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PROTECTION OF SMART SUBSTATION BASED ON WLAN COMPLIET WITH IEC 61850 USING TRAVELLING WAVE ANALYSIS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

PROTECTION OF SMART SUBSTATION BASED ON WLAN COMPLIET WITH IEC 61850 USING TRAVELLING WAVE ANALYSIS

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IEC 61850 is an important industry standard for substation automation. It is a suite of protocols that provides interoperability between different devices from different vendors in a substation environment. Among many other features, it has a unified application interface, unified model and provides seamless data access within the substation. Furthermore, it integrates security and functions that contribute to increasing the system reliability.

To this date IEC61850 based protection is primarily built on fiber-based high-speed Ethernet Local Area Network (LAN) because of its high bandwidth and noise immunity. However, fiber-based Ethernet LAN is expensive and therefore may not be economically viable for medium voltage/low voltage (MV/LV) distribution network. In its place, Wireless Local Area Network (WLAN) technology can be adopted as a viable alternative to support distribution substation applications. Recent wireless network solutions such as IEEE802.11n offer sufficient data rates for high-speed applications with low installation costs and speedy deployment. However, WLAN is not sufficient for remote control communications in distribution grids due to its limited radio span of around 100m typically. Much more work is needed to assess WLAN for other substation applications such as control, monitoring, metering, protection and automation, due to its limited bandwidth and coverage.

In this thesis, wired and WLAN merging units (MUs) combined with breaker and protection and control (P&C) intelligent electronics devices (IEDs) have been modeled using the Opnet modeler in order to evaluate the performance of different applications in the substation.

After modeling of the MU and P&C IED according to the IEC 61850 stack, the performance of various smart distribution substation applications has been evaluated in terms of average and maximum message end-to-end delays and throughput.

Although fiber optics offers very high data rate there is a limitation on its use for protection based on traveling waves. This is because the sampling frequency of traveling waves necessarily needs to be high to capture all the details of the transient waves. This is especially so when there are multiple MUs sharing the process bus. Hence, to achieve fast protection based on the transient signal detection that emanates from the fault location, it is necessary to redesign the MUs so that they can implement fast compression and feature extractions and also to re-factor the SV message.

This thesis next proposes a novel pre-processing technique for high-sampling traveling waves using packing and compression or feature extraction. Packing and compression result in throughput and end-to-end delay improvement, while feature extraction gives improvement in protection and at the same time, reduces the required sampling frequency to the same level as in the traditional method. This proposed technique is shown to outperform traditional impedance-based techniques which suffer from low accuracy and are time consuming.

In addition, distance protection IED based on traveling waves (PDTW) that is compliant with IEC 61850 has been designed, and it can be used for wide area protection instead of using the traditional phasor measurement unit. Different scenarios of protection based on traditional and travelling waves have been tested and it was shown that WLAN can indeed be used for different protection applications.

In addition, an analysis of the packet format of SV messages has been made. Essentially, there is as yet no particular format for WLAN that has been recommended for IEC 61850. Henceforth, a new WLAN packet format for different protections based on traditional and travelling waves have been designed after re-factoring the original SV packet format. The indoor and outdoor substation noise at 2.4 and 5.0 GHz bands respectively, was generated by way of the simulator to study its impact on the performance of WLAN, particularly on throughput and end-to-end delay. The simulation result shows that the end-to-end delay of sample value (SV) and generic object oriented substation event (GOOSE) message increased and WLAN throughput decreased as signal-to-noise ratio (SNR) reduces, and the band of 5.0GHz is more sensitive to noise.

Finally, in order to reduce traffic intensity on WLAN, the evaluation of Zigbee and 6LoWPAN working in co-existence with WLAN has also been done for different applications and in compliance with IEC 61850 protocols.

Abstrak tesis ini dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENLINDUNGAN SUB STESYEN BERDASARKAN WLAN YANG MEMATUHI IEC 61850 MENGGUNAKAN ANALISIS GELOMBANG BERJALAN

Oleh

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IEC 61850 adalah standard industri yang penting untuk automasi pencawang. Ia adalah satu set protocol yang menyediakan saling tindakan operasi antara peranti-peranti yang berlainan daripada vendor yang berlainan di dalam persekitaran pencawang. Antara ciri-ciri lain, ia mempunyai antara muka aplikasi yang bersatu, model bersatu dan menyediakan akses data yang lancar di dalam pencawang itu. Tambahan pula, ia menggabungkan keselamatan dan fungsi yang menyumbang terhadap peningkatan kebolehpercayaan sistem.

Setakat ini perlindungan berasaskan IEC61850 terutamanya dibina berasaskan Rangkaian Kawasan Setempat Ethernet (LAN) kelajuan- tinggi berasaskan-gentian kerana lebar jalur yang tinggi dan keimunan hingarnya. Walau bagaimanapun, Ethernet LAN berasaskan-gentian adalah mahal dan oleh itu mungkin tidak berdaya maju untuk rangkaian pengedaran voltan sederhana/voltan rendah (MV/LV). Sebagai ganti, teknologi Rangkaian Kawasan Setempat Wayarles (WLAN) boleh diguna pakai sebagai alternatif yang berdaya maju untuk menyokong aplikasi pencawang pengagihan. Penyelesaian rangkaian wayarles baru-baru ini seperti IEEE802.11n menawarkan kadar data yang mencukupi untuk aplikasi berkelajuan-tinggi dengan kos pemasangan yang rendah dan pelaksanaan pantas. Walau bagaimanapun, WLAN tidak mencukupi untuk komunikasi kawalan jauh di dalam grid pengagihan kerana span radio yang terhad iaitu sekitar 100m biasanya. Banyak lagi usaha diperlukan untuk menilai WLAN bagi aplikasi pencawang lain seperti kawalan, pemantauan, permeteran, perlindungan dan automasi, kerana kelebaran jalur dan liputan yang terhad.

Di dalam tesis ini, unit-unit bercantum (MU) berwayar dan WLAN digabungkan dengan pemutus dan peranti elektronik pintar (IEDs) bagi perlindungan dan kawalan (P&C) telah dimodelkan menggunakan pemodel Opnet untuk menilai prestasi aplikasi-aplikasi yangberbeza di pencawang itu.

Selepas pemodelan MU dan IED P&C mengikut timbunan IEC 61850, prestasi pelbagai aplikasi pencawang pengagihan pintar telah dinilai dari segi kelengahan mesej purata dan maksimum hujung-ke-hujung dan truput.

Walaupun gentian optik menawarkan kadar data yang sangat tinggi ada had penggunaannya untuk perlindungan berasaskan gelombang bergerak. Ini kerana kadar persampelan gelombang bergerak semestinya perlu tinggi untuk menangkap semua butiran gelombang fana. Ini lebih-lebih lagi apabila terdapat pelbagai MU berkongsi bas proses. Oleh itu, untuk mencapai perlindungan segera berdasarkan kepada pengesanan isyarat fana yang berasal dari lokasi kerosakan, adalah perlu untuk direka bentuk semula MU supaya mereka ini boleh melaksanakan mampatan dan pengekstrakan ciri yang cepat dan juga memfaktor semula mesej SV.

Tesis ini seterusnya mencadangkan satu teknik pra-pemprosesan baru untuk persampelan-tinggi gelombang bergerak menggunakan pembungkusan dan pemampatan atau pengekstrakan ciri. Pembungkusan dan pemampatan menghasilkan peningkatan daya pemprosesan dan kelewatan hujung-ke-hujung, manakala pengekstrakan ciri memberikan peningkatan perlindungan dan pada masa yang sama, mengurangkan kekerapan persampelan yang diperlukan sehingga tahap yang sama seperti dalam kaedah tradisional. Teknik yang dicadangkan ini terbukti mengatasi prestasi teknik berasaskan-galangan tradisional yang mengalami pengurangan ketepatan dan yang memakan masa.

Di samping itu, IED perlindungan jarak berasaskan gelombang bergerak (PDTW) yang mematuhi IEC 61850 telah direka, dan ia boleh digunakan untuk perlindungan kawasan luas berbanding dengan penggunaan unit pengukuran pemfasa tradisional. Senario perlindungan yang berbeza berasaskan gelombang tradisional dan bergerak telah diuji dan telah ditunjukkan bahawa WLAN memang boleh digunakan untuk aplikasi-aplikasi perlindungan yang berbeza.

Tambahan lagi, analisis format paket mesej SV telah dibuat. Pada dasarnya, setakat ini belum lagi ada format tertentu untuk WLAN yang telah disyorkan untuk IEC 61850. Selepas ini, format paket WLAN baru untuk perlindungan-perlindungan yang berbeza berdasarkan gelombang tradisional dan bergerak telah direka selepas memfaktor semula format paket SV asal. Hingar dalaman dan luaran pencawang pada jalur 2.4 dan 5.0 GHz masing-masing, telah dijana melalui simulator untuk mengkaji kesannya ke atas prestasi WLAN, terutamanya pada daya pemprosesan dan kelengahan hujung-ke-hujung. Hasil simulasi menunjukkan bahawa kelengahan hujung-ke-hujung nilai sampel (SV) dan mesej peristiwa pencawang generik berorientasikan objek (GOOSE) telah meningkat dan truput WLAN menurun apabila nisbah isyarat-ke-hingar (SNR) menurun, dan jalur 5.0 GHz adalah lebih sensitif kepada hingar.

Akhir sekali, untuk mengurangkan kesesakan trafik di WLAN, penilaian ZigBee dan 6LoWPAN yang bekerja bersama dengan WLAN juga telah dilakukan untuk aplikasi-aplikasi yang berbeza dan secara mematuhi protokol IEC 61850.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AP	Access Point
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
APDU	Application Protocol Data Unit
ASDU	Application Service Data Unit
BER	Bit Error Rate
BSS	Basic Service Set
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CT	Current Transformer
CF	Compression Factor
DAS	Distribution Automation System
DAPs	Data Aggregation Points
DCT	Discrete Cosine Transform
DERs	Distributed Energy Resources
DGs	Distribution Generations
DGT	Distributed Generation Trip
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DWT	Discrete Wavelet Transform
EPRI	Electrical Power Research Institute
EMD	Empirical Mode Decomposition
EMI	Electro Magnetic Interference
FFD	Full Function Device
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GOOSE	Generic Object Oriented Substation Event
GSSE	Generic Substation Status Event
HF	High Frequency
HMI	Human Machine Interface
HHT	Hilbert - Huang Transform
HSR	High-availability Seamless Redundancy
HT	High Throughput

ICB	Intelligent Circuit Breaker
IDMT	Inverse Definite Minimum Time
IEC	International Electro technical Commission
IED	Intelligent Electronic Device
IEEE	The Institute of Electrical and Electronic Engineers
IP	Internet Protocol
IOU	Input Output Unit
IWLAN	Industrial Wireless Local Area Network
LAN	Local Area Network
LOS	Line Of Sight
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Medium Access Control
MATLAB	Matrix Laboratory
MIMO	Multiple Input Multiple Output
MMG	Mathematical Morphological Gradient
MMS	Manufacturing Message Specification
MPC	Master Protection Centre
MSE	Mean Square Error
MSV	Multicast Sample Value
MTBF	Mean Time Between Failure
MU	Merging Unit
NSIT	National Institute of Science and Technology
OLTC	On Line Tap Changer
OSI	Open Systems Interconnection
OFDM	Orthogonal Frequency Division Multiplexing
OPNET	Optimized Network Engineering Tool(software)
P2P	Point-to-Point
P2MP	Point-to-Multi Point
P&C	Protection and Control
PAN	Personal Area Network
PLC	Power Line Communications
PRD	Percent Residual Difference
PRP	Parallel Redundancy Protocol
PSCAD	Power system Computer Aided Design

PSRC	Power System Relaying Committee
PT	Potential Transformer
QoS	Quality of Service
RFD	Reduced Function Device
RFI	Radio Frequency Interferences
RTP	Real Time Playback
RTS	Request To Send
RTT	Round Trip Time
RSTP	Rapid Spanning Tree Protocol
SAS	Substation Automation System
SAV	Sample Analogue Value
SCL	Substation Configuration Language
SCADA	Supervisory Control and Data Acquisition
SCSM	Specific Communication Service Mapping
SEL	Schweitzer Engineering Laboratories
SIR	Source Impedance Ratios
SINR	Signal to interference plus noise ratio
SISO	Single Input Single Output
SGCN	Smart Grid Communication Network
SNR	Signal to Noise Ratio
SNTP	Simple Network Time Protocol
STBC	Space-Time Block Coding
SV	Sampled Values
SMV	Sample Measured Values
TC	Technical Committee
TCI	Tag Control Identifier
TCP	Transmission Control Protocol
TLV	Type, Length, Value
TPID	Tag Protocol Identifier
TT	Transmission Time
TWIDi	Traveling Wave Detector Index
UDP	User Datagram Protocol
VLAN	Virtual Local Area Network
VHF	Very High Frequency

WAN	Wide Area Network
WAP	Wide Area Protection
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WHT	Walsh Hadamard Transform
WSN	Wireless Sensor Network
6LoWPAN	IPv6 over Low power Wireless Personal Area Networks

CHAPTER 1

INTRODUCTION

This chapter introduces the work carried out this thesis. It covers the motivation of the power grid, an overview of the IEC 61850 standard, motivation of the research work as well as problem statements. Finally, it lists the research objectives, give a brief outline of the research methodology and outline the organization of the thesis.

1.1 Motivation on the Power Grid

The power grid is an interconnected network that delivers electrical energy to its users. Due to the increase in energy demand, more infrastructures as new distribution lines and longer transmission lines are needed to deliver extra electricity to consumers.

Today, the power grid has become extremely complex and immense. Reliable and efficient power grid must always be ensured practically with the advent of renewable sources and distributed energy resources (DERs). This leads to the need for the smart grid.

The smart grid means a "computerized" and "modernized" electric utility grid. Among the main objectives of the smart grid are to improve the efficiency, reliability and quality of the overall power system. This is done by, among other things, allowing users to adjust their energy consumption, by decreasing the load on the power grid during the climate change and by consolidating the power systems with real-time controlling and monitoring capability.

In smart grids, high speed digital communications and computing resources are integrated into the grid devices. Intelligent controllers and sensor are also embedded in the power grid to gather data for automatic control. These intelligent devices have a communication network interfacing with each other and the control centers [1], [2].

The integration of an advanced communications infrastructure into the power grid will enable the achievement of the above-mentioned goals (reliability, efficiency, and quality) of the smart grid. In other words, a smart grid communication network is regarded as the heart of the smart grid. The idea of the smart grid is to assist such functions as smart metering, electric vehicle charging, transmissions and distribution automation, as depicted in Fig. 1.1.

Most of the parts in smart grids from generation to distribution need communication network capabilities. It is the smart grid communication network (SGCN) that makes the power grid "smart". Good communications improve the reliability and efficiency of the power grid. To achieve a robust and secured SGCN is a challenging task. Smart grid is a complex system performing different functions from generation, transmission, distribution, and users; the SGCN connects millions of devices of different types in different topologies. As such SGCN must be made to be self-organizing, distributed, scalable, and robust in its protocol.

Thus, because of its criticalness, smart grids need to have a round-the-clock protection and the protection requires a fast and reliable communications network. With this fast and reliable network, fast tripping can be implemented, providing stability, safety, reducing fire damage, and damage of electrical equipment's.

Fault detection and system restoration for transmission grid and distribution network need to transmit short messages with very high reliability and stringent delay. The availability of many different communication methods presents another challenge in SGCN, such as point-to-point, multi-point-to-point, and point-to-multipoint. Some sections or links in SGCN are implemented by way of wireless communications networks. Many challenges related to wireless communications such as multi-path fading, radio frequency interference (RFI), electromagnetic interference (EMI) can cause packet loss and delay. The SGCN should have the ability to estimate the channel quality and adapt well to the change. The nodes in SGCN should have self-healing features to be robust against node failures, and finally the SGCN must be able to detect and react to any failures fast.

IEC 61850 is the initial scope of supporting communications inside the substation automation systems. It is a worldwide protocol used in the advent of smart grid. It has a strict time delay constraints in that the power system protection operation delay time should be between 3 and 10ms, and the probability of not receiving protection message within 10 sec must be less than 0.0001[3]. The applications of this standard have brought significant changes to the instrumentation, communication, protection and control.

IEC 61850 is intended to be mapped on Ethernet as a layer 2 communication network technology because Ethernet is the dominant technology for local area network (LAN) and it brings significant advantages of high bandwidth and low latency especially with the use of fiber optics at the physical layer. Hence, Ethernet is appropriate for sub-station indoor LAN with applications that require high bandwidth data transfer for measurements and time-critical functions such as protection services. However, when IEC 61850 is extended to support large-scale communication networks between substations and between control centers and substations and DERs, Ethernet is no longer a good solution due to the high set-up costs and cable usage related scalability problems for all connections.

Protection based on IEC 61850 standards reduces the number of wiring connections, and thus reduces cost and improves maintenance. With IEC 61850, communications between protection and control relays become very reliable, especially due to system redundancy. Digital microprocessor-based relays designed for IEC 61850 can easily share data between them to improve the protection and control. Process bus for IEC 61850 improves the control and protection since there is no need to change its hardware as previously done and all that is needed is the change in software algorithms for IEDs that receive sample value (SV) from Merging Unit (MU). IEC 61850 protocol provides interoperability between IEDs from different suppliers which is a major concern in SAS communication. Today, many research focus on the revolution in application and communications with IEC 61850.

Some of the most important protections are distance-line protection and differential protection. The former is mostly done using phasors while the latter is based on impedance, reactance or admittance. Fault can be identified with, less precisely.

Protection based on travelling waves in transmission line reduces the tripping time, averaging of approximately 10ms or more in time saving. This stems from the fact that many protection relays are based on phasors which need a full cycle to observe to estimate accurate phasor.

One can reach ultra-fast tripping today by using feature of transient signal of current and voltage during fault occurrence. With fast tripping, it implies more power is transmitted, electric power stability goes up, improved safety and reduced damage, reduced fire risk, and less nuisance to the customers. However, protection based on travelling wave is more precise, therefore the objectives of a power grid are to make electric power safer, more reliable and more economical.

For power generations, apart from the traditional non-renewable fuel sources such as diesel, coal, and nuclear, there are other alternative sources of energy, such as wind turbine, photovoltaic panels, so fast relay based on travelling wave brings benefits to these non-traditional sources to integrate with power systems more smoothly. Fast relay based on travelling waves are more dependent on networks and less dependent on sources, thus fast tripping are useful for these sources and bring the protection to a new level. By speeding up the protection from 20ms to 4ms, it creates more benefits for our industry.

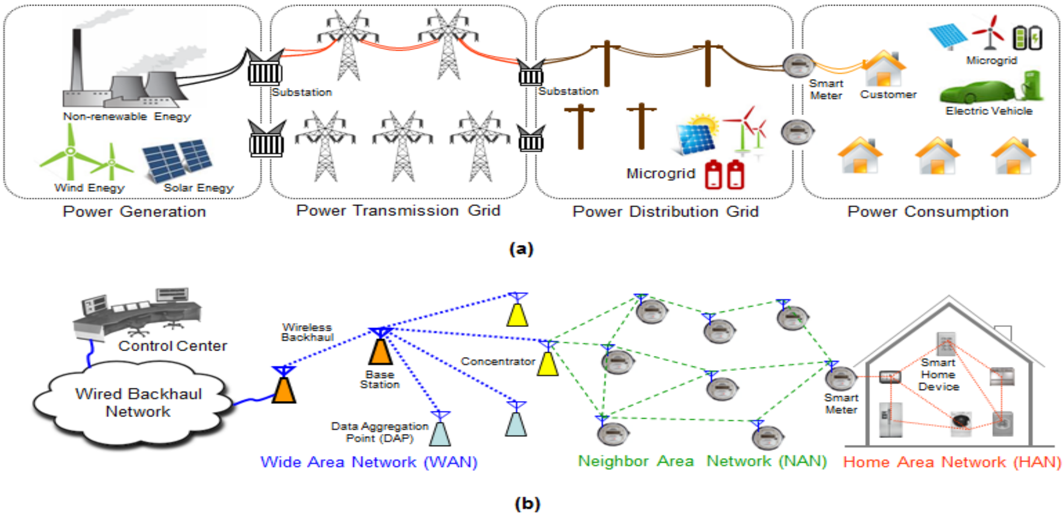

Figure 1.1: Smart Grid Revolution. (a) Power system. (b) Smart grid communications network [4]

1.2 IEC 61850 Standard for Substation Protection and Automation

Among the great benefits from the modernization of IEC 61850 is that it is a suite of protocols, not just one. IEC 61850 is fully compatible and interoperable with other manufacturer's devices and are easily integrated.

IEC 61850 is the standard communication protocol that meets the communication requirement of the electrical utility industry. In 1999, the electrical power utilities started to work extensively on this issue. The resulting communication protocol standard is known as IEC 61850. Its specification is composed of 10 parts whereas a typical substation automation system consists of three parts; the switchgear and associated current transformers (CTs) and power transformers (PTs), the protective relay or intelligent electronic devices (IED) as it is called because of the enhanced functionality (event logging, waveform capture, communication and programmable logic control), and finally the logical graphical human machine interface (GUI). The control center and communications link between devices completes the utility communication model. This arrangement enables communications between devices within the substation, communications between devices and the control center, and communications between clients at the control center.

The IEC 61850 communications model divides the communications into three areas; the substation to the control center, the station bus, and process bus. From 1994 Electric Power Research Group (EPRI) in North America, and the Institute of Electrical and Electronics Engineers (IEEE) started the task of defining a station bus, and this new phase was called UCA 2.0[5]. In 1996 the Europe technical communities TC57 joined and began to work with IEC 61850 with a focus similar to that of UCA2.0, in which the substation bus peer to peer (P2P) message service called GOOSE was specified [6]. In 1997 the UCA community and TC57 community worked together to define the common international standard IEC 61850 specification, with this new specification the UCA2.0 GOOSE message was renamed

UCA2.0 GSSE, and the enhanced GOOSE was specified to UCA2.0 GOOSE. IEC61850 P2P services are the same as in UCA2.0 GOOSE with enhanced functionality. IEC 61850 is much more than application data protocol and communication, logical nodes and data which are defined within (IEC 61850-7-4/-7-3), it has service interface which is defined within (IEC61850-7-2), also a station bus defined within (IEC61850-8-1), and there is the process bus defined within (IEC61850-9-2). There are also different layers of the information that represents the different functions modelled such as the circuit breaker, over-current protection, distance protection etc. Next, the information model exchange were defined and later the network stack layer that is used to share that information. Three protocols are used in the station bus; they are IEC 61850-8-1, TCP/IP application layer, GOOSE/GSSE link layer protocol, and time sync SNTP (simple network time protocol). Also three protocols are used in the process bus; they are (IEC 61850-9-1, IEC 61850-9-2), sample value protocol (link layer), GOOSE/GSSE (link layer), and time sync (SNTP) [6].

The IEC 61850 protocol has the advantage of worldwide acceptability for cross-border transmission of data within electrical installations. This protocol data is defined in the form of software objects with a specific name and behavior. This allows for the interoperability between devices produced by different manufacturers [5]. In view of IEC 61850, protocol diversity and integration problems have been regarded as a thing of the past. The time and costs of configuration, commissioning and maintenance can be reduced. The reduction of costs is made with this protocol, and communication becomes more reliable, since one communication channel is used for all data in real time, synchronized through the Ethernet. By closing the gaps between substations and control center and between the process and bay level, the IEC 61850 standard seamless communication will overcome the last of the communication discontinuities; also it can combine the MU and Breaker IED into one product for the optimized application of the process bus and improve the mean time between failure (MTBF). Furthermore it can combine all protection functions in a single IED device. The resulting protection system reliability improves\ the MTBF further, but this system does not work in cases of distributed protection schemes such as bus or line differential [6]. Reference [7] dwells into the IEC 61850 performance of the process bus through the Ethernet network.

1.3 Motivation for the Research Work

Distributed Energy Resources (DERs), a term referring to any small power source that be aggregated to provide energy demands, are being increasingly integrated in the distribution systems and resulting in complex power flow scenarios. In such cases, effective control, management and protection of distribution systems becomes highly challenging. Thus, protective systems must rapidly sense and isolate faults within a specific time constraint to minimize the damage and improve system stability.

Currently the communication networks in substations are largely based on fiber optic, since it supports high data rate and immune to EMI/RFI interference. Over the past few years improvement in wireless communication systems has made possible to offer much higher data rates, low installations cost, enhanced reliability and flexibility of data acquisition, which are not the strength of wired technologies for substation automation purposes.

Fast protection with IEC 61850 using traveling wave techniques requires a high sampling frequency to capture the characteristic of the fault with high accuracy. This needs to be in the range between 200 KHz and 1 MHz, thus WLAN with a speed ranging between 54 Mbps and 600 Mbps cannot support such applications because of unacceptable time delays.

Chapter 2 presents the ability of wireless communication to support applications in power protection stations. The literature highlights the limitations of wireless technology for time critical applications in electrical substation environment. The main challenges of wireless communications are its relatively low data rate, its susceptibility to EMI/RFI interference, and the congestion of unlicensed frequencies. With the recent advancements in wireless LAN technologies, the use of wireless technologies in IEC 61850 based substation automation system need to be re-evaluated in terms of communication performance for protection and control applications.

1.4 Problem Statement

Wireless network technology compliant with IEC 61850 can be effective for the control, measurement, managements and protection of distribution systems in smart grids.

As highlighted earlier, the IEC 61850 communication protocols has become a global standard that deals with field, originally for substation automation, but has now expanded to deal with many equipment domains including substation automation, distributed energy resources (DER), distribution automation, customers, generation, WAN application between substation and others.

Fiber optic is a good solution to connect between DERs and distributed automation system (DAS), but it is not economical for rural areas where the DERs are sparse, or for MV/LV (Medium voltage/Low Voltage) distribution substation. Instead, wireless communication is a viable alternative to provide links between DERs and DAS which should keep the grid reliable and match the electricity supply domain at all-time [8].

Using Wireless LAN in protection, monitoring and control are beset with many challenges such as fading, radio frequency interference (RFI) and electromagnetic interference (EMI). Thus, this thesis will examine various techniques to overcome the challenges highlighted above, and fulfill the requirement of substation automation.

1.5 Aims and Objectives

The main aim of this thesis is to enable fast protection with IEC 61850 for substation automation system based on travelling waves over band-limited wireless channel. Thus, the objectives can be listed as follows;

1- To reduce end-to-end (ETE) delay of measured sample value message needed to redesign the MU IEDs (intelligent electronic devices) compatible with IEC 61850 having numbers of real time data acquisition channels for sampling a fault transient voltage and current signal at predefined sampling frequency and capable of implementing the advanced digital signal processing techniques in order to reduce the packet length and sampling frequency of this message in MU, to enable IEC 61850 protocol to be used for fast protection, and achieve operating time tripping in the order of 4ms as recommended by IEC 61850-5.

2- To refactor the standard sampled value (SV) messages that can deal with intermediate data from compression after packing or feature extraction suitable for Wireless LAN technologies, to give an acceptable end-to-end (ETE) delay of packet transfer recommended by IEC 61850-5; the acceptable delay are between 3-20ms as depicted in table 2-1.

3- To develop a travelling wave real time protection (TWRP) IED or TWIED, that measures the travelling wave generated from the fault, over a wireless communication backbone network. This IED can be used for protection with IEC 61850 for intra substation and wide area network applications rather than using phasor measurement unit (PMU).

4- To evaluate and compare the performance of traditional and travelling wave methods of IEC 61850 running on Ethernet and WLAN respectively, in terms of sampling frequency, packet length, signal-to-noise ratio, data rate and bit error rate.

Figure 1.2 shows the scheme diagram for objectives and main aims.

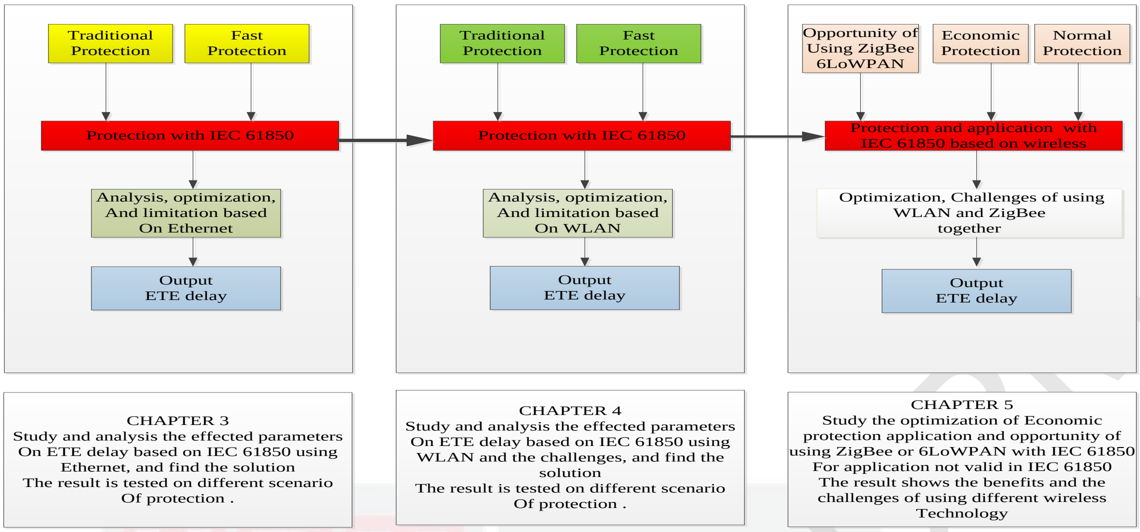

Figure 1.2: Investigation of protection success with IEC 61850 through the work

1.6 Overall Methodology and Research Scope

The focus on this thesis is on the design and analysis of a real time protection model for MU IED and TWRP IED based on travelling wave analysis. The thesis focuses on the following matter:

1- Development of a noise model using MATLAB, at 2.4 GHz, and 5.0 GHz ISM band, in order to study the effect of S/N ration on ETE delay.
2- Modeling, using OPNET simulator tool, of a combined MU, Breaker IED and P&C IED in wired and wireless network, compliant with IEC 61850 protocols.
3- Development of a mathematical model and evaluation of maximum throughput and delay for WLAN technologies validated using Opnet simulator tools.
4- Derivation of mathematical models for analyzing real time protection for different communication channels in process field in order to assess the impact of each parameter, like data flow, maximum reliable transmission frequency, Ethernet switch performance and data processing capability of MU and P&C IED to achieve the protection requirement mentioned in IEC 61850-5.
5- Analysis of the performance of protection for IEC 61850 based on traditional and travelling wave methods respectively, considering sampling frequency, packet length, signal to noise ratio, data rate and bit error rate.
6- Analysis of the performance of ZigBee and 6LoWPAN compliant with IEC 61850, in order to be used in coexistence with WLAN for specific application within the substation.

The performance parameters are the end-to-end (ETE) delay of GOOSE and SV messages using different scenarios in substations. The radio frequency interference

(RFI) and electromagnetic interference (EMI) effect was assumed to follow Gaussian probability distribution function based on literature review.

1.7 Contributions of the Thesis

The main contributions of this thesis are as follows:

1- Investigation of IEEE 802.11n WLAN as the network infrastructure for power grid protection and automation which is a band-limited channel subject to propagation impairments and interference, offering two benefits MIMO diversity, and MIMO multiple streams.
2- Development and analysis of fast protection based on travelling wave techniques with pre-processing that reduce ETE delay of trip message, and then proves the ability of implement this type of protection over band limited channel (WLAN) with IEC61850,
3- Development of an intelligent protection IED based on travelling waves that can be used for Wide Area Network (WAN) rather than using phasor measurement unit (PMU) techniques. This reduces the trip time and improves the power system stability.
4- Integration of DERs (distributed energy resources) with SAS (substation automation system) using WLAN technology in the power system. The communication network, between different DERs and substations requires a WAN which can be implemented using TWIED.

Research scope of this thesis is indicated as in the shaded portion of figure 1.3. This thesis focuses on fast protection based on transient signal which are generated by the fault. The proposed technique can be used within substation, between substations, and wide area network. It improves ETE delay performance over the previous techniques [8-10].

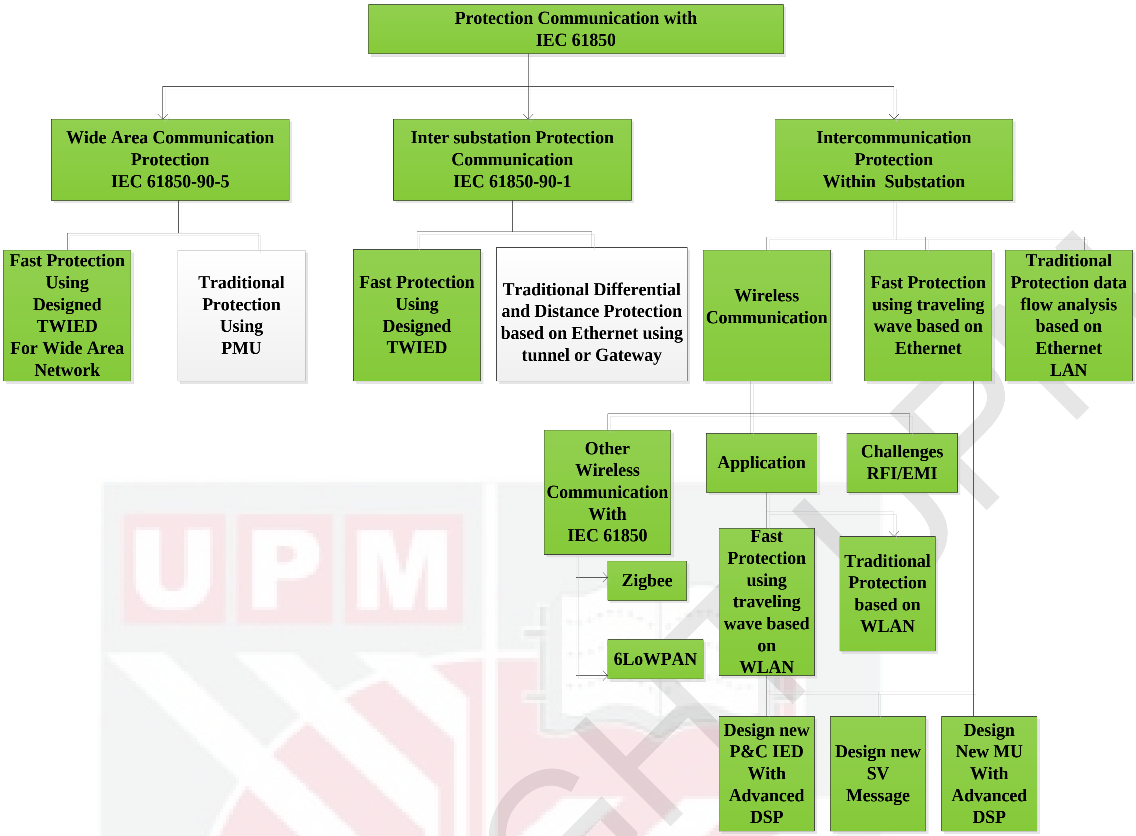

Figure 1.3: Research contribution and the Study Flow Research Work

1.8 Thesis organization

This thesis is organized as follows.

The first chapter introduces the research study, the IEC 61850 protocol, the problem statement, objectives, a brief research methodology, and summarizes the contributions. The second chapter accounts the subject matter of this research, which covers IEC 61850 protocols, IEEE 802.11 wireless LAN, application of wireless LAN in smart distribution substation.

In chapter 3, the first part of the research methodology is described, i.e. protection using traditional and travelling wave methods based on Ethernet, which also considers the multiple MUs sharing the process bus, derivation of a mathematical model and a case study. Chapter 4 deals with the second part of the research methodology, i.e. evaluation of maximum throughput threshold and end-to-end (ETE) delay of IEEE 802.11 wireless LAN standard. Thereafter, The EMI generated from corona, lighting discharge, or switching operation of isolator switch or circuit breaker and the RFI from other radio devices installed in the vicinity of a substation may slow down the transmission of data by causing the WLAN to re-transmit messages, then the effects of EMI/RFI on performance of WLAN are studied. The implementation of wireless LAN-based communication network for various applications in smart distribution network are described next.

In chapter 5, the third part of research methodology is described, it includes the performance of wireless LAN communication network for various distribution protections; it is analyzed and simulated using OPNET, a well-known professional network software simulation package. Also, the impact of data rate, noise, bit error rate and distance, on ETE message delay and throughput are presented in detail. The final part of the thesis studies the use of ZigBee and 6LoWPAN as an alternative or in co-existence with IEEE802.11a/n, for substation protection and automation compliant with IEC 61850. Finally, the conclusion and future works are discussed in chapter 6.

1.9 Summary

This chapter gave a brief introduction to IEC 61850 standard for substation and smart grid automation. This leads to the identification of the research problem, followed by an outline of the thesis objectives. Next, a brief description of the research methodology is described. Finally an outline of the organization of the thesis is presented.

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