Power System Protective Relaying: basic concepts, industrial-grade devices, and communication mechanisms

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Contents

Power System Protective Relaying: basic concepts, industrial-grade devices, and communication mechanisms

This report provides a survey of protective relaying technology and its associated communications technology used in today's power transmission systems. This report is divided in two parts. In the first part, the operating principles of relay applications and the main components of protection systems are briefly introduced. This helps the reader to become familiar with the principles used by most common protective relays. A review and comparison between different vendors is also provided to highlight the industrial state-of-the art in this field. The second part is concerned mainly with power system relaying communication. The various protocols and network topologies used for protective relaying purposes are explained. Associated communication standards are outlined. The aim of this part is to provide background on the communication technologies used by protection system.

1 Introduction

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 " [1]. 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.

Relays are not required to operate during normal operation, but must immediately activate to handle intolerable system conditions. This immediate availability criterion is necessary to avoid serious outages and damages to parts of or the entire power network. Theoretically speaking, a relay system should be capable of responding to an infinite number of abnormalities that may happen within the network. 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. One promising way is to develop system wide protection and control mechanisms, complementary to the conventional local and zonal protection strategies. 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.

2 Main components of protection systems

The main components of protection systems are discussed briefly below.

- **Current & Voltage Transformer:** also called instrument transformers. Their purpose is to step down the current or voltage of a device to measurable values, within the instrumentation measurement range 5A or 1A in the case of a current transformers (CTs), and 110V or 100V in the case of a voltage (or potential) transformers (VTs/ PTs). Hence, protective equipment inputs are standardized within the ranges above.
- **Protective relays:** are intelligent electronic devices (IEDs) which receive measured signals from the secondary side of CTs and VTs and detect whether the protected unit is in a stressed condition (based on their type and configuration) or not. A trip signal is sent by protective relays to the circuit breakers to disconnect the faulty components from power system if necessary.
- **Circuit Breakers:** Circuit Breakers act upon open commands sent by protective relays when faults are detected and close commands when faults are cleared. They can also be manually opened, for example, to isolate a component for maintenance.
- **Communication Channels:** are the paths that deliver information and measurements from an initiating relay at one location to a receiving relay (or substation) at another location. The topic of communication channels is described in detail in this report.

3 Implementation of protective relays in power systems

In this section, protective relays are categorized depending on the component which are protect: generators, transmission lines, transformers, and loads.

3.1 Generator Protection

There are different protection schemes used for protecting generators depending on type of fault to which they are subjected. One of the most common faults is the sudden loss of large generators, which results in a large power mismatch between load and generation. This power mismatch is caused by the loss of synchronism in a certain generator - it is said that the unit goes out-of-step. In this case, an out-of-step relay can be employed to protect the generator in the event of these unusual operating conditions, by isolating the unit from the rest of the system. In addition, microprocessor-based relays have a built-in feature for measuring phase angles and computing the busbar frequency from the measured voltage signal from the VT [2]. Thus, phase angles and frequency measurements are also available for use within the relay. Figure 1 shows the connection of out-of-step relays for generator protection.

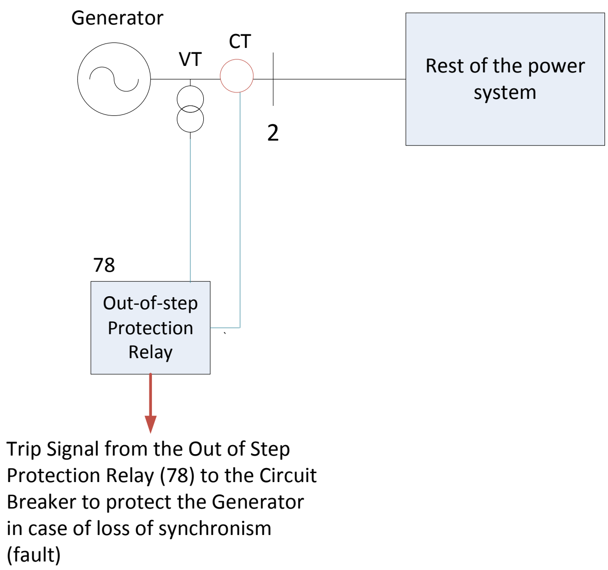
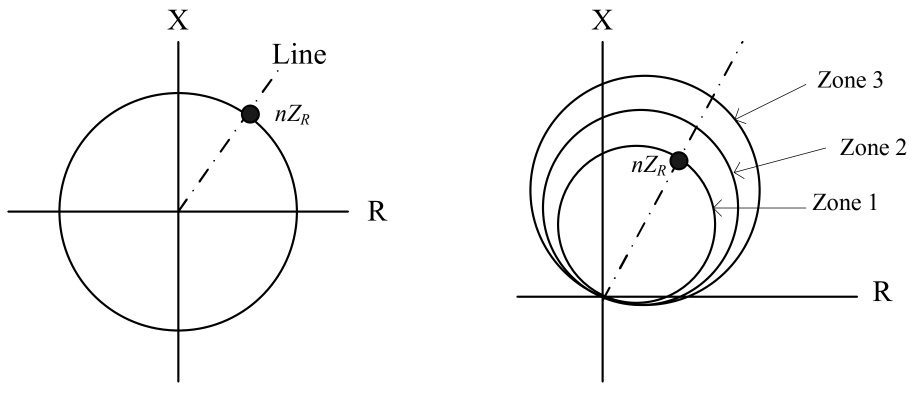


Figure 1: Implementation of out-of-step relays to protect generators

3.2 Line Protection

Transmission lines can be protected by several types of relays, however the most common practice to protect transmission lines is to equip them with distance relays. Distance relays are designed to respond change in current, voltage, and the phase angle between the measured current and voltage. The operation principle relies on the proportionality between the distance to the fault and the impedance seen by the relay. This is done by comparing a relay's apparent impedance to its pre-defined threshold value. Distance relays' characteristics are commonly plotted on the R-X diagram are shown in Fig. 2a whereas Fig. 2b represents the Mho relay which is inherently directional [3]. As an illustration in conjunction with the figure, suppose a fault arose, the voltage at relay will be lower or the current will be greater compared to the values for steady state load condition. Thus, distance relays activate when relay's apparent impedance decreases to any value inside the parametric circle. For this reason, the impedance of the line after the fault can also be used to find the location of the fault.

Like several engineering constructs, a backup is employed for redundancy. A minimum of two zones are necessary for primary protection of distance relays to address the faults at the far end of the protected line section near the adjacent bus. Such a criterion provides a safety factor to ensure that any operation against faults beyond the end of a line will not be triggered by measurement errors. Several protection zones can be built by using separate distance measuring units, which provided redundancy since both distance units



(a) Impedance (b) Mho

Figure 2: Distance relay characteristics

will operate for faults occurring in Zone 1. The key difference between the two redundant units is in the time delay; the unit covering Zone 1 would operate instantaneously whereas the unit designated in Zone 2 would have an added time delay between fault signaling and operation. Also, by modifying either the restraint and/or operating quantities, the relay operating circles can be shifted as shown in Fig. 2b.

In some applications, a further setting (Zone 3) is included, which is greater than Zone 2 setting. For a fault generated in Zone 1, Zone 3's operation occurs after a longer time delay than that associated with the Zone 2. Therefore, the delay acts as a temporal tolerance for the protective schemes within the fault zone. The delayed operation will trigger if the tolerance is exceeded. Hence, this setting provides a form of back up protection. Figure 3 depicts protection zones of distance relays. Typically, Zone 1 is set in range of 85% to 95% of the positive-sequence of protected line impedance. Zone 2 is set to approximately 50% into the adjacent line, and 25% into the next two lines for Zone 3 as described in [4]. The operation time for Zone 1 is instantaneous whereas Zone 2, and Zone 3 are labeled T_2 and T_3, respectively.

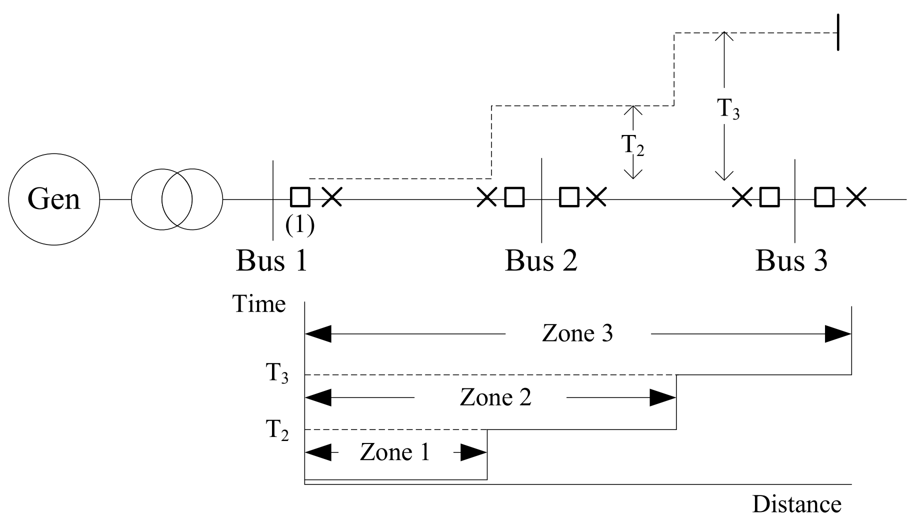


Figure 3: Protection zones of distance relays

Most of today's microprocessor- based relays implement multi-functional protection features. They are considered as a complete protection package in a single unit. In case of line protection via distance protection schemes, microprocessor-based relays also provide over current protection, directional over current protection (for selectivity in case of multiple parallel lines), under/over voltage protection, breaker failure protection (in case the breaker fails to trip even after receiving the trip command), etc [5]. Figure 4 shows the connection of a distance relay for line protection.

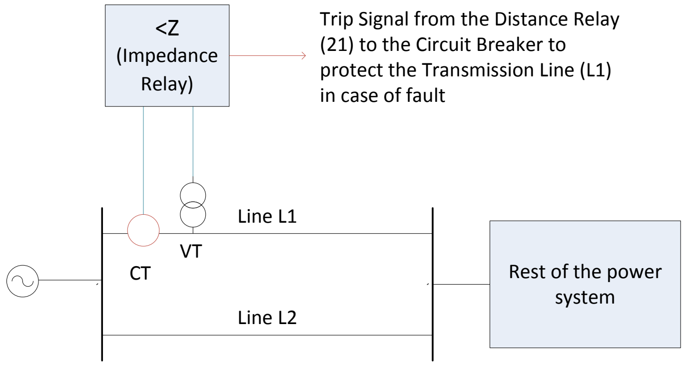


Figure 4: Implementation of a distance relay to protect transmission line L1

3.3 Transformer Protection

Each transformer unit can be protected by a differential relay. The protection principle of this relay is to compare the current inputs at both are high and low voltage sides of the transformer. Under normal conditions or external faults (also keeping into consideration of the transformer's turn ratio), the current entering the protected unit would be approximately equal to that leaving it. In other words, there is no current flow in the relay under ideal conditions unless there is a fault in the protected unit. Moreover, microprocessor-based relays incorporate other protection functions such as thermal overload (which tracks the thermal condition of the windings) and over/under frequency relays. These two relays work with each other because transformer energy losses tend to be raised with frequency increases, therefore thermal overload relays are also equipped to prevent the winding insulation damages [6]. Figure 5 shows the connection of a differential relay for transformer protection.

3.4 Load Protection

Electrical loads are commonly sensitive to the voltage variations which can cause serious load damages when high voltage fluctuations arise. In that case, loads can be protected by using over/under voltage relays. Figure 6 shows the connection of over/under voltage relay for load protection.

Table 1 summarizes all the protection schemes that are designed for the primary power system components discussed above. The table also states the required inputs for the relay to perform each particular protection function and the output parameters from relay in order to generate a trip command.

Table 1: Protection schemes for common system components

Component	Relay Type	ANSI Code	Operating Principle	Input Parameters	Output Parameters
GENERATOR	Out-of-Step Relay	78	Relay tracks the impedance by detecting the variations of the voltage/current. The variations is small during normal conditions however it changes nearly stepwise in the case of fault conditions. This means that the impedance is changed abruptly.	Current and Voltage (V, I)	Impedance $(Z = \frac{V}{I})$
TRANSFORMER	Differential Relay	87	Protects the transformer from internal faults by taking the current inputs from both primary and secondary side of the transformer. The sum of these currents (taking into consideration transformer turns ratio) is zero under normal conditions or external faults but not equal to zero in case of fault conditions	Currents from primary and secondary side $(I_{primary}, I_{secondary})$	Current (I)
TRANSMISSION LINE	Distance Protection	21	A fault in a transmission line will result in the decrease of line impedance which is compared with a pre-defined threshold value. The trip signal will be sent to the breaker if the measured impedance is smaller than the threshold.	Current and Voltage (V, I)	Impedance $(Z = \frac{V}{I})$
	Over-current Protection	50/51	A fault in a transmission line will result in the increase of current passing through the line which is compared with a pre-defined threshold value. The trip signal will be sent to the breaker if the measured current exceeds the threshold.	Current (I)	Current (I)
LOAD	Under/Over Voltage Protection	27/59	A fault at the load bus will vary the terminal voltage. The measured voltage is compared with pre-defined threshold value. The trip signal will be sent to the breaker if it is lower/ greater compare to the threshold.	Voltage (V)	Voltage (V)

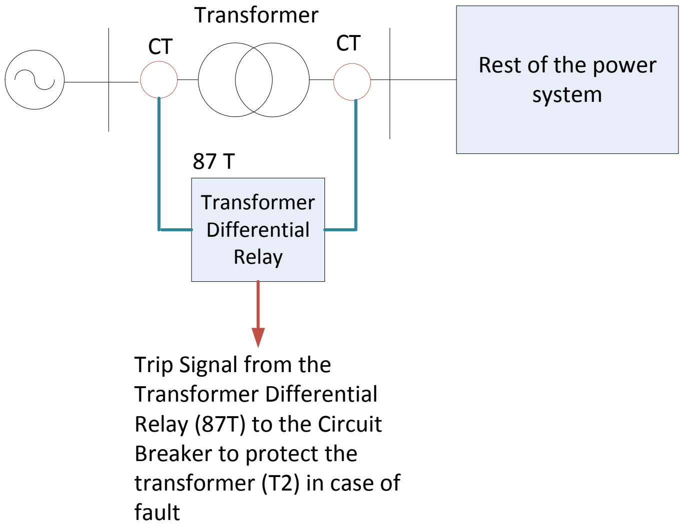


Figure 5: Implementation of differential relay to protect transformer

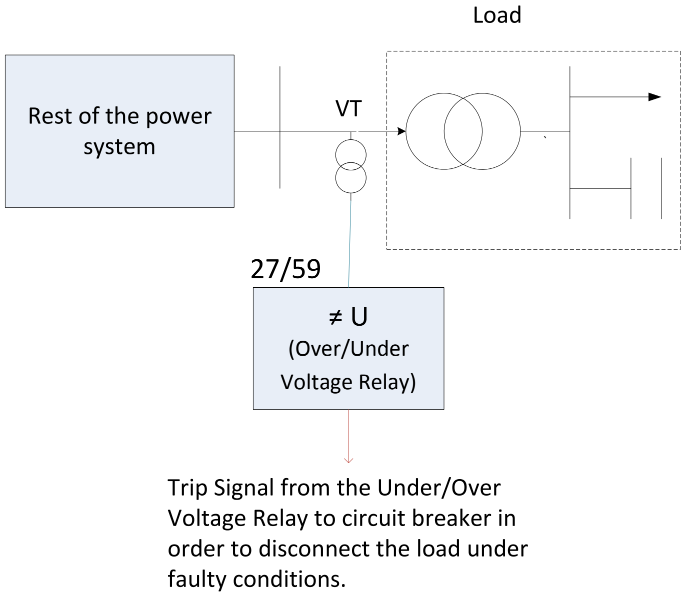


Figure 6: Implementation of an over/under voltage relay for load protection

Table 2-5 summarize the different types of protection for system components such as generator, transformer, transmission line and motor (load). These tables describe the causes and effects of various faults which occur frequently in power systems. Moreover, the necessary protection schemes to protect against such faults are also mentioned.

In addition, the characteristics of relays such as available measurements, operating times and communication protocols, from different vendors are summarized in Table 6. These relays' characteristics are obtained from several manufacture product manuals General Electric (GE) [5, 7–10], Schweitzer Engineering Laboratories (SEL) [2, 11–14], Areva-Alstom [6, 15–18], and ABB [19–23].

Table 2: Generator protective relays

Important Protections for Individual Units					
Units	**Type of Protection**	**ANSI Codes**	**Causes**	**Effect**	**Protection Scheme**
GENERATOR	Protection against overload	49	Increased power on the generator's load side	Stator winding overheating	Thermal image relay (keeping track of temperature) / over current relay
	Protection against unbalanced loads	46	Sudden loss or connection of heavy loads, or poor distribution of loads	Generator's full capacity cannot be utilized, rise of negative sequence components (rotation in reverse direction) leading to heavy currents in the rotor	Negative sequence over current relay (unsymmetrical loads would give rise to negative sequence components)
	Protection against reverse power conditions	32	Parallel operation of a generator with other units may force motor behavior (due to load unbalance or poor load sharing between generators)	Generator behaves as motor and draws power from the network, turbine connected to generator will be damaged due to winding overheating	Directional power relay with reverse power setting option
	Out-of-Step protection	78	Loss of synchronism due to line switching, connection/disconnection of heavy loads, electrical faults, etc	Winding stress, high rotor iron currents, pulsating torques, mechanical resonances	Out of step protection relay which tracks the impedance calculated from measured voltage and current. In case of fault; there is nearly a step change in voltage/current
	Protection against frequency variations	81	Improper speed control, grid disturbance or sudden load cut off	Severe speed changes will cause over fluxing , serious damage to the turbine generator set	Frequency protection relay which tracks frequency and trips the breaker in case of abnormal frequencies
	Protection against under/over voltages	27/59	System disturbance or malfunctioning AVR	Over fluxing and winding insulation failure	Over/Under voltage relay with pre-set voltage limits defined in the settings
	Protection against internal faults (differential protection)	87	Internal faults (phase to phase and 3 phase to ground faults)	Gives Rise to Large amount of currents that can damage the winding	Differential protection with CTs on each side of generator (Unit Protection)
	Stator Earth Fault protection	64	Winding insulation failure, inter-turn fault	Thermal and magnetic imbalance and damage to rotor metallic parts	Isolated neutral and earth where voltage relay detect earth fault
	Loss of Field protection	40	Loss of exciter source, open or short circuit at the field winding	Loss of synchronism between the rotor and stator fluxes, draws reactive power from the grid and provokes severe torque oscillations	Impedance relay is used to implement this technique
	Rotor Earth Fault protection	61F	Winding insulation failure, inter-turn fault	Thermal and magnetic imbalance and damage to rotor metallic parts	Voltage relay energized by neutral VT (depends on type of neutral connection)
	Synchro Check	25	Verification whether synchronism exists or not, e.g. when paralleling of generator etc.	Checks that the electrically interconnected parts are synchronized or not	Synchrocheck relay that measures magnitude, phase angle and frequency difference of voltages on both sides of the breaker

Table 3: Transmission line protective relays

Important Protections for Individual Units					
Units	**Type of Protection**	**ANSI Codes**	**Causes**	**Effect**	**Protection Scheme**
TRANSMISSION LINE	Distance protection (Phase & Ground)	21	Reduction in overall line impedance (V/I) due to fault conditions	Fault current can overheat the transmission line and can cause damage to the conductor	Distance protection relay serves as a primary protection for transmission lines. It keeps track of the line impedance and sends trip signal to the breaker if the line impedance changes (due to fault)
	Over voltage protection	59	Lightning, switching, temporary over voltage	Give rise to transient over-voltages which can damage the insulation	Surge Arrestors/ Over-voltage relay with preset voltage limits defined in settings
	Power Swing Blocking	68	Line switching, generator disconnection, addition/loss of load	Loss of synchronism between a generator and the rest of the system as seen by the measured voltages, phase sequence, phase angles, frequencies resulting in swing in power flows	A blocking relay provides this protection and has the same type of characteristic as a distance relay
	Over-current protection (Phase & Ground)	50/51	Due to short circuit, single phase to ground or phase to phase faults. Can occur due to tree limbs falling on lines, etc	Gives rise to heavy current that flows through the winding conductor and causing overheating of the conductor which will deteriorate it	An over current protection relay which also serves as a back up for distance protection is used. In case the distance protection (primary protection) malfunctions, over-current protection will send trip commands
	Earth Fault protection	50N/51N	Direct connection to ground of one or more phases	Gives rise to higher voltages on other lines and stresses the insulation of cables and other equipment connected to the system	Over-current relay that continuously monitors the current through the neutral and sends trip signals to the breaker upon fault detection

Table 4: Transformer protective relays

Important Protections for Individual Units					
Units	**Type of Protection**	**ANSI Codes**	**Causes**	**Effect**	**Protection Scheme**
TRANSFORMER	Protection against overload	58	Increased power on secondary side of transformer	Transformer Overheating	Thermal image relay (keeping track of temperature) / over current relay
	Over-current protection	50/51	Phase and ground faults	Over current can cause damage to windings	Over-current relays
	Earth Fault protection (Stator & Rotor)	50N/51N	Poor insulation, direct connection to earth	Causes current imbalances in the system	Over-current relays with neutral module
	Differential protection	87	Internal faults within the protected zone	Internal faults can be short circuits, or earth faults, or overloading which can cause damage to transformer windings	Differential protection with CTs on each side of transformer (Unit Protection)
	Directional protection (Phase and Neutral)	67/67N	Fault in nearby (parallel) feeder/bay causing tripping in the healthier feeder/bay due to poor selectivity of the relay	Tripping of additional feeders, thus pushing the system towards larger outages	Directional Over-current relay detects the direction of current flows in to and flow out from the protected unit. A trip signal will be sent to breakers if direction of flow-in and flow-out current are not the same
	Breaker Failure protection	50 BF	Breaker malfunctioning	Unable to isolate faulty equipment due to tripping failures (longer existence of fault currents, thus more damage to equipment)	Breaker failure relay which operates with its algorithm to try to open the breaker, otherwise it sends trip command to nearby breakers to isolate the faulted equipment to stop feeding fault currents

Table 5: Motor (Load) protective relays

Important Protections for Individual Units					
Units	**Type of Protection**	**ANSI Codes**	**Causes**	**Effect**	**Protection Scheme**
MOTOR (LOAD)	Protection against overload	49	Increase of load torque, or decrease in the motor torque due to busbar voltage or decrease in DC Field current (Synchronous motors)	High currents drawn by the motor affects insulation, and thus reduces the machines life expectancy	Thermal image relay (keeping track of temperature and has a thermal time constant) / over-current relay
	Short circuit	50/51	Phase to phase short circuit in the winding , at the motor terminals or between cables	Destroy the machine due to over-heating and electro-dynamic forces created by the high currents	Over-current relay with a preset value which sends a trip signal if the current exceeds its preset value
	Earth fault protection	50N/51N	Machine insulation damage	Results in a fault current that flows from windings to earth via stator laminations	Over-current relays with neutral module
	Number of starts supervision	66	If the operator (or by automatic function) tries to switch on the motor more than an specific number of times within a specific time-interval	The thermal state of the machine changes when a number of starts occur. Adequate cooling of machine is required before the machine is given another start, otherwise the life expectancy of the machine will decrease due to insulation deterioration	Notching or jogging relay that uses a counter to control the number of starts within a certain time. They take into account the machine thermal state and do not allow any further starts if the machine has already attained specific starts within a specific time
	Under voltage protection	27	System disturbance or load increase	Under voltage results in over-currents which can damage insulation	Under voltage relay with pre-defined voltage limits defined in the relay's settings
	Loss of synchronism (synchronous machines only)	55	Increase in load causes a decrease in the busbar voltage, or due to decrease in the field current that causes the motor torque to decrease	Damage occurs to the dampers and rotor windings due to loss of synchronism	Power factor relay that responds to the change in power factor that occurs when there is pole slipping (weakening of synchronizing torque to maintain synchronism under the same load)
	Protection against unbalanced loads	46	Sudden loss or connection of heavy loads or poor distribution of loads	Gives rise to negative sequence components (tries to rotate rotor in reverse direction) causing heavy currents in the rotor causing damages	Negative sequence over current relay (unsymmetrical loads will give rise to negative sequence components)

Table 6: Comparison of Relay Characteristics between different vendors

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

Comparison of Relay Characteristics between Different Vendors

Characteristic	Protection Relay	Vendors			
		GE	**ABB**	**SEL**	**ALSTOM**
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 2.5s each
Operation Time	Generator Protection	5 to 30 ms	About 15 ms	< 20 ms	<30 ms
	Differential Protection		< 35 ms		< 33 ms
	Over-current Protection	20 to 30ms	< 30 ms	<25 ms	<30 ms
	Distance Protection	10 to 30 ms	< 30 ms	<30 ms	17 to 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				

Comparison of Relay Characteristics From Different Vendors					
Characteristic	**Protection Relay**	**Vendors**			
		GE	**ABB**	**SEL**	**ALSTOM**
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	Volts per hertz; 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; Volts/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; Volts/Hz; over/under frequency	Over/under frequency; trip circuit supervision; rate of change of frequency

<table>
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<tr><th rowspan="2">Characteristic</th><th rowspan="2">Protection Relay</th><th colspan="4">Vendors</th></tr>
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<tr><td rowspan="5">Communication Method</td><td>Generator Protection</td><td rowspan="3">RS232; RS485; IEC 61850; ModBus TCP/IP; DNP 3.0; IEC 60870-5-104</td><td rowspan="2">RS232; RS485; IEC 61850-8-1; IEC 60870-5-103; LON; SPA; DNP 3.0; ModBus RTU/ASCII</td><td rowspan="4">SEL; ModBus TCP/IP; DNP; FTP; IEC 61850; MIRROR BITS; EVMSG; C37.118 (synchrophasors)</td><td rowspan="5">RS232; RS485; Courier/K-BUS ModBus; IEC 60870-5-103; DNP 3.0; IEC 61850</td></tr>
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<tr><td>Distance Protection</td><td>RS232; RS485; DNP 3.0; ModBus RTU/ASCII</td></tr>
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3.5 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 follow.

- **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 IEDs 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 IEDs 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) [24]. 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 6), but this software is not available for the REG 670 relay [25]. 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 [26] 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 by 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.

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

4 Communications in power system protection

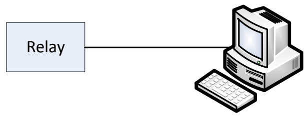
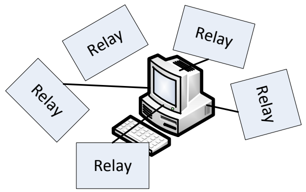
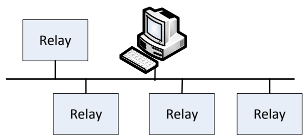
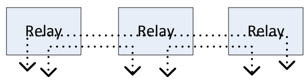
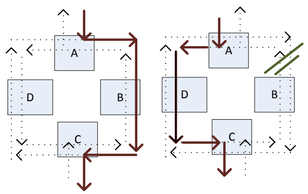
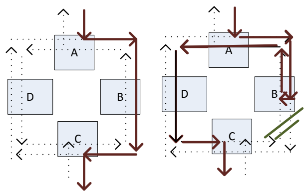
A communication system consists of a transmitter, a receiver and communication channels. Type of medias and network topologies in communications provide different opportunities to advance the speed, security, dependability, and sensitivity of protection relays. There are a few types of communication media such as micro wave, radio system, fiber optic, etc. The advantages and disadvantages in communication medias which are currently in operation (both analog and digital) and different network topologies are summarized in Table 7 and Table 8 [27], respectively.

Table 7: Comparison of Communication Medias

Media	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[3] in order of 250 ms rule out most protective relay applications [28].
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

[3]transmitting back and forth the signal 36,000 km between the earth and the satellite

Table 8: 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 case of 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.

Description of Different 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 6. 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.

4.1 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. Figure 7 shows the RS232 protocol configuration.

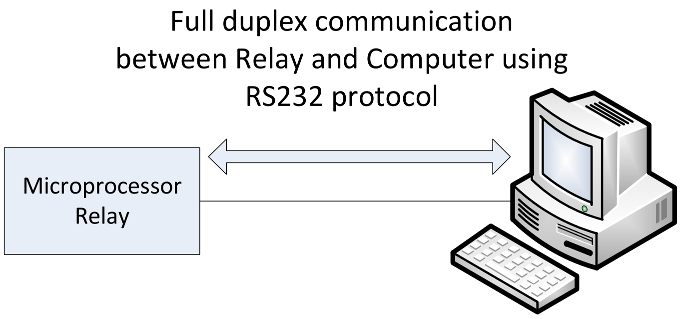


Figure 7: RS232 Protocol configuration

- **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”. Figure 8 and 9 show a simple RS485 protocol configuration in the unicast and the broadcast mode, respectively.

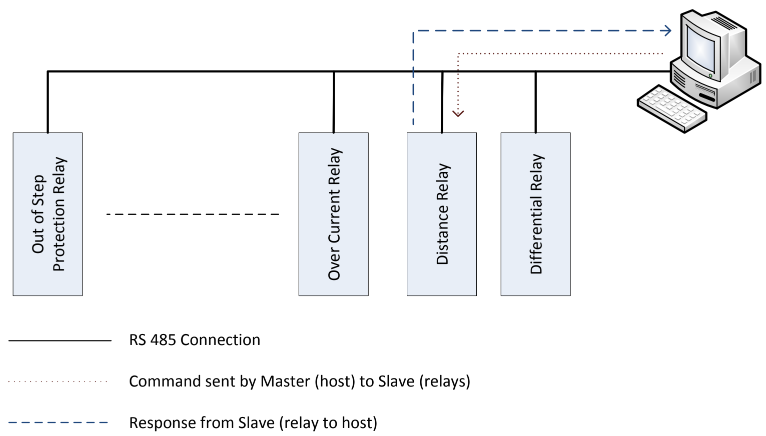


Figure 8: RS485 Protocol configuration: Unicast mode

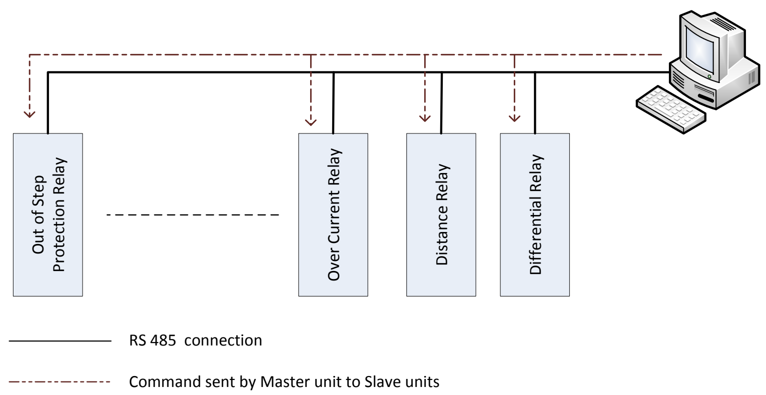


Figure 9: RS485 Protocol configuration: Broadcast mode

4.2 Layered Based-protocols

Other protocols mentioned in Table 6 are developed by the Open Systems Interconnection (OSI) model [29]. 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. Figure 10 demonstrates data communication using OSI model where "H" represents "headers". Table 9 describes function of each layer.

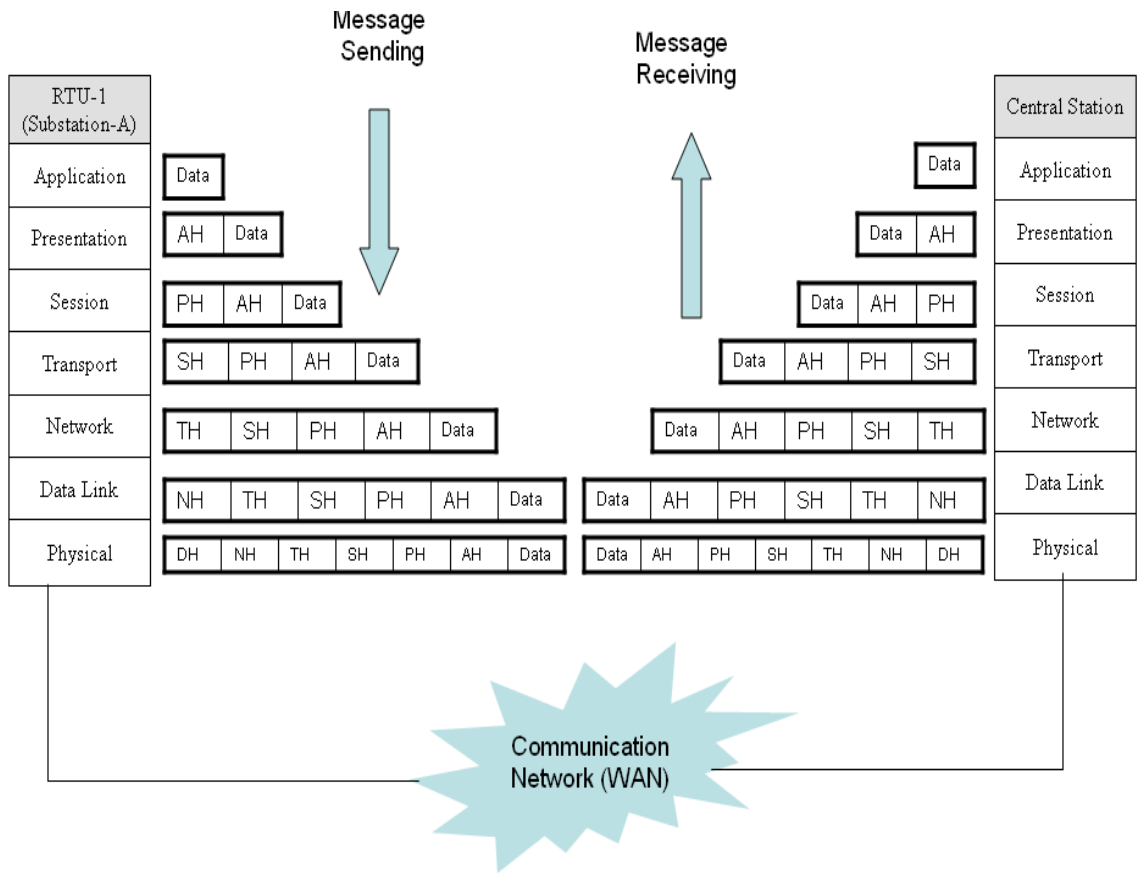


Figure 10: OSI model

Table 9: Functions of OSI model

Layers	Function
Application (**A**)	Offers direct interaction of user with the software application. Adds an application header to the data which defines which type of application has been requested. This forms an application data unit. There are several standards for this layer e.g. HTTP, FTP, etc.
Presentation (**P**)	Handles format conversion to common representation data and compresses and decompresses the data received and sent over the network. It adds a presentation header to the application data unit having information about the format of data and the encryption used.
Session (**S**)	Establishes a dialogue and logical connection with the end user and provides functions like fault handling and crash recovery. It adds a session header to the presentation data unit and forms a session data unit.
Transport (**T**)	Manages the packet to the destination and divides a larger amount of data into smaller packages. There are two transport protocols, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), in this layer. Reliability and speed are the primary difference between these two protocols. TCP establishes connections between two hosts on the network through packages which are determined by the IP address and port number. TCP keeps track of the packages delivery order and check of those that must be resent. Maintaining this information for each connection makes TCP a stateful protocol. On the other hand, UDP provides a low overhead transmission service, but with less error checking.
Network (**N**)	Controls the routing and addressing of the packages between the networks and conveys the packet through the shortest and fastest route in the network. Adds a network header to the Transport Data Unit which includes the Network Address.
Data Link (**D**)	Specifies Physical Address (MAC Address) and provides functions like error detection, resending etc. This layer adds a Data Link Header to the Network Data Unit which includes the Physical Address. This makes a data link data unit
Physical	Determines electrical, mechanical, functional and procedural properties of the physical medium.

Some of protocols, mentioned in Table 6, that are derived from OSI model are described below:

- **DNP 3.0** [30]

  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 (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 milliseconds [31].

- **ModBus** [32]

  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 accuracy in the 100 microsecond range [33] 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 hands, GPS provides higher accuracy (in the range of 1 microsecond [33]) 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 milliseconds [31].

  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 one second 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. Figure. 11 shows the Protocol Data Unit (PDU) for ASCII and RTU frame formats.

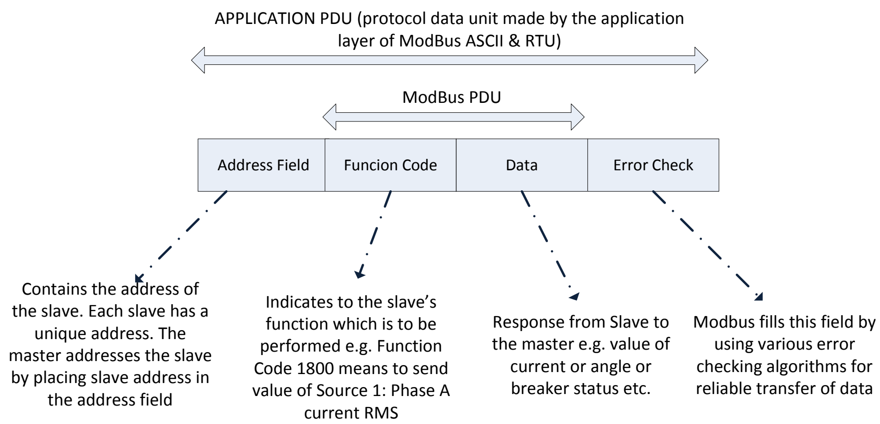


Figure 11: ModBus ASCII & RTU Protocol Data Unit (PDU)

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. Figure. 12 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 [34].

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 [35]. In addition, the ModBus protocol is a prototype for proprietary protocols such as **K-BUS** [36] and **SPA** [37] protocols which are of Areva-Alstom and ABB, respectively.

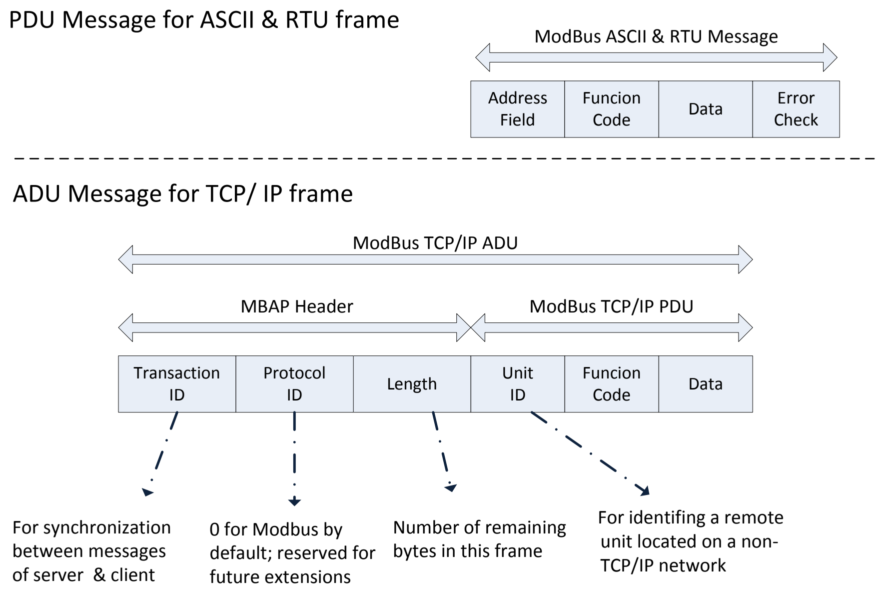


Figure 12: Message frame comparison between ModBus PDU and ADU

- **IEC 61850** [32]

  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 milliseconds [31]. 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 [38] and [39].

- **LON** [40]

  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.

4.3 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 media. 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 PC via an Ethernet port. The propagation delays associated with the communication is dependent on the media and physical distance while the delay associated with transducers used, DFT processing, data concentration, and multiplexing are fixed. The associated delays for various communication medias when using PMUs are summarized in Table 10 [41].

Table 10: Associated Delays with Various Communication Medias

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

However, the time duration of different delays has been an ambiguous issue on the communication timing. Reference [41] 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 [42] (see Table 11) and it is doubtfully cited in certain number of publications as in [43–45]. 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.

Table 11: Time estimates for steps in wide area protection [43]

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

5 Summary

A literature survey on protective devices has been presented in this report. The survey includes all capabilities available from the different relay types of 4 of the most dominant vendors in the market. It also include information about relay measurements, 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, the comparison between different communication protocols which considering various architecture aspects and configuration are presented. The objective is to provide general information of each protocol. Protocol selection depends mainly on application-specific requirements and functions to be carried out. In addition, the medias' advantages and disadvantages (shown in Table 7) and communication delay (shown in Table 10) have to be weighed and chosen based on the required control dynamics and operating economics of the power system. Finally, we highlight that there are contradictory statements establishing 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 WAMS, WACS and WAPS. Experimental studies are necessary to clarify these contradictions.

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