the trip command may be issued to the ZPMU to isolate the faulty region.

The Zigbee has a defined data transmission rate at 250 kbps. On the other hand, each ZPMU has to exchange at least 30 bytes with the ZIED in 20 ms duration through the Zigbee network. Thus, a maximum of 1500 bytes can be exchanged with the ZIED by each ZPMU in 1 s. The data in the ZIED are again transferred to the PC using serial communication. Thus, the communication speed of the serial channel must be sufficiently high enough to transfer all the data from the ZIED to the PC without any data loss.

The speed of UART to USB converter is limited to only 115.2 kbps. Once communication is established between a ZPMU and the ZIED, unnecessary repeated transmission of certain bytes such as SYNC, SOC and CHECK, is avoided to the PC so as to reduce the frame length that is transmitted from the microcontroller in the ZIED to the PC. This leaves with only 24 bytes of data. Thus, at least ten ZPMUs can be connected in the network.

It is also observed that the number of transmitted bytes is directly proportional to the sampling frequency ($f$), the number of signals ($s$) and the number of phases ($n$) of the system [6]. Mathematically, the number of transmitted data bytes ($B$) can be represented as:

$$B = f \times n \times s$$

Further, data compression technique can be used for increasing the communication speed.

5.3. Latency estimation

The ZPMU uses a 16-bit addressing mode and transmits data at the rate of 250 kbps. The time taken on the air to transmit 31 bytes is approximately 1.408 ms. Time taken for Clear Channel Assessment (CCA) is 0.128 ms. With CCA clear, the time required to send 31 bytes in air for “best case” is 1.536 ms. If CCA is blocked, after an attempt of at least five times, the time taken to transmit 31 bytes in “worst case” is approximately 10.368 ms.

5.4. Measurement accuracy

Since CTs and PTs have been utilized for stepping down the voltage and current levels before the signals are sampled by the ADCs, there lies a possibility of error introduction in the
measured values of the signal magnitudes and phase angles. This error may be due to the ratio error or the phase angle error of the instrument transformers.

Unnecessary introduction of phase angle errors due to non-simultaneous conversion by the ADCs is avoided by feeding the clock pulse from the PLL to all the ADCs at the same instant which is also in synchronization with the GPS.

While the magnitude of the signal can be obtained by rms principle from the sampled values, an estimation of the phase angle is obtained from the zero crossing instants of the two signals that may lie on either the rising or the falling edges. If the zero crossing lies between two samples, further interpolation is applied in the region between the two samples to determine the exact zero crossing instant. Hence, an error of maximum 10 μs may be introduced during phase calculation considering 100 interpolation values in between successive samples. This is an additional feature of the proposed system as the maximum error that can be introduced in a 50 Hz system should not exceed 31 μs as per C37.118.1 standard [22, Section 4.3.]

The calculation of active and reactive powers using the Sample Shifting Technique utilizes the voltage and current samples only. In other words, no extra measurement is required for their calculation.

The frequency of the signal is calculated by computing the time period of the signal which is the duration between two successive rising edges or falling edges of the signal. The change of frequency between two consecutive cycles of a signal is also computed to evaluate ROCOF.

On the other hand, there may be a communication error in the Zigbee itself only when its receive signal strength (RSSI) is below some threshold value or all the communication channel is engaged by some other user. Otherwise Zigbee has its inbuilt capability to check the bit error using preamble and CRC checking. If any error occurs during the communication, Zigbee simply ignores the entire packet. In this case, the entire packet will be lost.

Various literature surveys show that the propagation inside a building is influenced by the layout of the building, its construction materials as well as building type (sports arena, residential home, factory, etc). Within a building, path loss factors are as follows: (i) Partition losses (same floor); (ii) Partition losses between floors and (iii) Signal Penetration into Buildings. In order to establish a RF link between an outside and an inside node it must have to penetrate from outside transmitter to the inside of buildings. However the signals are attenuated, the path loss during penetration has been found to be a function of the frequency of the signal (penetration loss decreases with increasing frequency) and the height of the building (penetration loss decreases with the height of the building up-to some certain height). The RSSI is inversely proportional to the transmission distance which is indicated in Table 2. The transmitted signal strength was −12 dBm. It can be observed that the signal strength reduces further if there are concrete obstacles in between [23].

### 5.5. Detection of abnormal condition

The fault detection in the system has been carried out by utilizing sequence components. According to Fortescue’s theorem, three unbalanced phasors of a three phase system can be resolved into three balanced systems of phasors known as zero, positive and negative sequence components. The state of a system, whether healthy or faulty, can be determined by observing the magnitude and phase angles of the sequence components of the respective phases [21,24].

### 5.6. Verification of the proposed method with RTDS

The experimental setup of the hardware using RTDS that has been used in the laboratory for performance study is shown in Fig. 10. As shown, three ZPMUs are interfaced to the RTDS.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Distance (in meters)</th>
<th>No. of walls in between</th>
<th>Received signal strength (in dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>2</td>
<td>−69.17</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>3</td>
<td>−53.19</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>4</td>
<td>−85.18</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>3</td>
<td>−85.34</td>
</tr>
</tbody>
</table>

![Experimental setup of the hardware using RTDS](image-url)

![Phase currents during line to ground fault condition](image-url)
Sequence component analysis of the currents provides the results as shown in Table 3. Although there should be no other sequence components present during the healthy conditions except the positive ones, the slight unbalance in the currents at the outgoing bus end causes the negative as well as the zero sequence components to exist.

(ii) Line to ground fault condition

Fig. 9 shows the RSCAD model for the line to ground fault condition of phase A. The current waveforms of different phases are shown in Fig. 11 where CRT1RE, CRT2RE and CRT3RE are the currents flowing in the phases A, B and C respectively at the outgoing bus end. CRT1RE also indicates the current flowing from phase A to the ground during the fault condition. The respective phase currents after the occurrence of the fault are as follows:

\[ I_a = 5.86\angle 0^\circ \text{ kA}; \quad I_b = 0.84\angle -127.4^\circ \text{ kA}; \quad I_c = 0.84\angle -263.5^\circ \text{ kA} \]

The sequence components of the currents during the fault condition are shown in Table 4. It can be observed from the table that during a line to ground fault, all the sequence components are present in an appreciable amount. Comparison of the phase angles of the positive and negative components shows that they differ in phase by almost 180°.

(iii) Line to line fault condition

The line to line fault is created by shorting the phases A and B of Fig. 9 with the RSCAD software. The corresponding current waveforms are shown in Fig. 12 where CRT1RE, CRT2RE and CRT3RE are the currents of phases A, B and C respectively at the outgoing bus end. CRT1RE and CRT2RE also indicate the fault current flowing between the phases A and B due to a short circuit. The currents flowing in the phases A, B and C after the occurrence of the line-line fault are as follows:

\[ I_a = 9.62\angle 0^\circ \text{ kA}; \quad I_b = 9.06\angle -179.2^\circ \text{ kA}; \quad I_c = 0.91\angle -289.2^\circ \text{ kA} \]

The sequence component analysis of the currents after the occurrence of the fault provides the result as shown in Table 5. It can be observed that the magnitude of the zero sequence

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Sequence components of currents during healthy conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero sequence</td>
<td>( I_{a0} ) (kA)</td>
</tr>
<tr>
<td>0.006\angle164</td>
<td>0.006\angle164</td>
</tr>
<tr>
<td>Positive sequence</td>
<td>( I_{a1} ) (kA)</td>
</tr>
<tr>
<td>0.91\angle0.13°</td>
<td>0.91\angle-119.8°</td>
</tr>
<tr>
<td>Negative sequence</td>
<td>( I_{a2} ) (kA)</td>
</tr>
<tr>
<td>0.0046\angle-52.8°</td>
<td>0.0046\angle72.2°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Sequence components of currents during line to ground fault conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero sequence</td>
<td>( I_{a0} ) (kA)</td>
</tr>
<tr>
<td>1.75\angle1.82°</td>
<td>1.75\angle1.82°</td>
</tr>
<tr>
<td>Positive sequence</td>
<td>( I_{a1} ) (kA)</td>
</tr>
<tr>
<td>2.49\angle-3.39°</td>
<td>2.49\angle-123.4°</td>
</tr>
<tr>
<td>Negative sequence</td>
<td>( I_{a2} ) (kA)</td>
</tr>
<tr>
<td>1.62\angle3.2°</td>
<td>1.62\angle123.2°</td>
</tr>
</tbody>
</table>
components is very small in comparison with the positive and negative sequence components of the respective phase currents. Further, it can be also seen that the magnitudes of the positive and negative sequence components are almost same. However, these components also differ in phase by an angle of 180°.

(iv) Verification of ZPMU Readings with Transmission line simulator

In addition to the above, the performance of the system is also tested in the power system laboratory using a three bus 400 kV ac transmission line simulator as shown in Fig. 13. The length of the transmission line was set at 100 km and the line inductance was selected at 0.19 mH/km.

Table 6 shows the panel meter readings at the incoming and outgoing bus ends respectively. A customized ZPMU was used to acquire the data at the outgoing bus end. Comparing the data at the outgoing bus end, as acquired by the meters and at the control station, it is observed that there is a difference of 0.35% in the magnitudes of both $P_R$ and $Q_R$. The error can be further minimized by increasing the number of samples of the voltage and current at the receiving end of the transmission line.

6. Conclusion

The uniqueness of the proposed system is that a Zigbee enabled state-of-the-art microcontroller based ZPMU and ZIED are developed and tested in the laboratory with satisfactory results. Since Zigbee is itself a robust communication scheme, this WSN for substation monitoring is highly reliable. In the ZPMU, the phase angle is calculated from the voltage or current samples by comparing their zero crossing instants. The Sample Shifting Technique makes it possible to calculate active and reactive power from voltage and current samples only without calculating the power factor angle.

The sensing of power flow direction has been provided to the ZPMUs as an added feature of standard C37.118. This power flow direction sensing is helpful in realizing the import or export of power.

The Zigbee module is used in order to mitigate the strong EMI and RFI prevailing in the substation arena. Inherent data whitening principle is used for security purposes.

The ZPMUs are smart enough to monitor the parameters instead of sending all the samples to the ZIED, it only sends the magnitudes and phase information, active and reactive power, frequency, ROCOF and direction of power flow. In its added advantages, if any abnormal condition is detected the PC may ask the voltage and current sample values from the ZPMU for better understanding and future analysis purpose. It also generates a trip signal to isolate the faulty zone.

Star topology of the Zigbee communication by considering a short range (~100 mt) of networking is proposed. It is presumed that the coverage area for 'process level' is well within
100 mt of range and hence all the equipments under this coverage area might have one-to-one correspond for the Zigbee routing. However, for a longer coverage range, mesh topology of Zigbee modules is to be adopted for which the rerouting capability, based on a suitable algorithm principle, is to be explored.

The system reliability can be enhanced by adopting Coding technique. The overall efficiency can be improved by using suitable data compression scheme. On the other hand, by eliminating the USB to UART converter, the use of the USB based microcontroller will enhance the total ZPMU numbers.

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References


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