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State-of-the-art in the industrial implementation of protective relay functions, communication mechanism and synchronized phasor capabilities for electric power systems protection

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ABSTRACT

Protective systems in electricity delivery networks have a major role to play in the increasing of renewable energy systems, and a broad understanding of their current a future application can aid into better taking them into account for achieving future energy networks that adapt for the incorporation of renewable energy generation sources. This paper provides a survey in the state of the art of protective relaying technology and its associated communications technology used in today's power transmission systems. The paper also provides the fundamental knowledge concerned with power system relaying communications. The unifying theme of this paper is to highlight that the future potential of these devices lies in realizing the possibility of going beyond their traditional application as stand-alone equipments with the single role of acting "the last line of defense" so that they can be handled with the increment of renewable energy power delivery systems in near future.

Contents

1. Introduction

Protective relays are usually expected not to operate during normal operating conditions, but must immediately respond to handle intolerable disturbances in power networks. This immediate availability criterion is necessary to avoid serious outages and damages to parts of or the entire power network, and more importantly, to ensure the safety of personnel. Ideally, a protective relay system should be capable of responding to an infinite number of abnormalities that may occur in the power grid. However, in practice, some compromises must be made by comparing risks. It is quite difficult to ensure stability and security of the entire power system if only local measurements are employed in monitoring, protection and control schemes. In this context, the operation of protective relays is of importance to the avoidance of blackouts. Most blackouts are triggered by random events ranging from single to multiple equipment failures. More importantly, cascading phenomena are one of the principal contributors to the blackouts. In most cases of cascading phenomena, the protection systems, specifically relays, contribute to a substantial proportion of blackouts [1,2] since they are capable of inducing domino-effect component disconnecting.

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One promising way is to develop system wide protection and control mechanisms, complementary to the conventional local and zonal protection strategies, using synchronized phasor measurements (PMUs) and wide-area monitoring, protection and control systems (WAMPAC). In order to implement such mechanisms, synchronized phasor measurement may serve as an effective data source from which critical information about the system's condition can be extracted. Synchronized phasor measurement capabilities are now one of the features available in the most advanced protective relays commercially available, and the use of this feature is proliferating. Indeed, early applications of this technology for the synchronization of distributed generation to large power grids [3] and for islanding management [4] show a promising opportunity for the use of this technology in the combination of traditional protective devices for the integration of distributed renewable sources of energy [5,6].

Protective systems in electricity delivery networks have a major role to play in the development of renewable and sustainable energy systems, and a broad understanding of their current a future application can aid into better taking them into account to corporate with increasing of renewable energy generation sources. To this aim, this paper provides a survey in the state of the art of protective relaying technology and its associated communications technology used in today's power transmission systems. The paper summarizes the operating principles of relay applications, the available measurements used by relays and the protection schemes for various faults that occur frequently in power system. This aids readers to become familiar with the principles used by most common protective relays. Moreover, a review and comparison between different relay manufacturers is also provided to highlight the industrial state-of-the art in this field. The paper also provides the fundamental knowledge concerned with power system relaying communications. The various protocols and network topologies used for protective relaying purposes are explained. Associated communication standards are outlined in order to create a background on the communication technologies used by protection systems. The aims of this paper are the following:

- To briefly describe the impact of renewable energy sources on protection systems, and new required functions in protective relays needed to cope with these energy sources.
- To give readers a comprehensive overview of the state-of-the-art in the implementation of protective functions available in today's relays.
- To provide a general summary of fundamental concepts used for traditional power system protection.
- To give a comprehensive and detailed overview of the communication mechanisms used for power system relaying.

The unifying theme of this paper tries to highlight that the future potential of these devices lies in the possibility of going beyond the common view which catalogs them as stand-alone equipments with the single role of protection which should act as "the last line of defense". Instead, it should be realized that they play in a vital role in improving the system awareness, improving system stability and security as shown in [7,8]. For example, the combination of protective functions and synchronized phasors in protective relays could aid in coordinating better with power system controllers to mitigate outages [9], and to enable the smooth integration of distributed renewable sources of energy [5]. To this end the authors have chosen to emphasize the aspects of the communication mechanisms used for protective relaying, and the requirements that they should meet.

The remainder of this paper is organized as follows. Section 2 describes the impact of renewable energy sources affecting protection systems. Section 3 provides the comparison of relay characteristics between different vendors are surveyed. Section 4 summarizes common communication mediums and network topologies. In Section 5, different communication protocols are summarized and communication delays are also discussed in this section. In Section 6 conclusions are drawn.

2. Impact of renewable energy on protection systems

The growth of renewable energy integration has increased gradually in the last decade seeking to replace conventional generation methods. We can categorize the connection between renewable energy sources and main power systems into two types; which are remote and local connections. Renewable energy sources are located far away from the load-centers require an investment in new overhead lines and significant extension of the existing main grid. A good example of required transmission lines installation is the "Three Gorges dam" hydro power plant in China which transmit power across the country. There are many research works that have been carried on for improving grid integration for this type of connection such as for wind turbines [10,11] or photovoltic [12,13] connection. Meanwhile, the second type of connection is where renewable energy plants are installed locally, allowing local consumers to generate electricity for their own. This connection type grows rapidly, especially in distribution networks due to no long-distance transmission lines requirements. In other words, having renewable sources close to the load location reduce transmission losses and preventing network congestions.

In spite of many economic and technical advantages, high penetration of them would cause some negative impacts on distribution network operation. That is because the distribution system are usually designed and operated assuming one direction along feeders. Once a set of protective devices has been coordinated under this paradigm, reversing or allowing multi-directional power flow in some particular operations according to the infeed from renewable energy resources can cause a serious protective device maloperations. This problem has occurred in many countries, for example in Germany [14], UK [15], and South Korea [16]. This implies that and increasing amount of renewable energy resources (with intermitted energy productions) requires a larger focus on the operational planning and the actual on-line operation of power networks due to: increased need for balancing of production and demand, more adequate monitoring, more need for reserves, storage capability, etc. In addition, more challenges brought by the impact of distributed resources on distribution relay protection are summarized by IEEE-Power System Relay Committee, which can be found in [17].

In order to solve undesirable consequences (regarding integration of renewable sources) on protection systems, new functions are required in protective relays when compared to traditional devices. These functions would allow relays to change predefined-settings to ensure that the entire power system is protected at all times. Technical requirements for new protection system paradigms consist of [18]:

- Relays that satisfy the selectivity requirement. This is because the current time-graded protection schemes used at MV and LV networks are inapplicable to handle bidirectional flows.
- Relays which allow using programmable/or different tripping characteristics that can be parameterized remotely or locally, either automatically or manually.
- Using new/existing communication infrastructures and/or standard communication protocols (for example, IEC 61850 or ModBus) that allows individual relays to exchange information

with a control room or among relays to guarantee a required application performance.

Some practical implementations of protective relays with programmable tripping characteristics can be found in [19], the software tools for setting these characteristics of different relay vendors are summarized in Table 1. Meanwhile, the adoption of communications processors with relays can be found in [20], more details regarding communication mechanism will be provide in Section 4.

3. Comparison of relay characteristic among different vendors

The IEEE defines protective relays as: "relays whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action" [21]. Relays detect and locate faults by measuring electrical quantities in the power system which are different during normal and intolerable conditions. The most important role of protective relays is to first protect individuals, and second to protect equipment. In the second case, their task is to minimize the damage and expense caused by insulation breakdowns which (above overloads) are called "faults" by relay engineers. These faults could occur as a result from insulation deterioration or unforeseen events, for example, lighting strikes or trips due to contact with trees and foliage.

The intention of this paper is not to indicate the strengths and weaknesses of relays from different vendors. Instead, the authors summarize important characteristics of different vendors' relays, thus readers might be able to select the one that is most best suited for their particular application. The characteristics of relays such as available measurements, operating times and communication protocols, from different vendors are summarized in Table 1. These relays' characteristics are obtained from several manufacture product manuals General Electric (GE) [22–26], Schweitzer Engineering Laboratories (SEL) [27–31], Areva-Alstom [32–36], and ABB [37–41].

3.1. Short description of programming and software features from different vendors

This section provides the short description of softwares' functionalities and features for the user interface. They are categorized by the different manufactures as follows.

- *GE*:
  - *ENERVISTA UR and ENERVISTA MII* are Windows-based softwares that allow users to communicate with relays for data review and retrieval, oscillography, I/O configurations and logic programming.
- *SEL*:
  - *ACSELERATOR QuickSet Software* provides analysis support for SEL-relays. It creates, tests, and manages relay settings with a Windows interface.
  - *SEL-5077 SYNCHROWAVE Server* provides phasor data concentration (PDC) for synchrophasor information, and transmit data to a display software in IEEE C37.118 format.
- *ALSTOM*:
  - *MICOM S1 Studio* provides user with global access to all IED's data by sending and extracting relay settings. It is also used for analysis of events and disturbance records which acts as IEC 61850 IED configurator.
- *ABB*:
  - *IED Manager PCM 600* is the toolbox for control and protection IEDs. It covers the process steps of the IED's life cycle, testing, operation and maintenance, to the support for function analysis after primary system faults.
  - *CAP 505 Relay Product Engineering Tool* is a graphical programming tool for control and protection units. It can be used both as a local system near the relay and as a central system connected to several relays.
  - *RELTOOLS* is management tool for controlling relays of the ABB-family. It allows the user to edit settings and to modify control logics.

Nevertheless, these tools support limited range of different protection and control products. For instance, the *PCM 600* tool supports the REG 670 relay (generator protection) but the software does not patronize to the REL 512 (distance protection) [42]. Another example is the *CAP 500* supports the RE_545 relay-family, this group of relays are differential, over-current, and over/under voltage protections (see Table 1), but this software is not available for the REG 670 relay [43]. This can imply that there is no interface between different tools. Moreover, only relays manufactured by SEL have implemented and support the IEEE C37.118 protocol [44] which is a standard for communicating synchrophasor measurements in real-time from a PMU to a Phasor Data Concentrator (PDC). This protocol is used to guarantee the data streams quality when aggregating them from different monitored power system regions. This feature would allow for a further exploitation of a transmission system operator's assets through the development of Wide-Area Monitoring System (WAMS), Wide-Area Control Systems (WACS), and Wide-Area Protection System (WAPS).
In practical terms SEL and Alstom provide a more consistent software interface to the IEDs using 1 single configuration and programming software, while GE and ABB require 2 and 3, respectively. It is apparent that there is a large practical disadvantage in learning and maintaining more than 1 software for IED configuration.

In addition, as mentioned in Section 1, in order to implement WAMS, WACS and WAPS, local measurements such as bus frequencies, voltage phasors, current phasors, and breaker status need to be transferred from different geographical locations, for example at distant substations and power plants. Most electromechanical relays (which are not designed to handle actual engineering analysis information in complex network topologies) are intentionally being replaced by the modern relays with communications channels, this opens an opportunity to actively incorporate them within WAMS, WACS and WAPS. However, to fully exploit the benefit of replacing these relays, the most advantageous options from both the practical[1] and future-looking perspective[2] are those providing consistency in the software used for management and that implement the latest IEC 61850 and IEEE C37.118 protocols. These channels can be utilized to support an analysis system capable of evaluating protection operation against unexpected and expected behaviors, pinpointing possible malfunctions and indicating problems that may rise in the future.

4. Communications mediums and networks

A communication system consists of a transmitter, a receiver and communication channels. Type of mediums and network topologies in communications provide different opportunities to advance the speed, security, dependability, and sensitivity of

[1] A common and transparent software platform to manage ALL protective relays.
[2] Those supporting the IEEE C37.118 protocol.

Table 1
Comparison of relay characteristics between different vendors.

Characteristic	Protection relay	Vendors			
		GE	ABB	SEL	ALSTOM
Units from manufacturer	Generator protection	G60	REG 670	SEL-700G	P-345
	Differential protection	T60	RET 545	SEL-487E	P-645
	Over-current protection	MIFII	REF 545	SEL-551C	P-145
	Distance protection	D60	REL 512	SEL-311A	P-441
	Over/under voltage protection	MIV	REM 545	SEL-387E	P-923
Available measurements	Generator protection	RMS and phasors (magnitude and angle) for currents and voltages; current harmonics and THD; symmetrical components; frequency, power; power factor; energy	Voltage; current; apparent power; reactive power; real power; frequency; power factor; the primary and secondary phasors	RMS and Phasors for currents and voltages; positive, negative and zero-sequence voltages and currents; system frequency; power; energy; power factor; V/Hz; generator thermal capacity	Current; voltage; power; energy; frequency; phase differential quantities; V/ Hz; rate of change of frequency; CTs current magnitude and phase
	Differential protection			RMS and phasors for currents and voltages; power; energy; differential harmonic quantities	Phase and neutral currents; frequency; power factor; maximum demand; power; differential currents
	Distance protection	RMS and phasors for currents, and voltages, and power metering	RMS and phasors for currents, and voltages, and power metering	RMS and phasors for currents and voltages; power; energy; power factor; frequency; demand and peak current; demand and peak power; sequence components	RMS and phasors for currents, and voltages, and power metering
	Over-current protection	Phase and ground currents; thermal image	Phase currents; line and phase voltages; frequency; power factor; energy; power; THD	Currents; residual ground current; negative-sequence current; demand metering values	Current; voltages; power; power factor; frequency; energy
	Over/under voltage protection	Phase, ground and phase-to-phase voltages; frequency	Phase currents; line and phase voltages; frequency; power factor; energy; power	RMS and phasors for currents, and voltages; power; frequency; V/Hz; harmonics; differential currents	Phase, ground and phase-to-phase voltages; frequency
Diagnostic features	Generator protection	Event recorder (1024 time-tagged events, oscillography for up to 64 records	1000 events time tagged, 100 disturbances	Event recorder (1024 time-tagged events)	512 events, 5 fault records, 10 maintenance records
	Differential protection		100 events each time tagged	Event recorder (1000 time-tagged events)	
	Distance protection		Fault records 20 (each 16 cycle),	Event recorder (512 time-tagged events)	500 events, 28 disturbance records each time-tag
	Over-current protection	Event recorder (32 events each time-tag), one oscillography record	Disturbance record for 16 waveforms and 16 digital signals (total 32)	Event recorder (20 time-tagged events)	512 events, 50 disturbance records each time-tag, 5 fault records
	Over/under voltage protection	Event recorder (24 events each time-tag), one oscillography record		Event recorder (512 time-tagged events)	Event records 75, fault records 5, disturbance records 5 of 2.5 s each

Operation time	Generator protection	5–30 ms	About 15 ms	< 20 ms	< 30 ms
	Differential protection		< 35 ms		< 33 ms
	Over-current protection	20–30 ms	< 30 ms	< 25 ms	< 30 ms
	Distance protection	10–30 ms	< 30 ms	< 30 ms	17–30 ms
	Over/under voltage protection	< 30 ms	< 30 ms	< 25 ms	< 30 ms
Programming and software features	Generator protection	GE ENERVISTA UR	Protection and control IED Manager PCM 600	ACSELERATOR QuickSet SEL-5030 Software	S1 Studio Software for editing and extracting setting files, extracting events and disturbance records
	Differential protection		CAP 505 Tools		
	Distance protection		RELTOOLS		
	Over-current protection	ENERVISTA MII	CAP 505 Tools		
	Over/under voltage protection				
Additional functions	Generator protection	Loss of excitation; generator unbalance; accidental energization; power swing detection; rate of change of frequency	Loss of/under excitation; restricted earth fault; over/under frequency; directional power; pole slip; thermal overload; breaker failure; rate of change of frequency	Over-current; restricted earth fault; over excitation; loss of field protection; over/under voltage; system backup; rate of change of frequency; thermal overload	Over/under voltage; over/under frequency; rate of change of frequency; loss of field; over fluxing; thermal overload
	Differential protection	V/Hz; over/under current; over voltage; over/under frequency; thermal overload; synchrocheck	Over-current; under impedance; earth fault; over load; over/under frequency; over/under voltage; over excitation	Over/under voltage; breaker failure; restricted earth fault; V/Hz; current imbalance	Restricted earth fault; thermal overload; V/Hz, over-fluxing; breaker failure; over/under frequency; CT/VT supervision
	Over-current protection	Thermal overload; cold load pickup; breaker failure to open	Earth fault; over/under voltage; thermal overload; breaker failure, auto reclosure	Auto reclosure; demand current overload; CT saturation	Auto reclosure; CT/VT supervision; overload; frequency protection; over/under voltage; cold load pick up
	Distance protection	Automatic reclosure; power swing blocking; breaker failure; current disturbance; over current; under/over voltage; directional elements	Breaker failure; auto reclosure; over/under voltage	Over-current; loss of potential; load encroachment	Over-current; power swing; thermal overload; auto reclosure; over/under frequency; breaker failure
	Over/under voltage protection	Voltage unbalance; under/over frequency; ground over-voltage	Over-current; earth fault; differential; under excitation; thermal overload; frequency	Over-current; differential; V/Hz; over/under frequency	Over/under frequency; trip circuit supervision; rate of change of frequency
Communication method	Generator protection Differential protection	RS232; RS485; IEC 61850; ModBus TCP/IP; DNP 3.0; IEC 60870-5-104	RS232; RS485; IEC 61850-8-1; IEC 60870-5-103; LON; SPA; DNP 3.0; ModBus RTU/ASCII	SEL; ModBus TCP/IP; DNP; FTP; IEC 61850; MIRROR BITS; EVMSG; C37.118 (synchrophasors)	RS232; RS485; Courier/K-BUS ModBus; IEC 60870-5-103; DNP 3.0; IEC 61850
	Distance protection		RS232; RS485; DNP 3.0; ModBus RTU/ASCII		
	Over/under voltage protection Over-current protection	RS232; RS485; IEC 61850; ModBus TCP/IP; IEC 60870-5-103	RS232; RS485; IEC 61850-8-1; IEC 60870-5-103; LON; SPA; DNP 3.0; ModBus RTU/ASCII	EIA 485; ModBus RTU; EIA 232	

Table 2
Comparison of communication mediums.

Medium	Advantages	Disadvantage
Transmission power line carrier	Economical, suitable for station to station communication. Equipment installed in utility owned area	Limited distance of coverage, low bandwidth, inherently few channels available, exposed to public access
Microwave	Cost effective, reliable, suitable for establishing back bone communication infrastructure, high channel capacity, high data rates	Line of sight clearance required, high maintenance cost, specialized test equipment and need for skilled technicians, signal fading and multipath propagation
Radio system	Mobile applications, suitable for communication with areas that are otherwise inaccessible	Noise, adjacent channel interference, changes in channel speed, overall speed, channel switching during data transfer, power limitations, and lack of security
Satellite system	Wide area coverage, suitable to communicate with inaccessible areas, cost independent of distance, low error rates	Total dependency to remote locations, less control over transmission, continual leasing cost, subject to eavesdropping (tapping). End to end delays[a] in order of 250 ms rule out most protective relay applications [46]
Spread spectrum radio	Affordable solution using unlicensed services	Yet to be examined to satisfy relaying requirement
Leased phone	Effective if solid link is required to site served by telephone service	Expensive in longer term, not good solution for multi channel application
Fiber optic	Cost effective, high bandwidth, high data rates, immune to electromagnetic interference. Already implemented in telecommunication, SCADA, video, data, voice transfer, etc.	Expensive test equipment, failures may be difficult to pin-point, can be subject to breakage

[a] Transmitting back and forth the signal 36,000 km between the earth and the satellite.

protection relays. There are a few types of communication medium such as micro wave, radio system, and fiber optic. The advantages and disadvantages in communication mediums which are currently in operation (both analog and digital) and different network topologies are summarized in Tables 2 and 3 [45], respectively.

5. Communication protocols

Communications protocols are sets of rules by which communication over a network is achieved. Communications protocols are responsible for enabling and controlling network communication. Protocols set the rules for the representation of data, the signals used in communications, the detection of errors, and the authentication of computing devices on the network. It is not mandatory for relay manufacturers to follow the same protocols as shown in Table 1. Communication protocols can be categorized into two groups which are (i) physical-based protocols and (ii) layered-based protocols. Both types of protocol are briefly discussed in this section.

5.1. Physical-based protocol

Physical based-protocols have been developed to ensure compatibility between units provided by different manufacturers and to allow for a reasonable success in transferring data over specified distances and/or data rates. The Electronics Industry Association (EIA) has produced protocols such as RS232, RS422, RS423 and RS485 that deal with data communications. In addition, these physical-based protocols are also included in the "physical layer" of the Open Systems Interconnection (OSI) model that will be explained in layered-based protocols, section below.

- *RS232 protocols*: The RS232 protocol is the most basic communication protocol which specifies the criteria for communication between two devices. This type of communication can be simplex (one device acts as transmitter and other acts as receiver and there is only one way traffic i.e. from transmitter to receiver), half duplex (any of the device can act as a transmitter or receiver but not at the same time) or full duplex (any of the device can transmit or receive data at the same time). A single twisted pair connection is required between the two devices. Fig. 1 shows the RS232 protocol configuration.
- *RS485 protocol*: This protocol is similar to the RS232 protocol which allows multiple relays (up to 32) to communicate at half-duplex. This half duplex scheme authorizes one relay either to transmit or receive command information. This means that the information is handled by polling/responding. The communication is always initiated by the "master unit" (host) and the "slave units" (relays) will neither transmit data without receiving a request from the "master unit" nor communicate with each other. There are two communication modes in RS485 protocol (i) *unicast mode* and (ii) *broadcast mode*. In the unicast mode, the "master unit" sends polling commands, and only one "slave unit" (assigned by an unique address) responds to its command accordingly. The "master unit" will wait until it obtains a response from a "slave unit"or abandon a response in case a pre-defined period expires. In the broadcast mode, the "master unit" broadcasts message to all "slave units". Figs. 2 and 3 show a simple RS485 protocol configuration in the unicast and the broadcast modes, respectively.

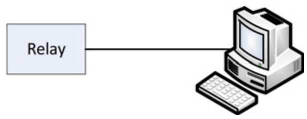
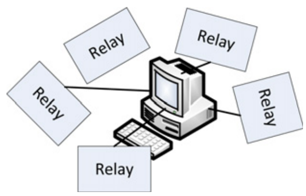
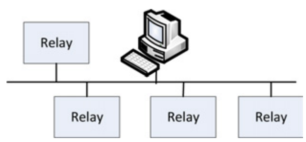
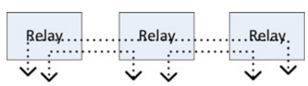
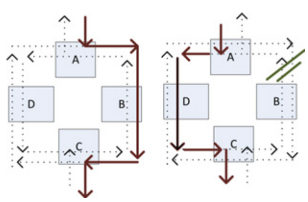
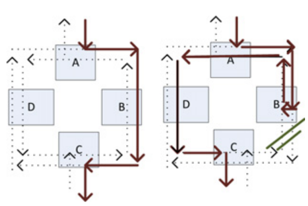
5.2. Layered-based protocols

Other protocols mentioned in Table 1 are developed by the Open Systems Interconnection (OSI) model. This model is a product of the Open Systems Interconnection effort at the International Organization for Standardization. The model sub-divides a communication system into several layers. A layer is a collection of similar functions that provide services to the layer above it and receives services from the one below. On each layer, an instance provides services to the instances at the layer above and requests service from the layer below. When data is transferred from one device to another, each layer would add the specific information to the "headers" and the information will be decrypted at the destination end. More details regarding OSI model can be found in [47].

Some of protocols, mentioned in Table 1, that are derived from OSI model are described below

- *DNP 3.0* [48]: The Distributed Network Protocol (DNP) 3.0 is a protocol developed to achieve interoperability standard between substation computers. This protocol adopts layers 1, 2 and 7 from the OSI model for basic implementation. A fourth layer (a pseudo-transport layer) can be added to allow for the message segmentation. This DNP 3.0 protocol with a pseudo-transport layer is called the Enhanced Performance Architecture

Table 3
Comparison of different communication network topologies.

Topology	Graphical model	Advantages	Disadvantages
Point-to-point network is the simplest configuration with channel available only between two nodes		Suitable for systems that require high exchange rate of communication between two nodes	Communication can only be transferred between two nodes, disconnection of the communication channel will lead to a total loss of information exchange
Star network consists of multiple point-to-point systems with one common data collector		Easy to add and remove nodes, simple in managing and monitoring, node breakdown does not affect rest of the system	The reliability of entire network depends only on single hub failure
Bus network has single communication path which runs throughout the system to connect nodes		Bus network is not dependent on a single machine (hub). This provides high flexibility in configuration (easy to remove or add nodes and node to node can be directly connected).	High information load might delay the communication traffic speed. Also, it is sometime inefficient to utilize communication channels since the information cannot be exchanged directly between the desired relay and hub without passing through relays along the communication path. In other words, some relays may receive information packets which are unnecessary for them. Thus, it is also hard to troubleshoot the root cause of problem when needed.
Linear drop and insert network consists of multiple paths for relays to communicate with each other. Information between two non-adjacent nodes can be transferred directly passes through intervening node(s)		When a certain communication channel drops, its bandwidth can be balanced by other channels	Lack of channel backup against fiber or equipment failure
SONET path switched ring comprises of two separate optical fiber links connecting all the nodes in counter rotating configuration. In normal case, the information is transferred from A to C through outer ring (via B) which is the primary route (left figure). However, if channel failure occurs, the information is transferred through inner ring which is secondary route (right figure)		This type of network is redundant which means that channel failures will not affect the communication process	An unequal time delay between transmitter and receiver might cause the false operation of protective relays when there is a switch to from primary to secondary route in the caseof channel failure
SONET line switched ring has the same structure as SONET path type however one path is active and other is a reserved one. Under normal condition, the active path transfers information via outer ring (left figure). However, in case of channel failure, the inner ring is activated to reverse and transmit information through another direction (right figure)		More efficient use of fiber communications for some applications	This communication type is not suitable for teleprotection applications since it requires complex handshaking (Synchronizing) that causes a delay of 60 ms.

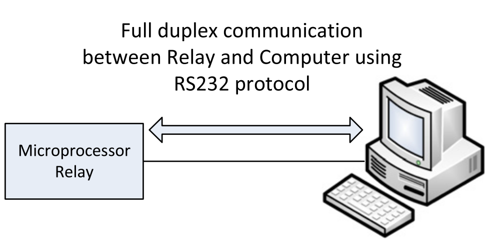


Fig. 1. RS232 protocol configuration.

(EPA) model. It is primarily used for communications between master stations in Supervisory Control and Data Acquisition (SCADA) systems, Remote Terminal Units (RTUs), and Intelligent Electronic Devices (IEDs) for the electric utility industry. This protocol does not wait for data as TCP/IP. If a packet is delayed, after a while, it will be dropped. This is because the protocol consists of embedded time synchronization (timetag) associated with messages. This timetag's accuracy is on the order of milliseconds. It is feasible to exchange messages asynchronously which is shown in a function of the polling/response rate. The typical processing throughput rate is 20 ms [49].

- *ModBus* [50]: ModBus is also a three-layer protocol that communicates using a "master-slave" technique in which only one device (the master) can initiate transactions (called queries). The other devices (slaves) respond by supplying the requested data to the master, or by taking the action requested in the query. This protocol does not consist of embedded time synchronization as in case of DNP 3.0 that each message is stored in an internal buffer. However, time synchronization can be implemented either using the external time synchronization source, such as Global Positioning System (GPS) or using the external timing mechanism, such as Inter-Range Instrumentation Group (IRIG) to keep Intelligent Electronic Devices (IEDs) in synchronism. In general, IRIG provides

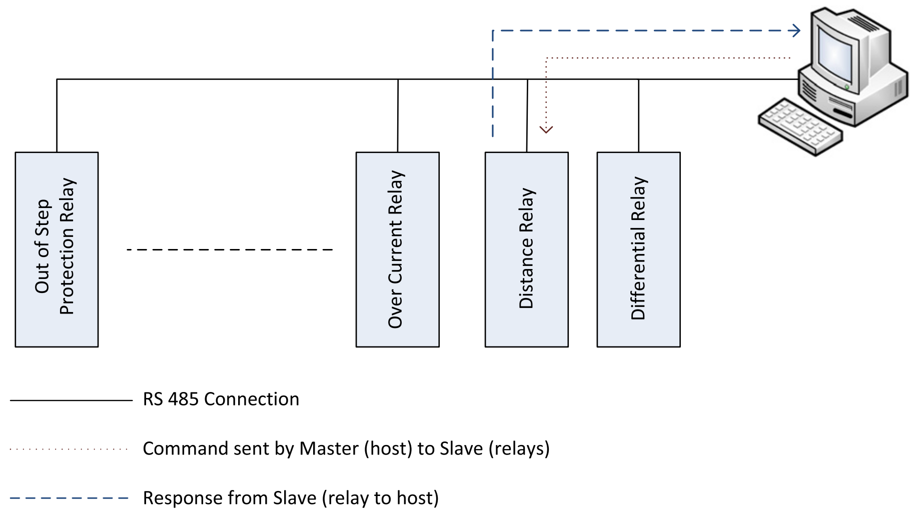


Fig. 2. RS485 protocol configuration: unicast mode.

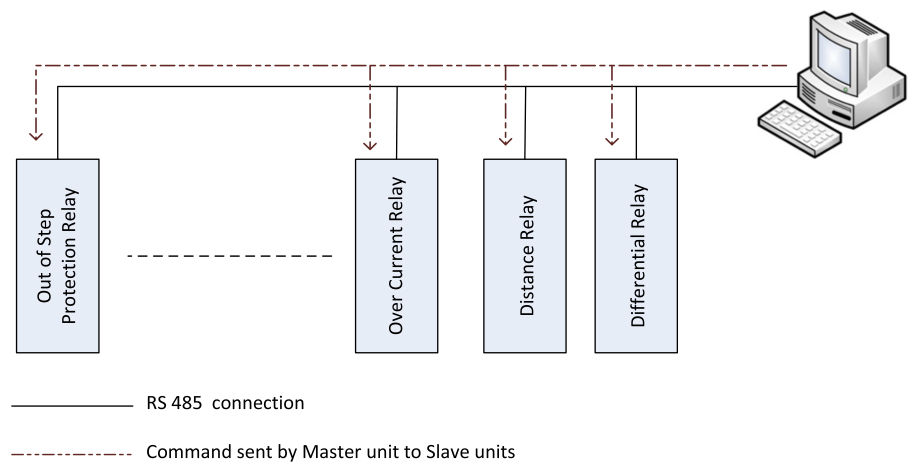


Fig. 3. RS485 protocol configuration: broadcast mode.

accuracy in the 100 μs range [51] but it requires dedicated coaxial cable to transport the timing signals which can be limitation for the number of connected devices (depending on cable length and device load). On the other hand, GPS provides higher accuracy (in the range of 1 μs [51]) compare to IRIG but cost and complications of antennas installation to every device are the restriction for the GPS deployment. Nevertheless, the choice of time synchronization protocol is usually dictated by the number and type of power system devices as well as the physical arrangement of the equipment. The typical processing throughput rate of ModBus protocol is 8 ms [49].

The protocol can be categorized into three frame formats which are American Standard Code for Information Interchange (ASCII), Remote Terminal Unit (RTU), and Transfer Control Protocol and Internet Protocol (TCP/IP) format. The ModBus ASCII and ModBus RTU are both used in serial communication. The difference between these ASCII and RTU frames is the format of communication message. In the ASCII format, two ASCII characters are used in each 8 bit byte message whereas two 4 bit hexadecimal characters (or 8-bit binary) are used in case of the RTU format. The advantage of ASCII format is that it allows time intervals of up to 1 s to occur between characters without causing an error. On the other hand, the greater character density in the RTU allows better data throughput compare with the ASCII for the same baud (modulation) rate however each message must be transmitted in a continuous stream. Fig. 4 shows the Protocol Data Unit (PDU) for ASCII and RTU frame formats.

Meanwhile, the ModBus TCP/IP is modified from the PDU frame with the Ethernet-TCP/IP as an additional data transmission technology for the ModBus protocol. First, an "Error Check" algorithm at the end of frame is removed and the Address Field (address of slave) is replaced by a new header called the ModBus APplication (MBAP) header. This header consists of (i) transaction identifier, (ii) protocol identifier, (iii) length field, and (iv) unit identifier. Fig. 5 shows the Application Data Unit (ADU) for TCP/IP frame format (compare with PDU message). In addition, details such as message format or function codes for all three frames format can be found in [52].

The difference between ModBus and DNP 3.0 is the communication purpose. ModBus is suitable for communication within substations that are used for communicating with devices meant for protection control and metering. Meanwhile DNP 3.0 is suitable for communicate outside the substations (communication of data from substation to master control centers). This is because the ModBus protocol has limited function codes while the DNP 3.0 supports the specific data objects that provide more flexibility, reliability and security. For example, the DNP 3.0 has 'Control Function Code' to perform specific function. The comparison between ModBus and DNP 3.0 can be found in [53]. In addition, the ModBus protocol is a prototype for proprietary

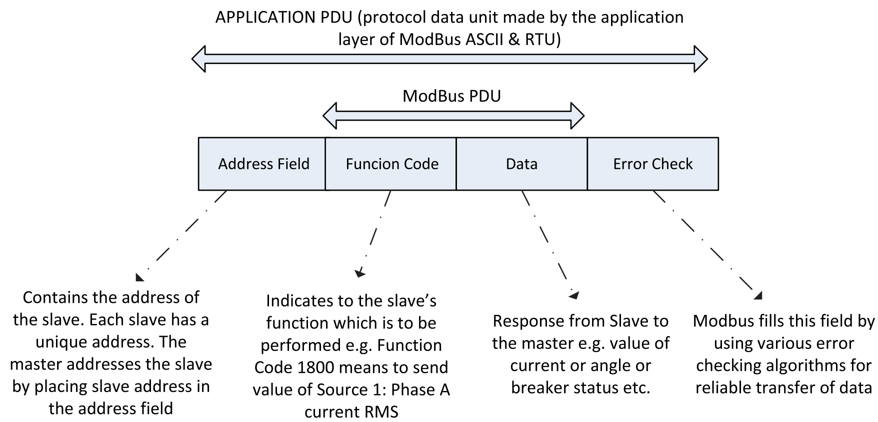


Fig. 4. ModBus ASCII and RTU Protocol Data Unit (PDU).

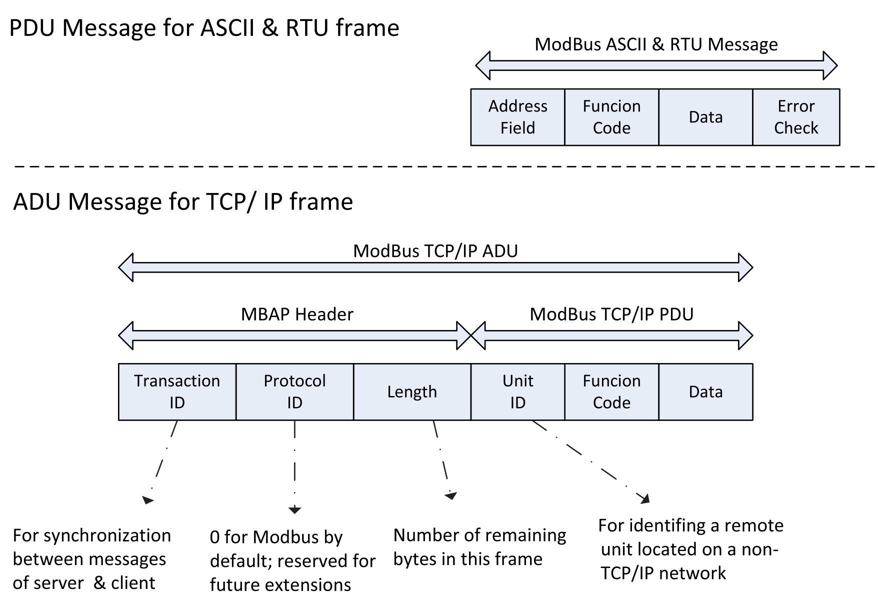


Fig. 5. Message frame comparison between ModBus PDU and ADU.

protocols such as *K-BUS* [54] and *SPA* [55] protocols which are of Areva-Alstom and ABB, respectively.

- *IEC 61850* [50]: IEC 61850 is an electrical substation standard promoted by the International Electrotechnical Commission (IEC). The data models defined in IEC 61850 protocol can be mapped to various protocols, for example to Generic Object Oriented Substation Events (GOOSE) that allows for both analog and digital peer-to-peer data exchange. The protocol includes time tags and also messages that can be exchanged asynchronously. The typical processing throughput rate is 12 ms [49]. IEC 61850 provides many advantage over other protocols such as programming can be done independent of wiring, higher performance with more data exchange, or data is transmitted multiple times to avoid missing information. More advantages can be found in [56,57].
- *LON* [58]: The Local Operating Network (LON) protocol equates all seven layers of the OSI model. It is capable of establishing network communications not only for power system applications, but also for factory automation, process control, building networks, vehicle networks, etc. This may be considered as a drawback in relay communication perspective since the LON protocol occupies seven layers in order to transfer information, thus it provides lower data exchange rates compare to the EPA model such as DNP 3.0.

5.3. *Communication delays in data delivery for synchrophasor applications*

The communication infrastructure is an essential element for protective relays and especially for WAMS, WACS and WAPS. PMU devices are used in order to transmit data from several parts of the system to a control center, therefore the communication network has a potential to be a bottleneck that impact the achievable wide area system's performance. Delay due to the use of PMUs depends on many components such as transducers that are involved starting from the initial sampling instant. The processing time required for converting transducer data, into phasor information depends on the selected Discrete Fourier Transform's (DFT) time frame. Moreover, the overall delay also caused by PMU's data size, multiplexing and transitions, and type of communication medium. Generally speaking, a Phasor Data Concentrator (PDC) receives data streams from PMUs, then correlates them into a single data stream that is transmitted to a

Table 4
Associated delays with various communication mediums.

Communication link	Associated delay one way (ms)
Fiber optic	100–150
Microwave	100–150
Power line	150–350
Telephone line	200–300
Satellite system	500–700

Table 5
Time estimates for steps in wide area protection [61].

Activity	Time (ms)
Sensor processing time	5
Transmission time of information	10
Processing incoming message queue	10
Computing time for decision	100
Transmission of control signal	10
Operating time of local device	50

PC via an Ethernet port. The propagation delays associated with the communication is dependent on the medium and physical distance while the delay associated with transducers used, DFT processing, data concentration, and multiplexing are fixed. The associated delays for various communication mediums when using PMUs are summarized in Table 4 [59].

However, the time duration of different delays has been an ambiguous issue on the communication timing. Ref. [59] further described that the delay caused by processing time (data concentrating, multiplexing and delay associated with transducers) is fixed and estimated to be around 75 ms. This is questionable, as the IEEE C37.118 standard does not specify how processing time must be implemented and therefore each manufacturer differs. As a consequence, processing time is not consistent between each manufacturer. Meanwhile this processing time delay is stated only 5 ms in [60] (see Table 5) and it is doubtfully cited in certain number of publications as in [61–63]. Hence, there is not actual consensus on the time delays involved in each stage of the process between measurement and concentration of synchrophasors. Experimental studies are necessary to establish these important characteristics and to clarify these contradictions.

6. Conclusion

Protective relay has a major role to play in the development of future renewable and sustainable power deliver networks. However, to properly include them in the development of these future systems a broad understanding of their current capabilities, industrial implementation, and future potential is necessary. To bring this understanding under a comprehensive perspective, this paper has presented an overview of available capabilities from the different relay types of the four most common vendors in the market. This includes information about measurements used and performed by the relays, the available capabilities within the relay to perform calculations, communication features, and the communication network and mechanisms used by the relays to send out any available information. Moreover, a comparison between different communication protocols which considers various architecture aspects and configuration, are presented—here the objective is to provide general information about each protocol. Protocol selection depends mainly on application-specific requirements and functions to be carried out. In addition, the mediums' advantages and disadvantages (shown in Table 2) and communication delays (shown in Table 4) have to be weighed and chosen based on the required control dynamics and operating economics of the power system. An important fact that makes this a difficult process is that there are contradictory statements concerning the time-duration of different delays involved in delivering phasor data. This is important because protective relays are now providing synchrophasor capabilities and being used in WAMPAC, hence experimental studies are necessary to clarify these contradictions.

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