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Performance of communication networks for Integrity protection systems based on travelling wave with IEC 61850

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ABSTRACT

Smart grid system protection can be divided into wide area network, WAN, and substation area protections. The IEC 61850 Ed.1 standard contains models for SV and GOOSE messages that can be used in intra-substation protection. This paper investigates the WAN and substation area protections based on a travelling wave with IEC 61850 that have not been used in a product since 2016. The high sampling frequency for processing the travelling wave may block the communications channel and reduce security. In order to address this problem, an approach is proposed that is based on using real-time travelling wave signal packing with lossless compression and travelling wave feature extraction. The performance of these techniques has been tested using an OPNET modeler, while their validity has been tested through computer simulation. The application of WLAN based on transient travelling wave for real-time protection has also been investigated. The lower sampling, or transformed, data can be used for the applications of transient waves in digital substations. The comparison protection based on travelling wave between the Ethernet and second-generation WLAN results has also been discussed. An IED design is proposed for fast tripping that can be used in WAN protection based on the travelling wave. This work paves the way for other research to start developing fast protection systems based on travelling wave with IEC 61850.

1. Introduction

A wide area protection (WAP) system can be classified as centralized or decentralized and provides comprehensive protection over a wide geographical distance of interconnected power systems. A centralized WAP offers easy data access, but is prone to single node failure. On the other hand, decentralized WAP offers high reliability, but involves high communication costs and a limited extent for stability analysis. The IEC 61850-90-5 standard offers a wide-area protection system that is primarily based on phasor measurement units (PMUs). The PMU method requires a full cycle for accurate phase estimation, thereby resulting in delays of more than 20 ms that violate the delay requirements of the IEC 61850-5 standard.

The objective of power system protection is to isolate the faulted section of electrical power systems without any severer damage due to fault current. The main components of the transmission network are busbars and transmission lines, therefore fast clearing of fault and location is necessary. The conventional techniques for transmission line protection includes differential protection, over current and distance protection relays. The principle of the impedance method is simple but suffers from a low accuracy. Given its immunity to voltage variations, differential protection is widely used in power system protection, especially for bus-bars, transmission lines, and transformers. In addition, differential protection on long power transmission achieves low communication link latency by comparing the measurements that are received from the local and far ends of the terminal. A transient travelling wave is used in protection to evaluate the fault location and line. Ultra-high speed power system protection analysis based on IEC 61850 protocols present a topic that has not been investigated in the literature.

A travelling wave (TW) based method uses the incident and reflected travelling waves at both ends of the line. Faults on the power transmission network cause transients that propagate on the transmission lines as travelling waves that involve high frequency components and travel with a speed that is close to speed of light. Initially both incident and reflected transients exist on the line that causes these transients. However, only the transmitted transient exists on other

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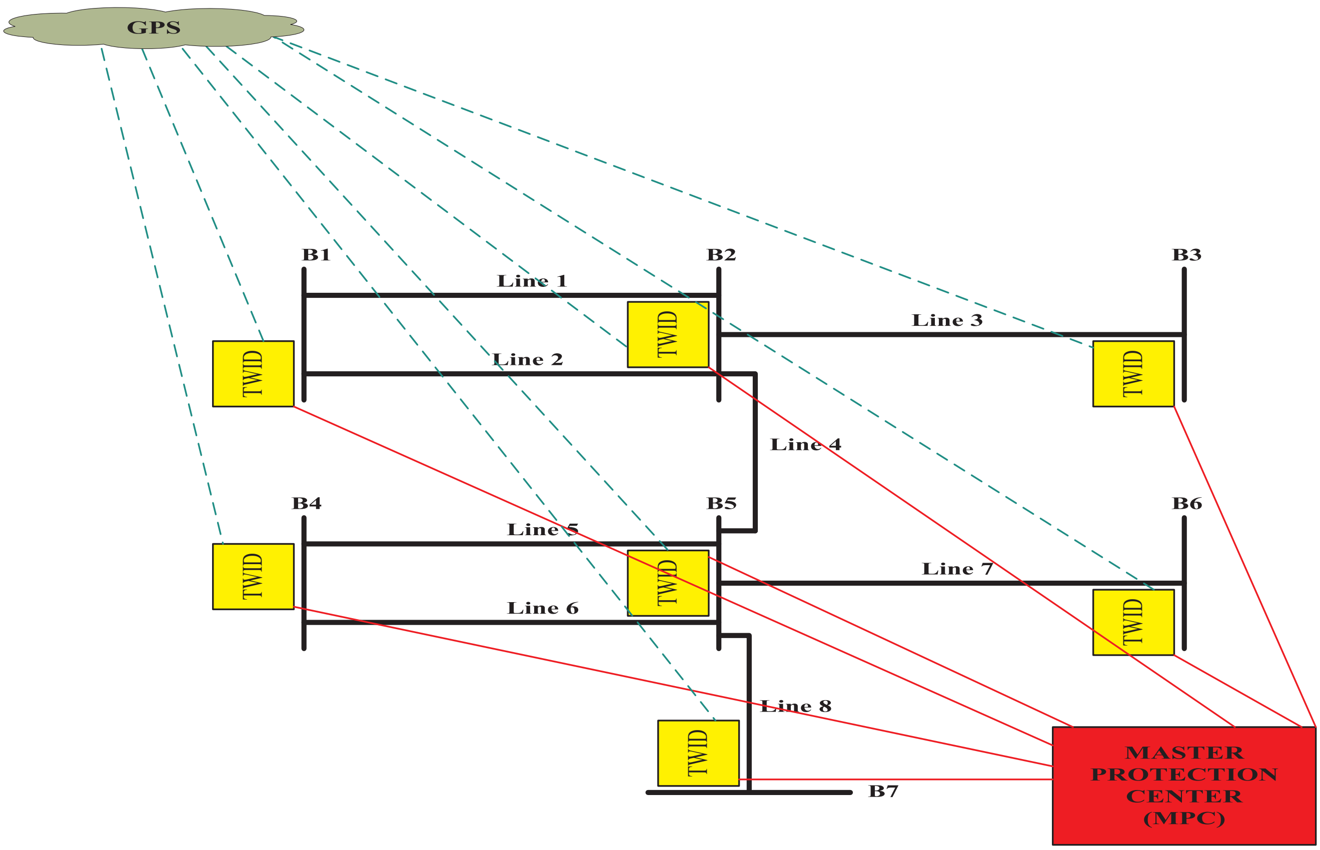

Fig. 1. Proposed WAP based on travelling wave.

transmission lines, which propagates away from the substation busbar. As shown in Fig. 1, the proposed system protection comprises travelling wave intelligent electrical devices (TWIEDs) that measure the fault-generated travelling wave, a master protection center (MPC), and a wireless communication backbone network. Given that this system uses data from neighboring buses, the failure of one TWIED does not necessarily result in the failure of the entire system protection. The IEC 61850-90-1 standard uses a proxy gateway, or tunneling data communication, among substations to implement a long transmission line protection that is similar to differential or distance protection. By contrast, the IEC 61850-90-5 standard maps GOOSE and SV messages with the UDP/IP layer, and then transfers these messages to other substations in WAN. The current power systems have become highly complex by integrating Distribution Energy Resources (DERs) with distribution systems, thereby introducing new challenges in the effective control, measurement, management, and protection of distribution systems. Fast tripping presents a useful technique for non-traditional sources because of its low dependence on sources and high dependence on the network [1]. As an emerging technique, ultra-high-speed line protection offers a novel way to trip line faults within a few ms [2]. The lower sampling data or transformed data must be used for the application of transient waves in digital substations. The different communication protocols in smart grids have also introduced new challenges. IEC 61850 is a worldwide protocol known for its flexible configuration, functional allocation, and ability to determine the interoperability of devices from different vendors. The National Institute of Standards and Technology identify IEC 61850 as one of the key enabler standards for smart grids.

The first edition of IEC 61850, which was in effect between 2003 and 2005, guided the use of communication protocols in substations. The second edition, which was in effect between 2008 and 2012, guided the use of IEC 61850 for communication in power utility automation and smart grids. Editions 2.1 and 3 have been designed to introduce further improvements for communication in the smart grid domain. The IEC-61850-based substation protection has numerous applications in different disciplines including automation and control systems, integrated communications, computing and many more. Fault protection and location can be performed using IEEE 802.11n WLAN or Ethernet in compliance with IEC 61850. The impedance method reveals the high bit rate of these methods. Fast protection systems based on travelling waves have attracted wide usage because of their high immunity to CT saturation, system oscillation, transition resistance, and neutral point operation modes. Protection is a time critical event that requires a fast and reliable communication network.

The travelling wave must have a sampling frequency ranging from 200 kHz to 1 MHz to obtain a highly accurate and valid sampling data. Multiple MUs sharing the same process bus are similar to a video conference with multiple terminals via a video conference [3,4]. Sending high-definition video signals from these terminals will result in a long delay that does not meet the requirements of IEC 61850-5 [5]. Similarly, when multiple MUs share the same process bus, using a high sampling frequency will result in long delays that do not meet the protection and control requirements of IEC 61850-5.

This paper proposes two ways to address this problem. First, the travelling wave signal must be assembled and compressed. Second, the travelling wave with feature extraction must be used. This paper advocates the wide application of travelling waves in digital substations with IEC 61850.

The performance and limitations of WLAN in fast protection systems based on travelling wave are investigated in detail in [6], while the different industrial applications of this technology are cited in [7–14]. However, no survey has examined the application of fast tripping systems in substations, WAN, and WLAN based on travelling waves. Furthermore, using second generation IEEE 802.11n supporting IEEE 802.11i with enhancement MAC Layer the advanced security and QoS can be achieved using wireless communication technology.

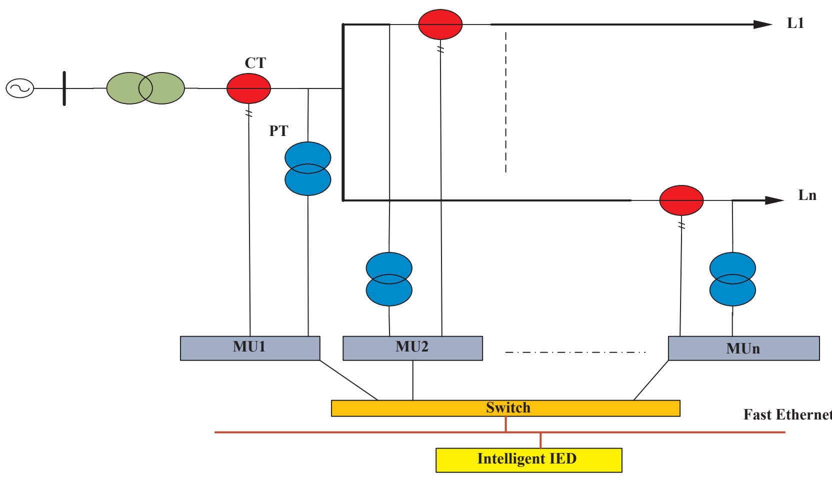

Fig. 2. Multiple MUs network communication of process level based on IEC 61850.

This paper assesses the performance of WLAN based on smart distribution substation applications in compliance with IEC 61850. This research is also the first to examine the fault detection and protection performance of WAN based on feature extraction in compliance with IEC 61850.

The rest of this paper is organized as follows. Section 2 describes the fast tripping technique based on travelling wave signals. Section 3 analyzes the communication model. Section 4 analyzes the data processing techniques. Section 5 describes the design of ultra-fast tripping IED. Section 6 is the comparison with previous work. Section 7 describes the service modeling of IEC 61850-90-5 based on travelling wave. Section 8 presents a WAN substation communication scenario. Section 9 concludes the paper.

2. Fast tripping based on travelling wave

Fig. 2 presents the process level communication in a substation with IEC 61850. The merging units (MUs) collect the measurements from the process field using the current and potential transformers, and then send these measurements by transmitting an SV message to the protection and control IED through the Ethernet communication link. In a wireless topology, the MUs are connected to the IED via an access point (AP) through a free channel.

The communication delay in process buses is affected by the communication model, channel bandwidth, advanced technology Ethernet switch for SAS and AP, and real-time signal processing capabilities of the P & C IED and MU.

Power systems face transmission line faults under the influence of lightning, wind, ice, and snow. The protective system must rapidly sense and isolate these faults within a specific time frame to minimize the damage. Transmission line protection based on distance relay and line current differential often faces longer delays than protection based on travelling wave, with the latter reducing the delay by less than 4 ms. Reducing the delay will improve the stability of the power system, conserve energy, and benefit alternative generation sources that are connected to the power grid, such as solar and wind energy. Protection relay greatly depends on the networks rather than on the source. By contrast, since IEC 61850 designs are based on unlimited bandwidth channels, then channel bandwidth does not represent any issues [15,16].

Given that fast protection based on travelling wave with IEC 61850 requires a high sampling frequency that ranges between 200 kHz and 1 MHz, the WLAN with a speed ranging between 54 Mbps and 600 Mbps cannot support such an application because of unacceptable time delays. This paper addresses such problem via packing and compression as well as feature extraction based on a mathematical morphological gradient (MMG), Hilbert–Huang transform (HHT), or wavelet transform.

3. Communication delay in process bus

3.1. Communication model

The main traffic in a process bus is generated from the SV message. The SV message traffic rates are affected by the number of MUs, packet length, and frequency of transmission as shown below:

$$r^{SM} = MU_n P^{SM} f^{SM} \tag{1}$$

where MU_n denotes the number of merging units, P^{SM} is the calculated packet length of the sample, f^{SM} is the transmission frequency, and r^{SM} is the SV message flow rate. These parameters are explained with packet formats of the SV message that are compatible with IEC 61850 as described in detail in [6].

Conventional power frequency protection determines the SV message flow rate using WLAN where $f^{SM} = 4000$ Hz, $MU_n = 1$, $P^{SM} = 135$ bytes, and single ASDU can be calculated as follows:

$$r^{SM} = MU_n P^{SM} f^{SM} = 1*135*8*4000 = 4.32 \text{ Mbps} \tag{2}$$

The SV message flow rate is computed as follows using Ethernet in [18] with $P^{SM} = 128$ bytes:

$$r^{SM} = MU_n P^{SM} f^{SM} = 1*128*8*4000 = 4.09 \text{ Mbps} \tag{3}$$

The SV message flow rate is then computed as follows using travelling wave protection with $f^{SM} = 200$ kHz minimum sampling frequency and five MUS in process bus:

$$r^{SM} = MU_n P^{SM} f^{SM} = 5*135*8*200{,}000 = 1080 \text{ Mbps} \quad \text{Using WLAN technology, and} \tag{4}$$

$$r^{SM} = MU_n P^{SM} f^{SM} = 5*128*8*200{,}000 = 1024 \text{ Mbps} \quad \text{Using Ethernet.} \tag{5}$$

From Eqs. (4) and (5) it can be concluded that channel B.W with 100Mbps cannot support one MU in the process bus using travelling wave protection.

3.2. Channel bandwidth

The optimum number of MUs that may share the same process bus and maximum sampling transmission frequency of the SV message can be calculated theoretically as follows:

$$f^{SM} = \frac{C\eta}{MU_n P^{SM}} \tag{6}$$

where η notes the maximum Ethernet channel portion (equal to 78%

Table 1
Relation between sampling frequency and ETE delay.

Sampling rate (kHz)	Interval of SAV packets (ms)	ETE delay (ms)
4	0.25	0.0005
6	0.166	0.0005
7.116	0.1405	0.0005
20	0.05	0.0005
40	0.025	0.0005
71.167	0.01405	0.0005
80	0.0125	0.0005
100	0.01	0.0005
7116.788	0.0001405	0.0005

in empirical tests), and C denotes the channel bandwidth. Table 1 show that the maximum sampling frequency which can be used with a specific channel. The maximum sampling frequency has a channel bandwidth of 10 Gbps = 7116.778 kHz and 100BaseT and 10BaseT channel bandwidths of 71.167 kHz and 7.1167 kHz, respectively. When the sampling frequency exceeds these values, the ETE delay linearly increases along with simulation time as shown in Fig. 3A. Fig. 3B and C show the relation between the number of MUs and the sampling frequency at traditional protection and protection based on travelling wave at different channels.

However, the travelling wave in real-time applications, such as protection, follows the process of the WLAN bus with IEEE 802.11a at 54 Mbps or with IEEE 802.11n at 600 Mbps. However, WLAN cannot support protection because of unacceptable time delays. By contrast, traditional protection can support such technology. Table 2 presents the end-to-end delays at different sampling frequencies and S/N ratios based on IEEE 802.11n with MIMO technology and quality of service (QoS) at the 2.4 GHz band. From this table it can be observed that the end-to-end delay without pre-processing does not meet the IEC 61850-5 requirement which is 3 ms. while the IEEE 802.11n can be used for

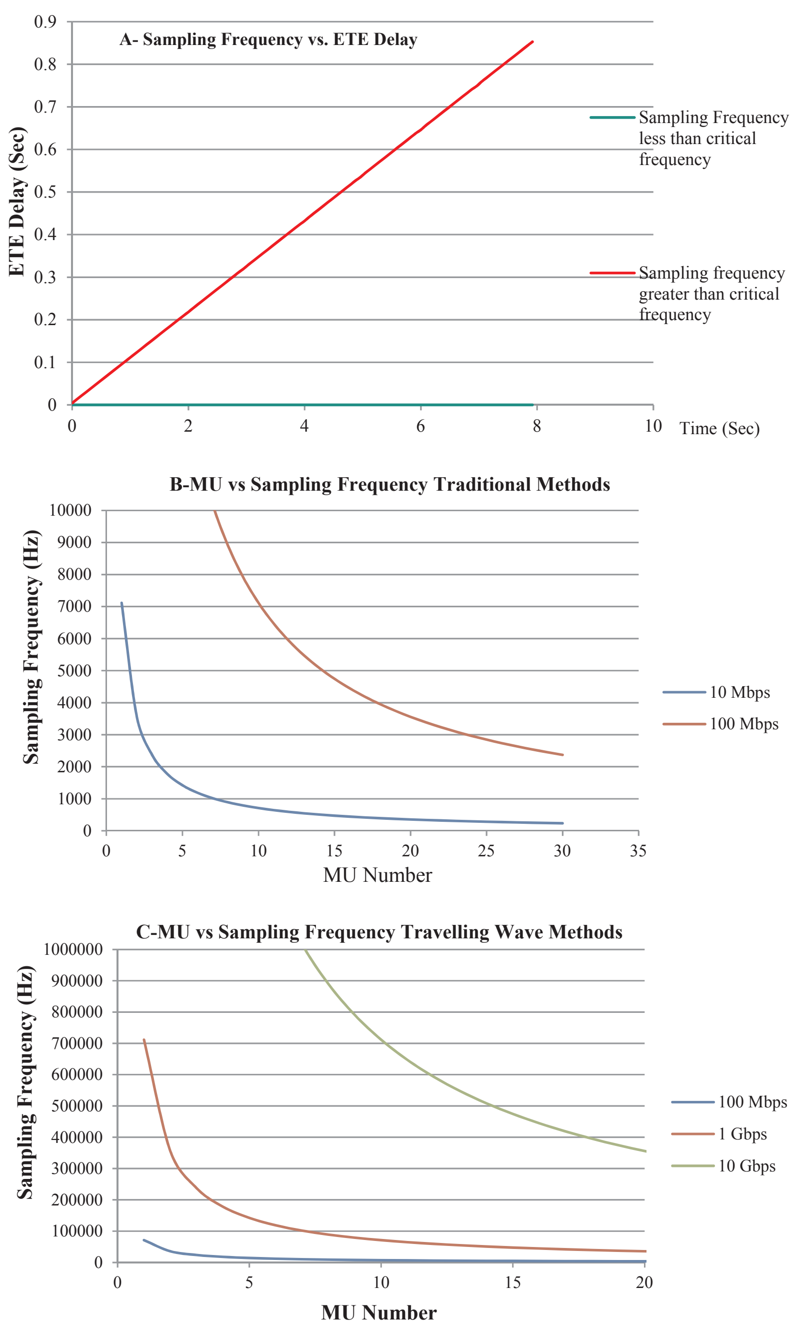

Fig. 3. A – Performance of SAV message ETE delay below and above the critical frequency, B – Relation between sampling frequency and number of MUs at power frequency protection, and C – Relation between sampling frequency and number of MUs based on the travelling wave technique.

Table 2
Relation between sampling frequency and ETE delay based on IEEE 802.11n with a QoS priority of 4 and a packet length of 135 and without packing and compression.

Sampling Frequency (MHz)	ETE Delay (ms)	No. of Spatial Streams	S/N
0.1	5.5	1	24 dB
0.2	5.5	1	
0.5	5.5	1	
1	5.5	1	
0.1	0.36	4	
0.2	1.9	4	
0.5	2.0	4	
1	2.0	4	
0.1	5	1	32 dB
0.2	5	1	
0.5	5	1	
1	5	1	
0.1	0.34	4	
0.2	1.8	4	
0.5	1.9	4	
1	1.9	4	

traditional protection, although not for fast protection based on travelling wave because the ETE delay for two MUs that share the same process bus is equal to 3.6 ms as calculated by the OPNET simulator at a 500 kHz sampling frequency. This delay violates the standards of IEC 61850-5.

3.3. Advanced technology Ethernet switch for SAS and AP

The relation between Ethernet switch performance and sampling frequency with port rate can be defined as follows:

$$f^{SM} = \frac{P_{fr}}{MU_n}, \tag{7}$$

where P_{fr} is the port rate of the Ethernet switch, which does not represent any bottleneck in communication.

In wireless networks, the switch is replaced by AP, which ensures QoS, reduces interference, prevents collision, and allows expandability in IEC-61850-based substation automation systems. The AP can also be connected to a wired Ethernet.

3.4. IEDs real-time signal processing capability

Single-chip integration can implement different algorithms for real-time signals at a very fast rate. The hardware becomes more advanced, and the different applications of IEDs in software transformation, coding, and decoding within microseconds make these tools suitable for fast tripping based on travelling wave after pre-processing.

4. Data pre-processing techniques

4.1. Travelling wave packing and compression using wavelet transform

Several techniques have been designed for the compression of signals in power system control and protection, including discrete wavelet transforms (DWT), fast Fourier transform, and discrete cosine transform. Given that DWT has a relatively better localization property than discrete Fourier transform in time and frequency domains, this technique can achieve a high compression ratio [19–22].

Packing reduces the transmission sampling frequency, while compression reduces the packet length. Reducing these parameters result in reduction of the data flow rate and ETE delay of SV messages in the process bus.

Wavelet transforms are used to decompose the travelling waves' fault signal into multi-level wavelet coefficients. At each level there is a threshold to reserved data whose absolute value is greater than threshold. Fig. 4 shows the wavelet data compression algorithm.

X_{rk} is the original signal to be compressed; $A_{j,K}$, $D_{j,K}$ are the approximation and details at each level. The threshold for every level is calculated by the equation

$$Z_j = Z_{th} \times \max\{|D_{j,k}|\}, \quad k = 1,2,...N_J$$

Z_{th} is the threshold coefficient, $0.1 < Z_{th} < 0.5$. The wavelet coefficient of every level will be reserved or ignored by the following relationship.

$$D'_{j,k} = \begin{cases} D_{j,k} & |D_{j,k}| \geq Z_j \\ 0 & |D_{j,k}| < Z_j \end{cases} \qquad k = 1,2,...N_j$$

Z_j is the threshold of scale j.

Four wavelet base functions are used for compression of the fault travelling wave (Bio34.3, Haar, Db8, and Coifl). For each wavelet base the threshold (Z_{th}) change in between 0.1 up to 0.5, the number of compression stage (J) changes from 1 to 11, and the effects of wavelet base, threshold, and number of compression stages on mean square estimation were drawn on the (MzJ) curve as shown in Fig. 5.

From this curve as J increased the mean square error also increased and M value changed rapidly for J greater than 6, also M increased as the threshold increased; the best value of M is when $J = 5$ and threshold = 0.5, and wavelet base is Db8. See Fig. 5 and Table 3.

The same procedure was repeated but in this case study it is for the relation between compression ratio (Rc), wavelet base, threshold value, and number of compression stages (J). The relation between compression ratio, threshold, and number of compression stages (J) was drawn in the (RzJ curve) as shown in Fig. 6.

From this curve as J increased the Rc decreases, with a sharp change in Rc for J greater than 2; as threshold increased the Rc also decreased,

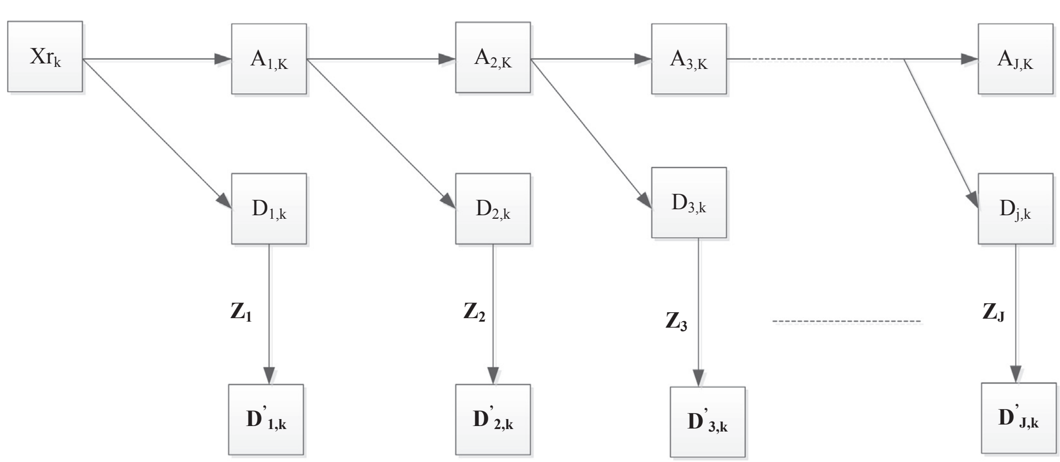

Fig. 4. Compression algorithm based on adaptive threshold decomposition.

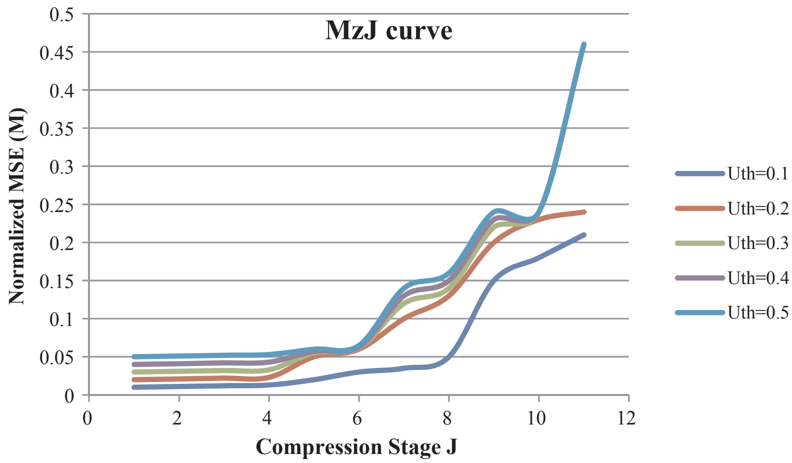

Fig. 5. Relation between mean square error, threshold level, and compression stage.

Table 3
Signal compression and percentage mean square error based on wavelet transform.

Wave Name	*cf* (Compression Factor)	*SNR* (dB)	*MSE* (%)
Haar	4.6	25.125	0.0321
Db8	10.04	41.9547	0.0010
Coif1	6.684	35.09	0.0320
Bior3.3	7.80	41.22	0.0203

with the best value of the threshold being in between 0.4 and 0.5 and number of stages = 5; the best compression performance is with the Db8 wave base as shown in Fig. 6 and Table 3.

Based on this analysis the Db8 can be selected for compression with five stages of decomposition. Fig. 7 shows the application of DWT on travelling wave fault voltage and current signal sampled at 200 kHz. Table 3 presents the compression ratios and MSE percentages at different waves following the adaptive threshold at each decomposition level. Fig. 8 shows the details-coefficients for fault voltage travelling waves of up to level 5.

A packing length of 50 and a compression ratio of 1:10 are applied in the simulation. The new packet of the SV message can be calculated as follows:

$$P^{SM} = \frac{108*50}{10} + 20 = 560 \text{ Bytes} \tag{8}$$

where 20 bytes represent the message header. The data flow rate can be computed as follows:

$$r^{SM} = MU_n P^{SM} f^{SM} = 1*560*8*\frac{200}{50} KHz = 17.920 \text{ Mbps}. \tag{9}$$

The communication data flow is reduced by 91.25% and 204.800 Mbps of uncompressed data flow are recorded.

To calculate total delay, we assume an MU processing time of 1 ms, including data packing time of 250 μsec, and P & CIED processing time of 1 ms. When the ETE delay of packet transmission taken from Table 4 based on 100BaseT using OPNET is equal to 0.41 ms, then the total time delay can computed as follows:

$$T = T_{MU} + T_D + T_{IED}. \tag{10}$$

where T = 1 ms + 0.41 + 1 ms = 2.41 ms, which is less than 4 ms and satisfies the requirements of IEC 61850-5. Therefore, packing and compression improve the performance, but does not meet the high sampling rate data transmission of multiple MUs.

The same procedure can be repeated using IEEE 802.11n WLAN technology, where the packet length of the SV message can be calculated as follows:

$$P^{SM} = \frac{98*50}{10} + 37 = 527 \text{ Bytes} \tag{11}$$

where 37 bytes represents the packet head. The communication data flow can be calculated as follows:

$$r^{SM} = MU_n P^{SM} f^{SM} = 1*527*8*\frac{200}{50} \text{ KHz} = 16.846 \text{ Mbps}. \tag{12}$$

The communication data flow is reduced by 92.2% and 216.00 Mbps of uncompressed flow are recorded. The entire communication process for WLAN is calculated using Eq. (10).

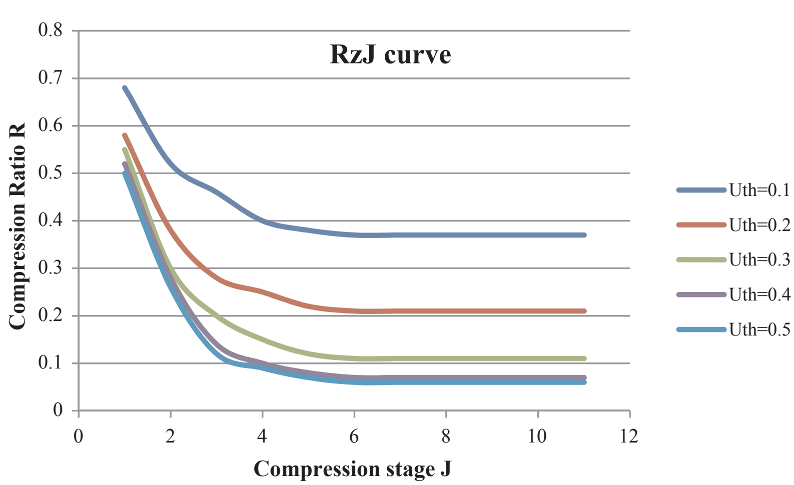

Fig. 6. Relation between compression ratio, threshold level, and compression stage.

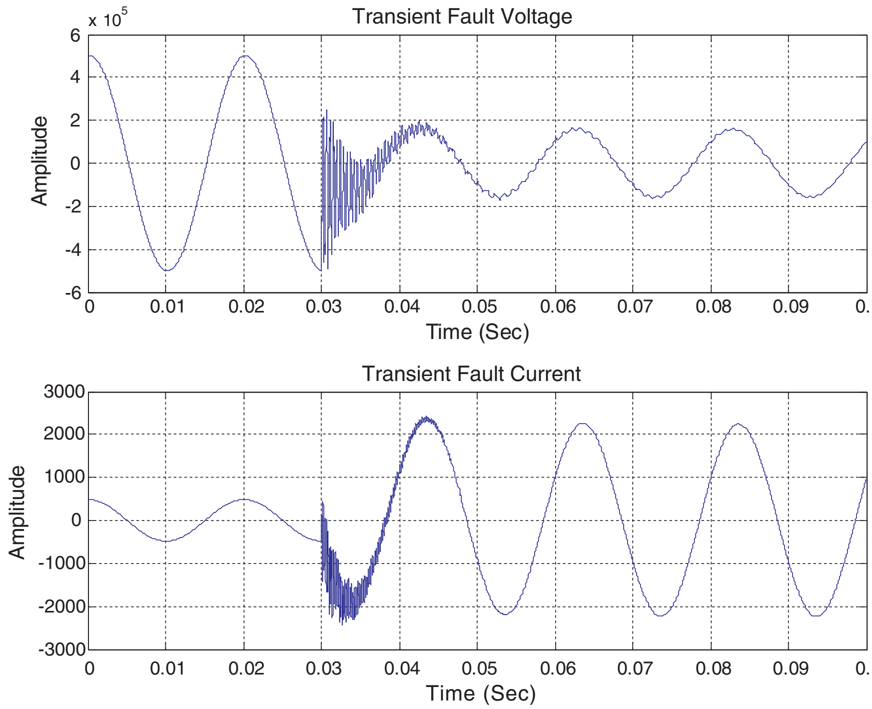

Fig. 7. Travelling wave fault voltage and current signal between phase and ground.

Following the same assumptions, the transmission delay can be measured using the OPNET simulator. Table 5 presents the end-to-end results after packing and compression which satisfies the IEC 61850-5 requirements.

The transmission delay at a 32 dB S/N ratio and a sampling frequency of 100–200 kHz does not exceed 47 μsec with four spatial streams. The total delay can be calculated as follows:

$T = 1\text{ ms} + 0.047\text{ ms} + 1\text{ ms} = 2.0477\text{ ms}.$

Although the time delay evaluated is acceptable per the IEC 61850-5 standards after packing and compression, the time delay does not meet the high sampling rate data transmission of multiple MUs sharing data in a process bus. Then in order to increase the number of MUs sharing the process bus, feature extraction should be used as shown in the next steps.

4.2. Protection based on feature extraction

Feature extraction is an alternative method that resolves the bottleneck in WLAN communication networks in accordance with IEC 61850. In this technique, the MUs send a few features, such as the signal amplitude and the polarity and amplitude of the head of the travelling wave, to the P & C IED during fault occurrence. These features can be extracted using DWT, HHT, and MMG, which are all applied for non-stationary signals. Specifically, DWT extracts the output depending on the sampling frequency and wave selection, while HHT extracts from the fault voltage (Fig. 7) the intrinsic mode functions (IMFs) (Fig. 9) with its on-time feature extraction, favorable frequency amplitude, and excellent polarity. As illustrated in Fig. 9, the IMF1 shows an abrupt change in the amplitude of voltage signal and frequency at time 0.03. These features must be extracted by the MU and relayed to the P & C IED for protection during fault occurrence with swift timings. MMG can also extract the polarity and time of the head of the travelling wave signal through simple mathematical methods, such as dilation and erosion [23].

Feature extraction solves the issues related to the communication process in three steps. First, MU fault feature extraction adds new extracted features from the faulted travelling wave to the SV message, and these features are then used by P & C IED to make the right decisions. These features include modulus maximum polarity and amplitude (extracted via wavelet transform or MMG), magnitude of the local maximum and instantaneous frequency (via HHT), and energy of the signal. Second, the extracted features are added to the application service data unit (ASDU), and then the IEC 61850-9-2 requires a restructuring SV to add these features to the ASDU dataset. The added intermediate features are then coded and decoded in type length value format. Fig. 10 shows a modified SV message format with one ASDU. Each ASDU contains several analog channels of basic data with new feature datasets. Third, the communication network message transmission and the transmission frequency of the SV message are reduced via feature extraction. The total communication delay can be calculated using Eq. (10).

Assuming that the MU can execute the feature extraction algorithm within 1 ms, the SV message delay is equal to 51 μs as measured using the OPNET simulator. According to IEC 61850-5, the acceptable maximum communication delay for the highest class (trip message) is as short as 3 ms. In this case, P & C IED has 1.95 ms to process and send the trip message. The transmission delay of a single sampling point SV message based on fast Ethernet is approximately equal to 40 μs as computed using the OPNET simulator. Therefore, no communication problem occurs as long as the interval time $T_{p\,\&\,CIED}$ is less than 1.96 ms. We record a total transmission time of 3 ms, which satisfies the protection requirement of IEC 61850-5. In this way, the sampling frequency of the SV message can be reduced to less than 1000 Hz as the power frequency transmits samples ranging between 1000 Hz and 51,200 Hz. The travelling wave frequency signal then becomes compatible with the frequency signal transmission.

5. Design of ultra-fast tripping IED supporting IEC 61850

The IEC 61850 servers define a hierarchical data model. The travelling wave real protection (TWRP) IED server comprises several logical devices, including a logical node, which is a key element in modeling application functions. The logical node contains the data object, while the data object contains the data attributes.

The IED functions must be defined, decomposed, and allocated to build the IED model following IEC 61850. There is no logical node related to the application for the travelling wave, and then two new

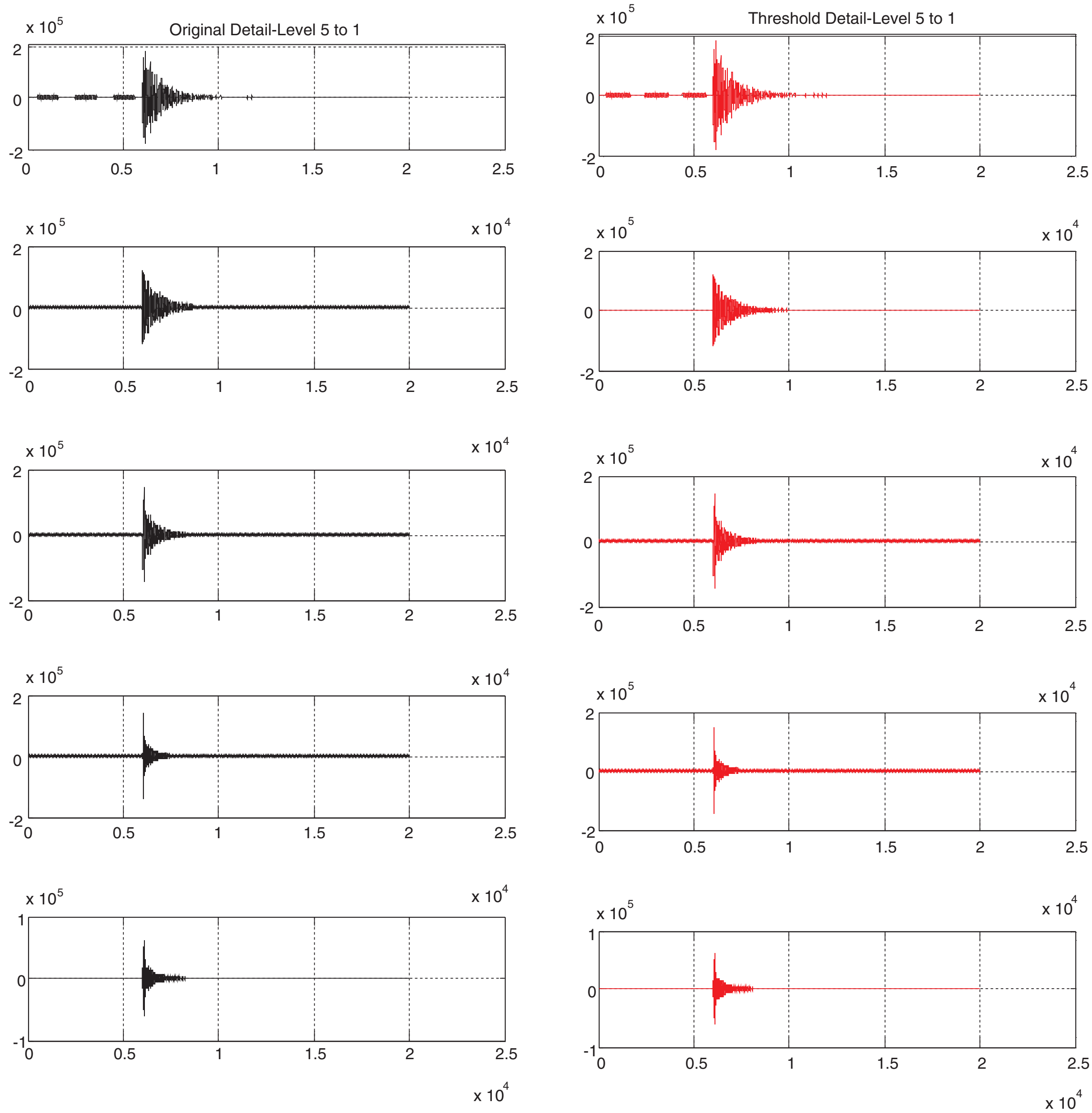

Fig. 8. Coefficients and transitions in the travelling wave signal.

Table 4
Relation between sampling frequency and ETE delay based on 100BaseT with a packet length of 527 bytes.

Sampling Frequency kHz	ETE Delay (ms)	No. of MUs
20	0.16	5
100	0.16	5
200	0.41	5
500	Overload	5
500	Overload	4
500	Overload	3
500	0.09	2
1000	Overload	2
1000	0.076	1

logical nodes are presented in Fig. 11A. The first type, related protection function travelling fault location (RTFL), calculates the distance of the fault location from source by recorded initial arrival time of travelling wave; while the second type, protection distance travelling wave (PDTW) based on feature extraction and initial travelling wave arrival time, makes real time protection based on travelling waves. These two nodes should have the ability to exchange data with the remote substation that is necessary in double-ended or Wide Area Network protection method using a PSCH logical node (LN). In addition, these are software logical nodes that interface to the process application, that model with information for software algorithm (information produced by software RTFL, PDTW…). These logical nodes can be easily added and fit the overall current IEC 61850 standard.

Other LN are such as voltage transformer (TVTR), the current transformer (TCTR), circuit breaker (XCBR), disturbance recording (RDRE), analog channel disturbance recording (RADR), circuit breaker status (GGIO) and historical data archiving (IARC). Finally, each physical device needs to have LLN0 and LPHD. More details about LN can be found in IEC 61850 documents.

Fig. 11B shows the communication among various TWRP functions compliant with IEC 61850. Internally some important features of the new logical node PDTW should have the important measurement attributes as shown in Table 6.

6. Comparison of packing and compression and feature extraction methods with previous work

The ETE delay performance of the SV message using transient

Table 5
Relation between sampling frequency and ETE delay based on IEEE 802.11 n with a packet length of 527 bytes, QoS of 4, packing, and compression.

Sampling Frequency (MHz)	ETE Delay (ms)	No. of Spatial Streams	S/N (dB)
0.1	0.09	1	24 dB
0.2	0.21	1	
0.5	0.47	1	
1	5.51	1	
0.1	0.081	4	
0.2	0.086	4	
0.5	0.35	4	
1	0.56	4	
0.1	0.083	1	32 dB
0.2	0.11	1	
0.5	0.42	1	
1	4.51	1	
0.1	0.047	4	
0.2	0.047	4	
0.5	0.162	4	
1	0.22	4	

protection are compared between our method of packing and compression and feature extraction, and previous techniques using the impedance method as reported in [17]. It can be seen from Fig. 12 that ETE delay for the impedance method reaches 65 ms which is not acceptable by IEC 61850, while delay using our packing and compression and feature extraction methods, is reduced to 25 ms and 0.2 ms, respectively. Clearly, the feature extraction method lies within the requirement of the IEC61850 standards. The sampling was made at 200 kHz.

7. Service modeling of IEC 61850-90-5 based on travelling wave measurement unit

In this model, different IEDs can exchange messages among them through WAN. The SV measurement message based on travelling wave after packing and compression or feature extraction must be mapped over UDP/IP protocols. Similarly, the GOOSE message in WAN must be mapped over TCP/IP. In this case, the packet adds the headers of IP, UDP, and TCP, and then adds an 8-byte time stamp to each SV packet and a 1-byte to the travelling wave detector index ($TWID_i$). IEC 61850-90-5 uses a 50 Hz sampling rate with PMU in WAN. In the proposed techniques, the transient travelling wave is sampled at 1 MHz, and all features are sent every 5 ms upon their extraction.

8. WAN substation communication scenario

We evaluate the communication performance based on the travelling wave protection in WAN as shown in Fig. 1.

Fig. 1 shows the proposed Wide Area Protection (WAP) system for transmission networks. This protection system comprises TWIDi at each busbar, which in turn is connected to the MPC through wireless communication networks. Each $TWID_i$ captures the initial travelling wave voltage that is produced by fault occurrence. The TWID detector calculates the transient energy signal based on discrete wavelet transform and then compares its signal with an adjustable threshold value. When the wavelet energy signal exceeds the adjustable threshold value (Eth), the TWID records the maximum of the first peak and the time instant with the help of GPS. The TWID samples the travelling wave fault signal at 1 MHz for 5 ms after fault occurrence.

The proposed MPC is a microcomputer that is connected to communication devices, a human machine interface, and a GPS clock. As shown in Fig. 1, the MPC is connected to the $TWID_i$ at all busbars through a communication network. MPC performs all calculations to determine the fault section in the transmission network, calculates the distance from the fault location, and sends a trip command to the $TWID_i$ that is connected to the faulted section to trip the associated circuit breakers. Each $TWID_i$ detects the fault upon its occurrence, and the $TWID_i$ nearest to the fault will send its data to the MPC. The other $TWID_i$ will also send their data with the aid of GPS. MPC will detect the faulted section based on the two maximum values of energies recorded by $TWID_i$. The bus and line faults are detected based on the energy ratio of the two maximum values of $TWID_i$ energy signals. MPC will detect and record the initial travelling wave arrival times for each $TWID_i$. The faulted section is determined by comparing the peaks of transient

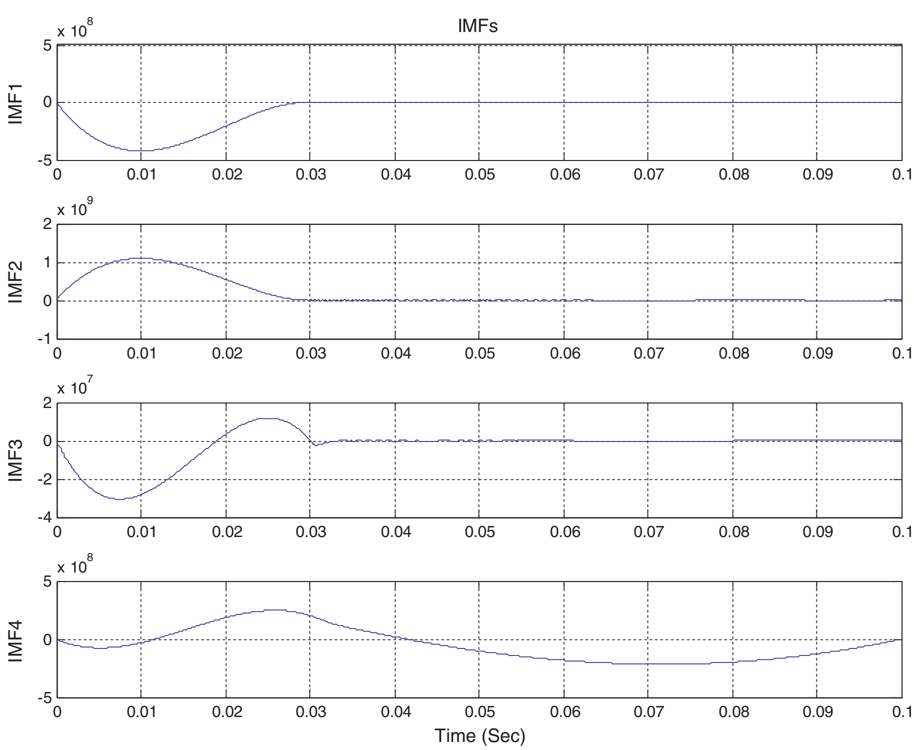

Fig. 9. Application performance of HHT during an abrupt change in signal.

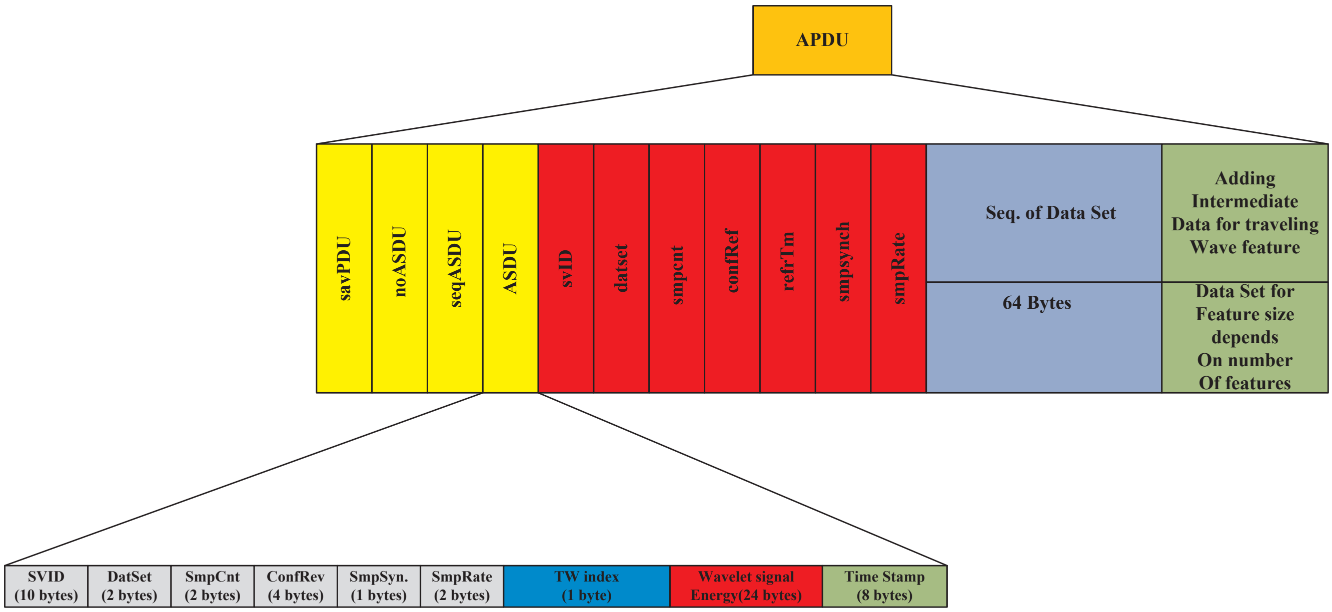

Fig. 10. Modified IEC 61850-9-2 SV message format with additional information added to ASDU.

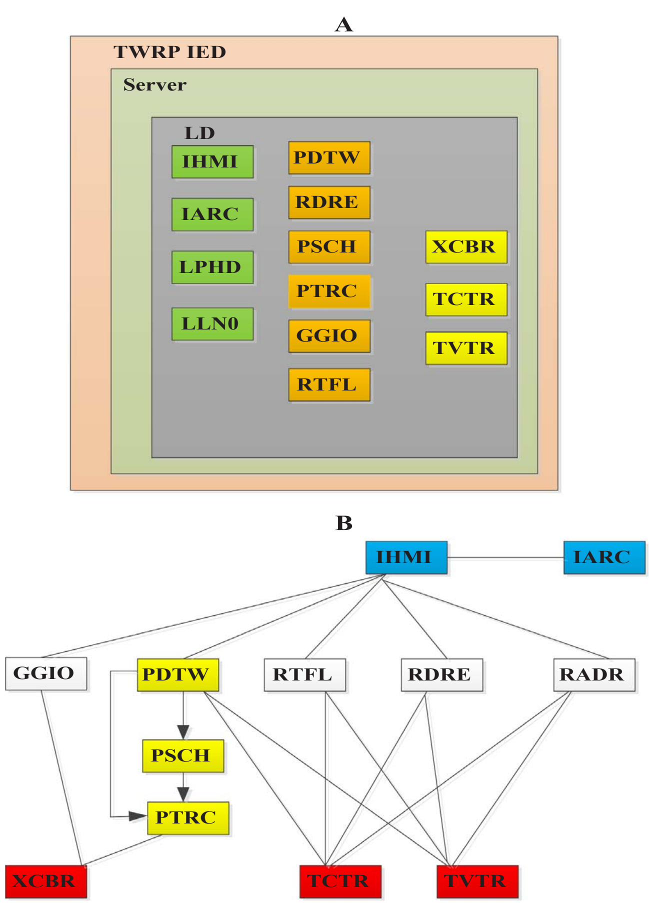

Fig. 11. A – TWRP IED model and B – Decomposition of TWRP functions.

Table 6
Some important data structure of new logical node.

Type	Data	Data attribute	Description	M/O
Public Logic Node Information	Mod	INS	Mode	M
	Beh	INS	Behavior	M
	Health	INS	Health	M
	NamePlt	LPL	Name plate	M
Status	LocStr	ACD	Arrival time of the initial travelling wave at local end	M
	RmStr	ACD	Arrival time of the initial travelling wave at remote end	O
Measure	FltLine	DPL	Fault Line	M
	FltDis1	MV	Distance to disturbance point (single- end-point)	O
	FltDis2	MV	Distance to disturbance point (double- end-method)	O
Setting	LineLen	ASG	Line length, km	M
	WavSpd	ASG	Wave speed	M
	RecordLen	ASG	Record length, ms	M

energy. The distance of the fault from the nearest bus is calculated via the double-end method using the chosen $TWID_i$ signals. Additional information, such as the energy of the signal extracted via DWT, time stamp, and TWID index, are incorporated into the existing logical node to transmit TWID in accordance with IEC 61850.

Sending an MMS message over WAN can be easily routed through the IP layer. However, the GOOSE messages, SVs, and TWID values can only be transmitted over WAN by mapping them over UDP/IP or TCP/IP or tunneling these messages across the network. The GOOSE message maps over TCP/IP, while the SV message maps over UDP/IP. Each $TWID_i$ sends the signal to the MPC in accordance with IEC 61850-90-5. Fig. 10 shows the new packet of SV message based on feature extraction.

We implement the scenario shown in Fig. 1 via WLAN multi-point to point communication while assuming that all buses can be covered using WLAN. In real WAN applications, each group of TWID can be divided into specific areas, with each area having a data collector that is connected to the control center through routers. The SV and GOOSE messages can be mapped over UDP/IP and TCP/IP, respectively.

Tables 7 summarize the total traffic flow communication in the intra and inter substations.

Table 8 presents the ETE delay of GOOSE and SV messages that are exchanged between TWIDs and the MPC. The ETE delay for these messages satisfies the protection requirements of IEC 61850-90-5.

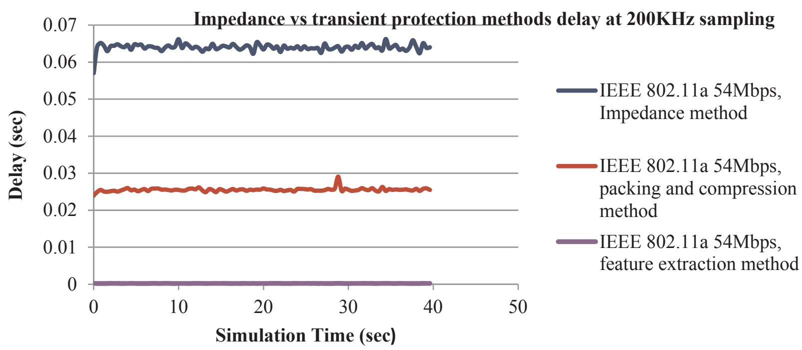

Fig. 12. ETE delay comparison of impedance method Ref. [17] vs our proposed packing & compressing and feature extraction methods.

Table 7
Communication in the intra and inter substations.

Network	Message Type	Communication Method	Transmission Output	Packet Size (bytes)	Priority	Transmission Time (ms)	Sampling Frequency (Hz)
Inter Substation	Routing GOOSE	TCP/IP	Burst	104	Highest	10–40	Variable
	MMS	Client/server	Burst	Depends	Medium	Non-time critical	Depends
	Routing SV	UDP/IP	Periodic	220	High	10	PMU = 50 TWID = 200
Intra substation	GOOSE	Publisher/Subscriber	Burst	230	Highest	3–10	Variable
	MMS	Client/server	Burst	Depends	Medium	Non-time critical	Depends
	SV	Publisher/Subscriber	Periodic	120–226	High	3–10	4000/12,800

Table 8
ETE delay for Fig. 1 with the sampling frequencies for SV and GOOSE equal to 200 Hz and 400 Hz, respectively, based on IEEE 802.11n. The QoS priority for these messages is equal to 4 and 7, respectively.

SV ETE Delay (ms)	GOOSE ETE Delay (ms)	No. of Spatial Streams	S/N
3.2	0.46	1	24 dB
3.0	0.40	2	
2.7	0.38	3	
2.3	0.34	4	
1.6	0.26	1	30 dB
1.4	0.22	2	
1.3	0.14	3	
1.2	0.1	4	

9. Conclusion

This paper examines fast protection based on travelling wave and discusses the communications data flow based on Ethernet or WLAN. The time delay can be affected by several parameters, such as packet length, QoS priority, sampling frequency, number of streams, and S/N ratios. However, the high sampling frequency requirement of travelling wave protection blocks the communication networks. This paper solves this problem through packing and compression as well as feature extraction. The simulation demonstrates that protection based on travelling wave with multiple merging units sharing the same process bus can be achieved after pre-processing. The SV packet is redesigned in accordance with IEC 61850, while the protection IED and its communication networks are designed based on travelling wave. This paper proposes a new protection scheme that can successfully locate the fault in the transmission network with high speed and accuracy based on TWID and MPC. WAP using travelling wave with IEC 61850 based on WLAN is proven as an effective tool that satisfies the time protection requirement of IEC 61850. This scheme can also determine the fault location on a large scale transmission network, thereby proving the effectiveness of the proposed technique.

The wide area protection using travelling wave has been proven as an effective tool for accurate and fast fault detection and location. Also, the scheme is able to determine the fault location on a large scale transmission network. This paper has proven that the fast protection communication scheme with IEC 61850 succeeds after pre-processing.

This research contributes further knowledge on the application of transient travelling waves in smart substations. Future works may include the cyber security and reliability of using WLAN for substation automation.

References

[1] Schweitzer EO, Kasztenny B, Guzmán A, Skendzic V, Mynam MV. Speed of line protection – can we break free of phasor limitations? In: 69th annual Georgia tech protective relaying conference Atlanta, Georgia, April 29, 2015.

[2] Schweitzer EO, Kasztenny B, Mynam MV. Performance of time-domain line protection elements on real-world faults. In: 42nd annual western protective relay conference, October 2015.

[3] Bin W, Xinzhou D, Fei X, et al. Analysis of data sharing for protection and control system in smart distribution substation. Proc CSEE 2011;31(s1):1–6.

[4] Mingjuan F. Development and Implementation of substation IED based on IEC61850. North China Electric Power University; 2010.

[5] Hui Z. Design and implementation of embedded video conferencing software. Hubei (Wuhan): Huazhong University of Science and Technology; 2010.

[6] Ali NH, Ali Borhanuddin M, Basir O, Othman Mohammad Lutfi, Hashim Fazirulhisyam, et al. Protection of smart substation based on WLAN complies with IEC 61850 using travelling wave analysis. Electr Power Syst Res 2016.

[7] Cena C, Valenzano A, Vitturi S. Hybrid wired/wireless networks for real-time communications. IEEE Ind Electron Mag 2008;2(1):8–20.

[8] Gungor VC, Sahin D, Kocak T, Ergut S, Buccella C, Cecati C, et al. Smart grid technologies: communication technologies and standards. IEEE Trans Ind Inf 2011;7(4):529–39.

[9] Parikh P, Kanabar M, Sidhu TS. Opportunities and challenges of wireless communication technologies for smart grid applications. In: Proc IEEE PES general meeting, July, Minneapolis, MN; 2010. p. 1–7.

[10] Gungor VC, Lu Bin, Hancke GP. Opportunities and challenges of wireless sensor network in smart gird. IEEE Trans Ind Electron 2010;57(10):3557–64.

[11] Abdel-Latif KM, Eissa MM, Ali AS, Malik OP, Masod ME. Laboratory investigation of using Wi-Fi protocol transmission line differential protection. IEEE Trans Power Delivery 2009;24(3):1087–94.

[12] Zhu Z, Lambotharan S, Chin W-H, Fan Z. Overview of demand management in smart grid and enabling wireless communication technologies. IEEE Wirel Commun 2012;19(3):48–56.

[13] Bouhafs F, Mackay M, Merabti M. Links to the future: communication requirements and challenges in the smart grid. IEEE Power Energy Mag 2012;10(1):24–32.

[14] Gungor VC, et al. A survey on smart grid potential applications and communication requirements. IEEE Trans Ind Inf 2013;9(1):28–42.

[15] Dong Xinzhou, Wang Jun, Shi Shenxing, Wang Bin, Dominik Bak, Redefern Miles. Travelling wave based single-phase-to-ground protection method for power distribution system. CSEE J Power Energy Syst 2015;1(2).

[16] Liu Jing, Duan Jiandong, Lu Hailong, Sun Yuanbing. Fault location method based on EEMD and travelling-wave speed characteristics for HVDC transmission lines. J Power Energy Eng 2015.

[17] Parikh PP, Sidhu TS, Shami A. A comprehensive investigation of wireless LAN for IEC 61850 based smart distribution substation applications. IEEE Trans Ind Inf 2013;9(3):1466–76.

[18] IEC standard for communication network and systems in substations. IEC 61850, 2003-04, 1st ed.; 2003.
[19] Shi Lei, Wang Hao, Zhao Hongli. Research and simulation of signal compression based on DCT. The second academic conference of signal processing and application; 2008.
[20] Chen Jiayuan, Zhang Qiuju, Yu Wenkai. Research on method of vibration signal compression for compressor based on DCT. Compressor Technol 2009;4:5–7.
[21] Zhang Ning. The signal compression of wavelet based on waveform matching. Xidian University; 2005.
[22] Santoso S, powers EJ, Grady WM. Power quality disturbance data compression using wavelet transform methods. IEEE Trans Power Delivery 1997;12:1250–7.
[23] Zhang XL, Zeng XJ, Li ZW, Deng F. Travelling wave fault location of transmission line using Hilbert-Huang transform. DRPT, 6–9 April, Nanjing, China; 2008.