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Integration testing of protection relays

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BACHELOR'S THESIS

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Abstract

This Bachelor's thesis has been made for the research and development department at ABB Oy, Distribution Automation. The purpose of Distribution Automation products is to improve the safety, the reliability and the performance of the power distribution process. This sets high demands on product testing and verification. Integration testing is a part of the test process aimed at exposing the problems that arise from the combination of modules.

The aim of this thesis work was to investigate the possibility to use SATEEN in the integration testing of protection relays. SATEEN stands for Substation Automation TEsting ENvironment and is originally designed for automated test execution in system-level testing. SATEEN is developed by ABB and only meant for internal use. Therefore there will be two versions of this Bachelor's thesis, one for internal use only and one official version. The official version contains only theoretical information about substation automation including protection relays and product development.

This Bachelor's thesis resulted in a set of test cases that can be used for both integration and regression testing. Information about these test cases and the system under test will be presented only in the internal version of this Bachelor's thesis.

Language: English	Key words: testing, integration testing, IEC 61850

The official version of this Bachelor's thesis is filed at the web library Theseus.fi.

EXAMENSARBETE

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Titel: *Integrationstestning av skyddsreläer*

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Abstrakt

Detta ingenjörsarbete har utarbetats för forsknings- och utvecklingsavdelningen inom ABB Oy, Distribution Automation. Syftet med deras produkter är att förbättra säkerheten, tillförlitligheten och prestandan i eldistributionsprocessen. Detta ställer höga krav på testning och verifiering. Integrationstestning är den del av testprocessen som är till för att exponera de problem som uppkommer vid kombineringen av moduler.

Syftet med detta ingenjörsarbete var att undersöka möjligheten att använda SATEEN i integrationstestandet av reläskydd. SATEEN står för Substation Automation TEsting ENvironment och är ursprungligen utvecklat för automatiska testsekvenser för testning på systemnivå. SATEEN är utvecklat av ABB och är endast ämnat för internt bruk. Därför finns det två versioner av detta ingenjörsarbete, en för internt bruk och en officiell version. Den officiella versionen innehåller endast teoretisk information om stationsautomation inklusive skyddsreläer och produktutveckling.

Detta examensarbete resulterade i en uppsättning av tester som kan användas både vid integrations- och regressionstestning. Information om dessa tester och testsystemet finns med i endast den version av examensarbetet som är ämnad för internt bruk.

Språk: engelska Nyckelord: testning, integrationstestning, IEC 61850

Förvaras: Den officiella versionen av examensarbetet finns tillgängligt i webbiblioteket Theseus.fi.

OPINNÄYTETYÖ

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Tiivistelmä

Tämä opinnäytetyö on tehty ABB Oy, Sähkönjakeluautomaation tutkimus- ja tuotekehitysosastolle. Sähkönjakeluautomaatiotuotteiden tarkoitus on parantaa sähkönjakeluprosessin turvallisuutta, luotettavuutta ja suorituskykyä. Tämä asettaa suuria vaatimuksia tuotteiden testaukselle ja verifioinnille. Integraatiotestaus on osa testiprosessia ja sen tarkoitus on paljastaa ongelmat, jotka syntyvät eri moduuleita yhdistettäessä.

Opinnäytetyön tavoitteena oli tutkia mahdollisuutta käyttää SATEENia suojareleiden integraatiotestauksessa. SATEEN koostuu sanoista Substation Automation TEsting ENvironment ja on alun perin suunniteltu automaattisten testisekvenssien suorittamiseen järjestelmätason testauksessa. SATEEN on ABB:n kehittämä ja on tarkoitettu ainoastaan sisäiseen käyttöön. Tästä johtuen löytyy kaksi versiota opinnäytetyöstä, yksi ainoastaan sisäiseen käyttöön ja yksi virallinen versio. Virallinen versio sisältää vain teoreettista tietoa sähköasema-automaatiosta, mukaan lukien suojareleet ja tuotekehitys.

Tämän opinnäytetyön tuloksena on sarja testejä, joita voidaan käyttää sekä integraatio- että regressiotestauksessa. Tietoa näistä testeistä ja testiympäristöstä esitellään ainoastaan opinnäytetyön sisäisessä versiossa.

Kieli: englanti Asiasanat: testaus, integraatiotestaus, IEC 61850

Arkistoidaan: Opinnäytetyön virallinen version on saatavilla ammattikorkeakoulujen verkkokirjastossa Theseus.fi.

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LIST OF TERMS AND DEFINITIONS

AI	Analog Input
AIM	Analog Input Module
BI	Binary Input
BO	Binary Output
CID	Configured IED Description (IEC 61850 XML file)
ConnPack	Connectivity Package
FB	Function Block
HMI	Human Machine Interface
HSI	Human System Interface
HW	Hardware
I/O	Input/Output
IEC	International Electrotechnical Committee
IEC 61850	Standard for communication in substations
IED	Intelligent Electrical Device
LN	Logical Node
MicroSCADA	Software for process control and monitoring
MMS	Manufacturing Messaging Specification
OLE	Object Linking and Embedding
OPC	OLE for Process Control
PCM600, PCM	ABB’s Protection and Control IED Manager
PLC	Programmable Logic Controller
PVC	Product Verification Center
SATEEN	Substation Automation TEsting ENvironment
SCADA	Supervisory Control And Data Acquisition
SCD	Substation Configuration Description (IEC 61850 XML file)
SCL	Substation Configuration Language (IEC 61850 XML file)
SG	Setting Group

SNTP	Simple Network Time Protocol
SUT	System Under Test
SW	Software
SYS 600	Process control and monitoring product
Tiger	Common IED Platform project
UTC	Coordinated Universal Time
WHMI	Web HMI
XML	eXtensible Markup Language

1 Introduction

What would the world of today look like without electricity? People use electricity every day and take it for granted that electricity is constantly available. It is actually the reliable electricity process that has made people require that there has to be electricity all the time without any interruptions. Since the consumption of electricity is constantly increasing, it sets higher demands on the power distribution process. As a result new products for power distribution must be developed all the time. A common feature for these products is that they must be constantly reliable throughout their life cycle. To achieve this requirement, heavy demands are set on testing and verifying these products.

1.1 Background

The client of my Bachelor's thesis work develops and produces protective relays for power distribution processes. The testing and verification of these products is a very important part of the development process. The integration testing has been one of the bottlenecks in the testing process. A couple of years ago the work began by trying to improve and speed up the integration testing. During this effort a test system for automated testing was built. The idea of this test system was to speed up the integration testing by using a software tool to automatically execute some of the tests. Due to lack of resources this test system hasn't been used that much and no scripts for automated test execution have been made. This resulted in the fact that all integration testing is still done more or less manually. /5/

1.2 Approach

The task to automate some parts of the integration testing can be solved in different ways. There are many software tools that help the test engineer to speed up the testing. However, this thesis will focus on investigating the possibility to use the software tool SATEEN for this purpose. To use SATEEN in integration testing, a system under test must be built up. The same test system that was built earlier will be used. All necessary modifications of the test system will be documented, i.e. every connection diagram will be updated. The test environment consists of a workstation with the necessary software, a PLC for I/O simulation, some kind of analog simulator, and other peripheral equipment such as network switches.

It makes no sense trying to automate all the tests. It is too time-consuming to try to automate complicated test cases. These complicated tests are much easier to execute manually. Therefore the first thing to do is to investigate what tests are suitable to be automated. These automated tests should be as comprehensive as possible. Everything from simply functionality tests, such as I/O tests, to more complicated tests like event reporting for a FB, should be tested. As communication protocol the IEC 61850-8-1 standard is used. These test cases can be expanded in the future so that IED's other communication protocols can also be used in the tests.

In normal cases all events are reported from the IED to a SCADA system. In these test cases SCADA will be left out and all test actions will be verified by events in the IEC 61850 OPC server. This keeps the system under test as simple as possible. It increases the chances of getting as automated and autonomous a test system as possible./10/

It is also important how the test result is presented. A good test report includes, besides the test result, information about when the test was started and finished and information about the tested object. This can be solved by dividing the test report into different sections. At the end of the report there is a short summary of the test result. In the middle of the test report there is detailed information about the test proceeding and result. Information about the test case and the tested object is presented at the beginning of the test report. This is a good way to get a well planned test report which is also easy to read.

1.3 ABB

ABB is a global leader in power and automation technologies. ABB was founded when ASEA AB of Sweden and BBC Brown Boveri LTD of Switzerland merged in August 1987. After this merger, ABB became one of the leading power technology companies in the world. Nowadays the ABB Group operates in around 100 countries and employs about 117 000 people. /3/

The business idea of ABB Oy, Distribution Automation is to develop, manufacture, market and deliver innovative protection and automation products for the distribution of electrical power. The aim is to make power distribution easier and more reliable even in the most demanding environments. Electrical utilities, power process industries and offshore operators are the end-users of the products. The turnover in 2009 was 83 MEUR for ABB Oy Distribution Automation and over 90 % of the products were exported. /8/

2 Distribution Automation

Electricity is delivered to the customers through generation, transmission and distribution systems. Reliable electric power systems serve customers with electricity without interruptions. Every functionality zone must fulfill its duties, generation facilities must produce enough power to meet the customer demand, transmission systems must transmit power over long distances without overheating, and distribution systems must deliver electricity to each customer. Figure 1 illustrates the process from power generation to distribution.

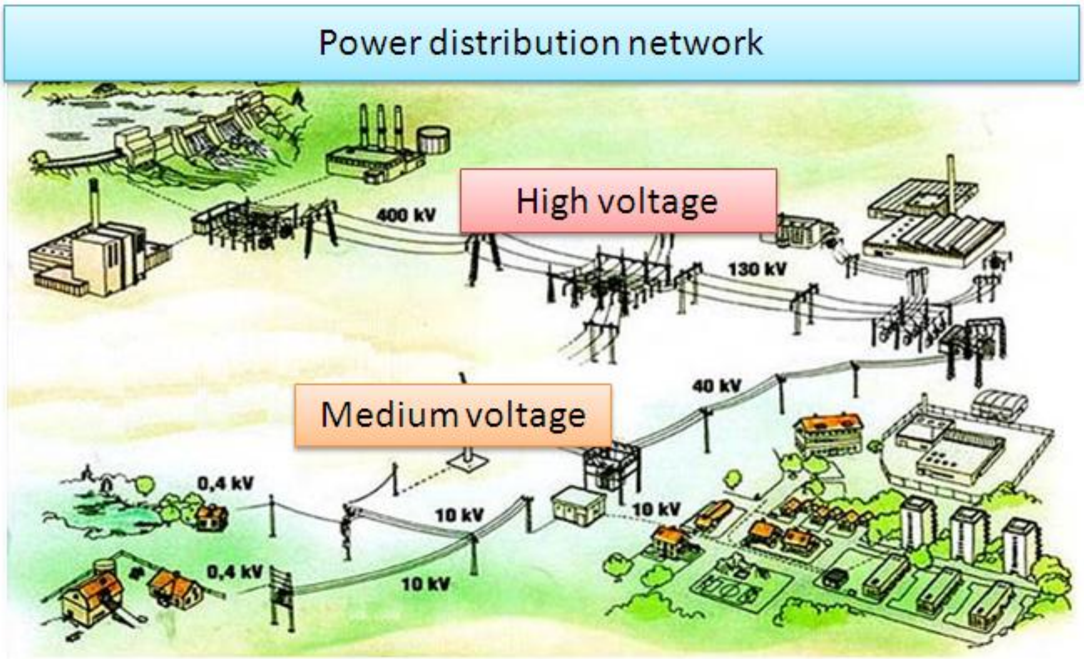

Figure 1. Electric power system /9/

Distribution systems begin with a distribution substation, where the voltage is stepped down to distribution levels. In the substation, the transmission line is connected to a disconnect switch, which is capable to visibly isolate the substation from the transmission line. The disconnect switch is designed to manually isolate the substation. Therefore it can't disconnect when the power is on in the substation line. The line is routed from the disconnect switch across transformers to a circuit breaker. The line between the disconnect switch and the circuit breaker is called busbar. Circuit breakers are used to interrupt any short circuits or overload that may occur on the distribution line. A circuit breaker must therefore be able to interrupt the circuit without letting the arc destroy any equipment. An arc is generated every time a live circuit is interrupted. There are different techniques to extinguish the arc. Vacuum and insulating gas are used to control the arc which is generated in the circuit breaker./10/

The circuit breaker itself can’t make any decisions when to interrupt the circuit. It is therefore connected to a protective relay. It is the protective relay that continuously measures and monitors the circuit. When an error occurs, the protective relay gives a signal to the circuit breaker, which in turn interrupts the circuit immediately. To get as quick a communication as possible between the circuit breaker and the protective relay, these are physically connected to each other by wires. The control between them is made with digital inputs and outputs.

For controlling and monitoring of substation real-time parameters, the SCADA system is commonly used. In this case a SCADA system consists of a HMI for presenting real-time parameters to the operator, a supervisory system for data acquiring, and other necessary equipment. This system is able to connect to the protective relay, both to get information (events) and to control the process. SCADA systems are widely used in power distribution processes because they can control real-time parameters via event, alarm and warning lists. This is the optimal way for a human to control and monitor not only the substation but also the entire power distribution process. /10/

These days a great effort is taken to automate and modernize substations all over the world. Some of the driving forces to increase and develop substation automation are the following:

- Reduced costs
- Improved efficiency
- Improved reliability

All these values improve the mission of the power distribution process, to serve the customer with electricity without any interruptions.

Figure 2 illustrates a feeder process. The protection relay operates and monitors the feeder application. It has access to the position indication for the circuit breaker, the disconnect switch and the earth switch. The protection relay can also give open and close commands to the circuit breaker. To make it possible for a human to monitor the entire distribution process, all protection relays are connected to a SCADA system. The connection between a SCADA system and a protection relay can be done with an IEC 61850 OPC server. With all parameters from the distribution process, the human can monitor the entire process.

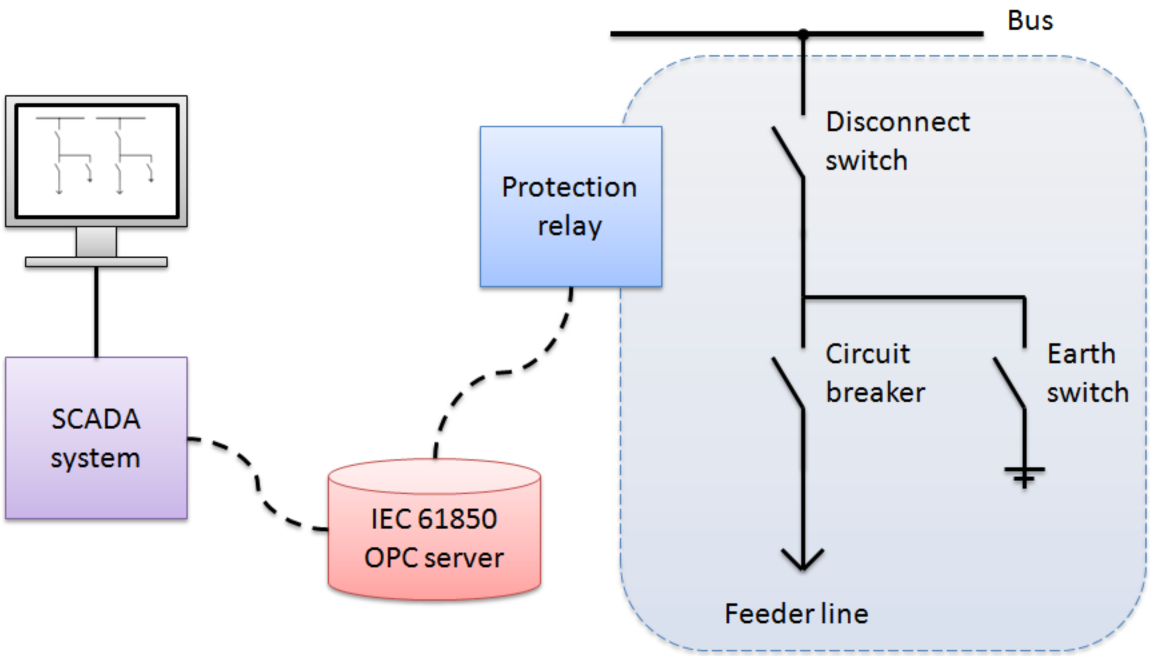

Figure 2. Substation Automation process for a feeder application

2.1 Protection relay

Substations and their powered grids must be protected from potential failure with sufficient protection facilities. For that purpose protective relays are used. The protection relay itself doesn't remove error possibilities, but it will reduce the damage caused by an error to a fraction of the damage occurred in an unprotected site. A properly designed and installed protection relay also has the advantage that only the failed grid will be separated from the net, in other words the functionality of the protection relay is selective. /26/

To minimize the damage when problems occur in the power system, protection relays focus on three main aspects: reliability, selectivity and speed of operation. Reliability ensures that the protection performs correctly in all kinds of situations. Selectivity means, as said before, that a minimal part of the system disconnects when the error occurs. Speed of operation, one of the most important features, minimizes the fault duration which in turn minimizes the damage of the power system. /13/

Protection relays can be divided into three different categories depending on the design. These categories are:

- Electromechanical relay
- Electronic relay (static relay)
- Microprocessor based relay

Originally all protection relays were of the electromechanical type. Electronic relays of the analog type, using discrete electric components, were introduced in the 1970s. The newest type of relay is the microprocessor based relay. This type of relay has been applied at an increasing rate, but it will take time before all electromechanical relays are replaced. There are many reasons why microprocessor based relays are so popular. Higher accuracy, reduced space, lower equipment and installation costs, wider application and setting capabilities are just some of the reasons. This thesis will deal only with microprocessor based relays. /13/

The basic architecture of a microprocessor based protection relay is presented in Figure 3. Analog measurements are connected to transformers that reduce the power system current and voltage quantities to low voltage. Filters, multiplexer and an analog-to-digital converter process the analog signal to a suitable digital signal for the microprocessor unit. The microprocessor unit is equipped with appropriate software to provide the required protection characteristics. The HMI module provides the possibility for the operator to locally parameterize and monitor the protection relay. All communication to other devices in the substation is done by the communication module. The digital input/output module supplies the microprocessor unit with the digital input values and also forwards commands like tripping, closing and alarms. /13/

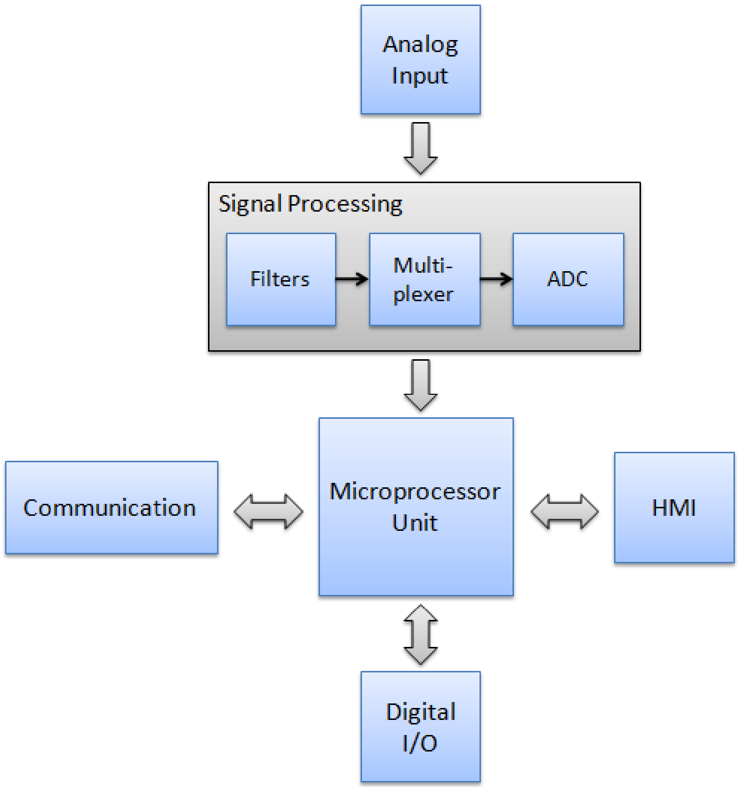

Figure 3. Basic architecture of the microprocessor based protection relay /24/

In addition to these modules, the protection relay also includes timers and the power supply module. The equipment of the protection relay differs depending on the configuration, while the modules presented in Figure 3 are included in all protection relays.

As low-energy devices the protection relays are not able to open and isolate the problem area. The protection relay gives a signal to circuit breakers and various types of circuit interrupters to isolate the problem area. Figure 4 illustrates a typical single-line connection of a protection relay in a feeder application. In this case the current transformer continuously measures the current in the feeder line. The current transformer is connected to the protection relay's analog inputs. When the current exceeds a specified limit, the protection relay gives a trip signal to the circuit breaker that opens the circuit. The trip signal is delivered from the protection relay with digital outputs. This protection is called overcurrent protection. In some situations the usage of voltage transformers is also necessary. A typical microprocessor based protection relay includes several types of protection functionalities.

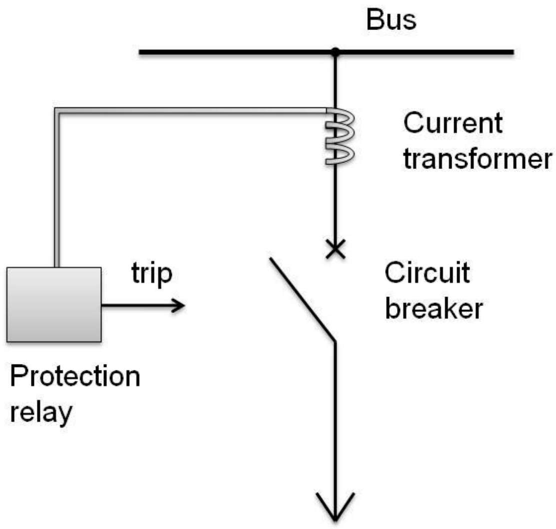

Figure 4. Single-line connection of a protection relay /13/

Some protection relays are also equipped with an arc-fault protection functionality. An arc is generated every time a live circuit is interrupted. This arc can cause significant material damages and long stoppages. The mission of the arc-fault protection is to extinguish the arc before any material damages are caused. This is why the arc-fault protection needs to be quick, to react before the arc has caused material damages. A protection relay with arc-fault protection uses light sensing inputs, which are connected to fiber optics placed strategically around the substation in order to detect the arc. /2/

The microprocessor based relay has the ability to record and display event reports. Event reports are a stored record of what the relay recorded and how it responded during a system fault or another type of event. This feature has provided the protection engineers with a powerful tool for analyzing the nature of power system disturbances and the performance of the protection system. One of the most crucial parts in the event report is the time stamp. To be reliable, the protection relay needs exactly the same time value as the surrounding system. Therefore the time synchronization of the protection relay is an important functionality. /13/

For a surrounding system like the SCADA system, the positioning of a switching device is crucial. Based on this information the operator can decide whether the circuit is interrupted and it is safe to perform maintenance on the circuit. Digital inputs of the protection relay are connected to sensors on the switching device to detect the position. With values of these inputs the protection relay can report the following positions: open, close, intermediate and faulty. These positions are reported for the circuit breaker, the disconnect switch and the earth switch.

The circuit breaker can be manually opened and closed, either locally from the local HMI or remotely from a SCADA system. For safety issues there needs to be a switch that determines from where the CB can be manually controlled. This local/remote switch is a part of the protection relay. In local mode only local operation is allowed and in remote mode only remote operation is allowed.

The word IED is widely used for the protection relay and from now on in this thesis IED refers to the microprocessor based protection relay.

2.1.1 615 series

ABB’s 615 series protection relay is a compact IED for utility distribution and industrial applications. The 615 series supports the IEC 61850 standard and offers also the DNP3 protocol, the IEC 60870-5-103 protocol and the industry standard MODBUS protocol. GOOSE messaging is available for IEC 61850 communication. The 615 series offers several configurations, line differential protection (RED615), feeder protection (REF615), motor protection (REM615), transformer protection (RET615) and voltage protection (REU615) configurations. /2/

Figure 5. 615 series /2/

There is a very wide range of protection functions and features for these relays, therefore only a few functions are presented. The 615 series protection relay has advanced earth fault and ground transient protection to detect fault in cables and overhead networks. These relays are also equipped with three-channel arc-fault protection. This protection ensures the personal safety during arc-fault in the circuit breaker. At the same time this protection reduces the material damages and minimizes system down-time. Depending on the configuration, there are different configuration dependent protections. Some of these protections are:

- Phase over- and undervoltage
- Residual overvoltage
- Over and under frequencies
- Frequency gradient-based

2.2 Substation communications

A key element in any substation automation is communications. There are two main areas, communication within substation, and between the substation and the "outside world". In this case the outside world represents other substations and network control centers. In protective relaying the IEC 61850 standard is the newest and is implemented in almost all new relays. Also other communication protocols are used in substation automation. Therefore IEDs have to support protocols like DNP3 and MODBUS. It is ideal if the IED supports parallel communication, i.e. two or more protocols can be used at the same time. /10/

Every communication system can be sub-divided into smaller parts called layers. The Open Systems Interconnection model (OSI model) is a seven layer model, which is widely used for the presentation of a communication system. /19/

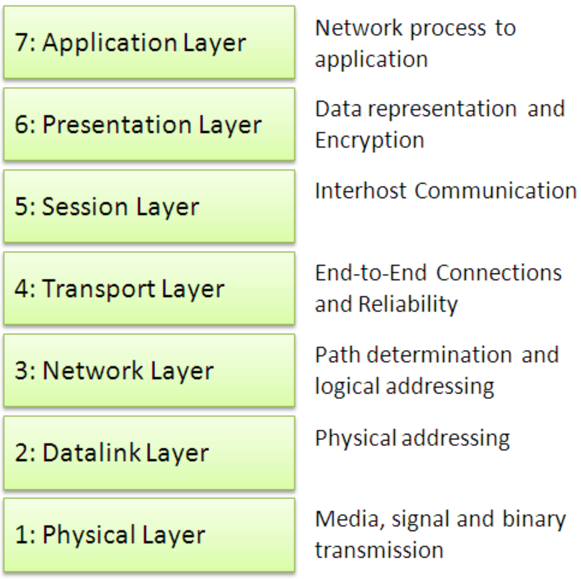

Figure 6. The seven layers of OSI /19/

2.2.1 IEC 61850

The IEC 61850 standard was founded to avoid problems between different manufacturers' communication solutions. This standard is also meant to be "future-proof", in other words, be immune to any future technological developments. IEC 61850 is a part of the International Electrotechnical Commission's (IEC) Technical Committee 57 architecture for electric power systems. To reach long-term interoperability, the approach taken in the IEC 61850 standard is to separate the domain related model for both data and communication services from the protocol. The OSI seven-layer stack is used to code and decode information into bit strings for communications over a serial link. The stack consists of Ethernet, TCP/IP and MMS layers. Only time-critical services are mapped directly to the Ethernet link layer. All other services are mapped in the MMS application layer, as shown in Figure 7.

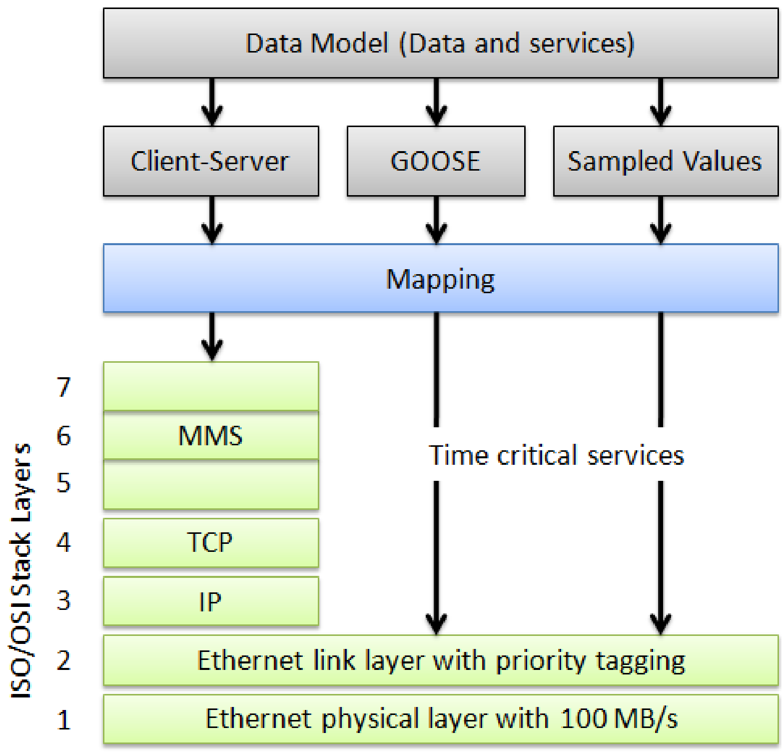

Figure 7: Mapping to the stack /4/

One of the most important parts of the IEC 61850 standard is the usage of XML-based SCL files. There is a wide selection of different SCL files. These files are constructed in the same methods and format, but are used for different purposes. For example, the SCD file is used for substation configuration and the CID file for IED configuration. Even though it is possible to extract an IED's configuration from the IED when it is connected to a network, there are several scenarios where the availability of a formal offline description language can bring very large benefits to users. One of the biggest benefits is that SCL allows the IEC 61850 applications to be configured offline without requiring a network connection to the IED.

The basic data model structure defined in the IEC 61850 standard is application independent. All application functions are broken down into small pieces, which can communicate with each other and can be implemented separately in the IEDs. In the IEC 61850 these basic objects are called logical nodes. The class name of the logical node refers to the function that the data objects belong to. The data objects themselves contain attributes, which may be seen as values or detailed properties of the data objects. The hierarchy of the data model is illustrated in Figure 8.

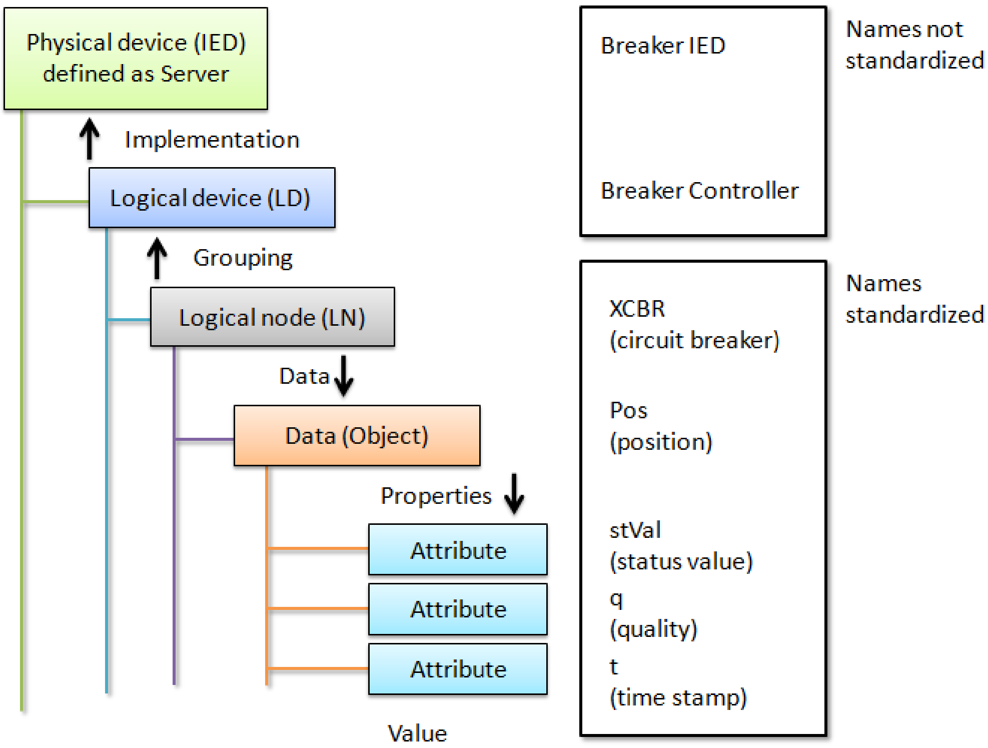

Figure 8: Hierarchical data model /4/

Interoperability also requires a standardization of the access to the data objects. Therefore there are standardized access services to the data objects. The most common ones include:

- Read: reading data such as the value of an attribute, e.g. stVal (see Figure 8)
- Write: for example writing the value of a configuration attribute
- Control: controlling switching devices and other controllable objects using methods like “select before operate” or “direct operate”
- Reporting: for example, event driven reporting after value changes

- Sampled value (SV): the SV service quickly transmits a synchronized stream of current and voltage samples

GOOSE is used in substation automation for fast horizontal communication between the IEDs. GOOSE can be used for direct data exchange of e.g. interlocking and blocking information between IEDs. According to the IEC 61850-8-1 standard, GOOSE uses a publisher/subscriber profile in which information is shared from one IED to one or several IEDs by using Ethernet multicast messages. A message is an image of a sent IEC 61850 data set which is defined in the configuration. The horizontal communication configuration consists of the IEDs' GOOSE control block, data set and GOOSE input configuration. The result of the configuration work is a system configuration file which can be downloaded to the IEDs. The used files in the workflow are IEC 61850 standard format SCL files. /4/

2.2.2 DNP3

The DNP3 was developed to achieve open, standards based interoperability between substation computers, RTUs, IEDs and master stations for the electric utility industry. It can be implemented using serial or IP communication. DNP3 uses the term outstation to denote remote computers that are found in the field. The term master is used for the computers in the control centers. Outstation gathers data like binary value for circuit breaker position or analog input values like current measurement. The master station deals with issues like opening or closing the circuit breaker. In order to keep the master’s database updated, the master sends requests to the outstation asking it to return the values in the outstation’s database. This is called polling. The outstation responds to the master’s request by transmitting the contents of its database. The DNP3 protocol also supports transmission of unsolicited messages. That is a mode of operating where the outstation spontaneously transmits a response without having received a specific request for the data. This mode is useful when the system has many outstations and the master requires notification as soon as possible after a change occurs. The DNP3 protocol is mostly used in distribution automation systems in America. /17/

2.2.3 MODBUS

MODBUS is a communication protocol developed by the Modicon company in the 1970's. Originally it was used for communication in PLCs and RTU devices. Later on the protocol has been used in a variety of different device applications. Today the protocol is mainly used over serial communication networks and Ethernet.

MODBUS is an application-layer messaging protocol, positioned at level 7 of the OSI model. It is a master/slave protocol and offers services specified by function codes. Valid function codes are in the range of 1 – 255. There can only be one MODBUS master unit on a MODBUS serial network. The MODBUS master unit communicates with one MODBUS slave unit at a time. Usually the master reads, or scans, data from the slaves cyclically. The master can also write data or give commands to the slave units. Each slave unit has a unique unit address. Thus the master can identify the slave with which it communicates. The MODBUS standard also defines the possibility for master broadcast transmissions. /20/

2.2.4 IEC 60870-5-103

IEC 60870 standard has six parts, defining general information related to the standard, operating conditions, electrical interfaces, performance requirements, and data transmission protocols. IEC 60870-5-103 is defined as a companion standard for the informative element of protection equipment. The official IEC 60870-5-103 standard dates back to 1997, but the protocol has its roots in the VDEW6 communication protocol from the late 1980's. The IEC 60870-5-103 standard defines communication for a serial, unbalanced link. Communication speeds are defined as either 9600 or 19200 baud.

The standard supports some specific protection functions and provides the developer which an opportunity to integrate their own protective functions on private data ranges. The possibilities to use vendor-specific functions are widely used by manufacturers of protection devices. As a result the compatibility between devices by different manufacturers cannot always be ensured. /7/

2.2.5 OPC

OPC is a series of standard specifications that specify the communication of real-time data between control devices from different manufacturers. Interoperability is assured through the creation and maintenance of open standards specifications. This reduces the number of duplicated effort required from hardware manufacturers and their software partners in order to get an interaction between these two parts. There are currently seven standards specifications completed or under development. The first standard, the Data Access Specification, resulted from the collaboration of a number of global leading automation suppliers working in cooperation with Microsoft. The specification, which was originally based on Microsoft's OLE COM technology, defined a standard set of objects, interfaces and methods for process control and automation applications. This standard set is made to facilitate the interoperability. OPC servers use Data Access to communicate with clients. Once the hardware manufacturers have developed their OPC servers for the new hardware device their work is done and can allow any user to access their device. /22/

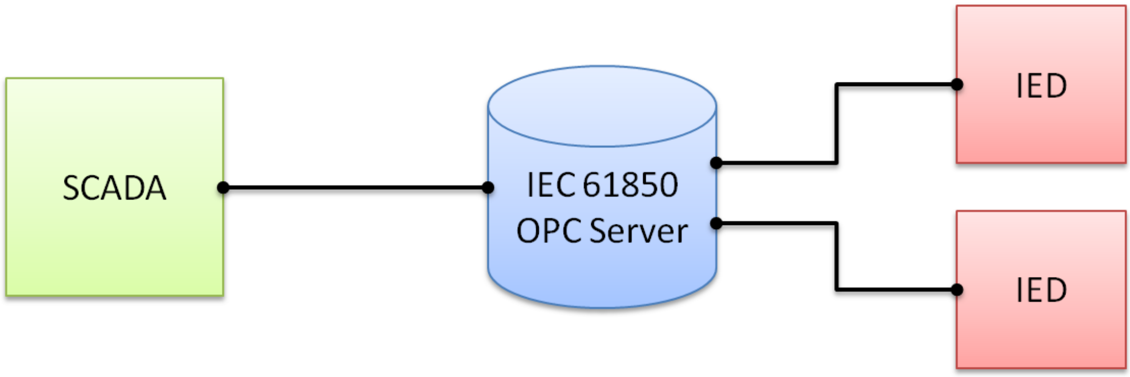

Figure 9. Communication between IED and SCADA

Figure 9 illustrates the communication between a SCADA system and IEDs. The SCADA system uses an OPC client to get access to the IEC 61850 OPC server. With the connection to the IEC 61850 OPC server the SCADA system gets access to the data of the IED. The same approach is taken with all communication between a client and an OPC server.

3 Research and Development

Product development is a very long process. The R&D process may start from an idea or customer requirement and if the project is successful it will result in a finished product. This product can be a device, service or information. In practice all products include information like user manuals. These are also part of the product. The product is what the company sells, it includes both the physical device and services. A product is also what the customer buys. The product is useful for the customer only if the product fulfills its function and creates values for the customer. To remain competitive, the company must continually research and develop new products in order to attract new customers and keep the existing customers. Therefore, R&D is a very important part of a successful company.

There are many process models for R&D projects. The waterfall- and the V-model are very popular models. The V-model is mainly used for software development processes and can be considered as an extension of the waterfall model. The V-model demonstrates the relationships between each phase of the development life cycle and its associated phase of testing. Figure 10 illustrates the V-model.

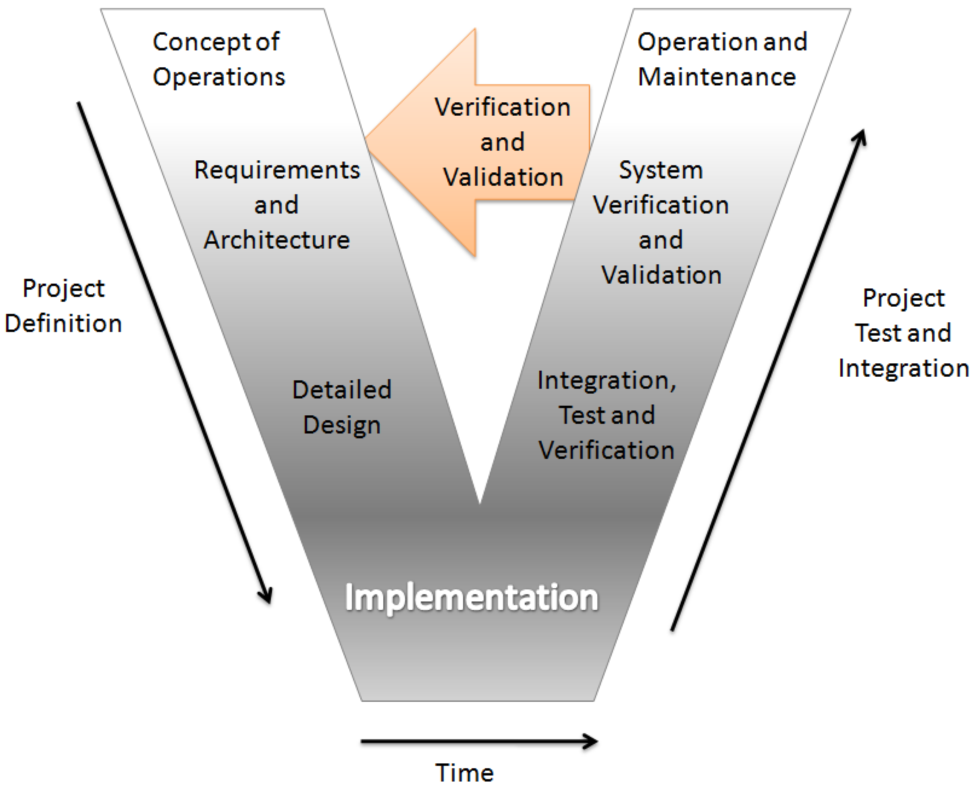

Figure 10. The V-model /18/

A relatively new process model for decision making in a project and project management is the Gate-model, which is also used at ABB. The Gate-model consists of 8 gates. The project starts with G0 and the last gate is G7. A gate is a decision point where it is decided whether to proceed with the project or to cancel it. The decision is made based on the project's benefits, status, risk, resources and technology considerations.

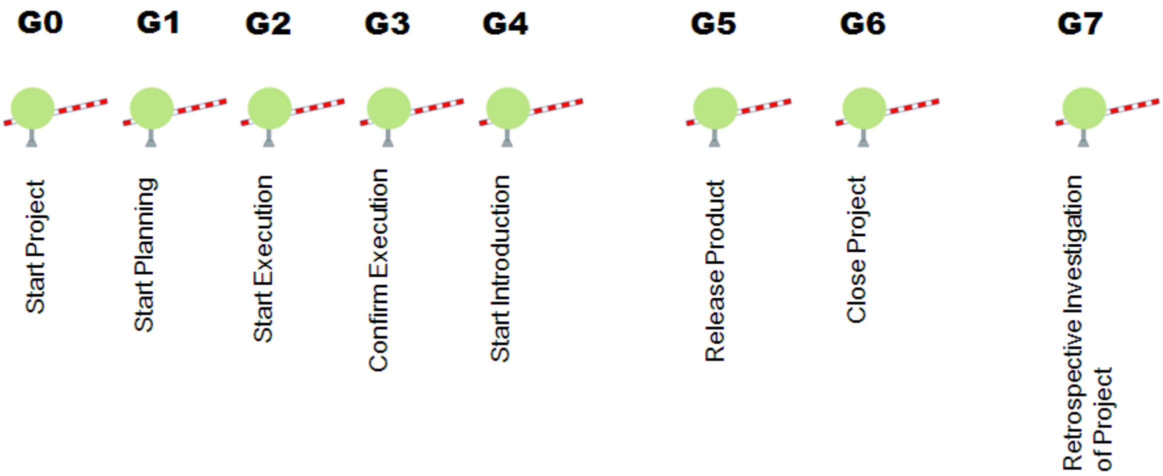

Figure 11. The Gate-model /16/

The most important gate is G5, where it is decided whether the product shall be released or not. After G5 the company can get revenues by selling the product. The Gate-model is mostly used as a checklist to ensure that crucial activities and best practices are built into all development projects. A well-designed Gate-model will increase a company's profits significantly and has de facto become a standard for leading product developers around the world. /23/

3.1 Testing and verification

According to the test strategy of ABB Oy, Distribution Automation, defects are much cheaper to fix if they are detected and fixed in an early phase /6/. Figure 12 illustrates that bugs found and corrected in the coding phase are much cheaper to fix than bugs that must be fixed in the post release phase. Therefore it is crucial to perform proper testing all along the product development project. By proper testing the cost-benefit ratio rises for the project and it also improves both the quality and the productivity for the product. Testing includes systematic search for errors and bugs, assurance of the product quality, verification and validation. /25/

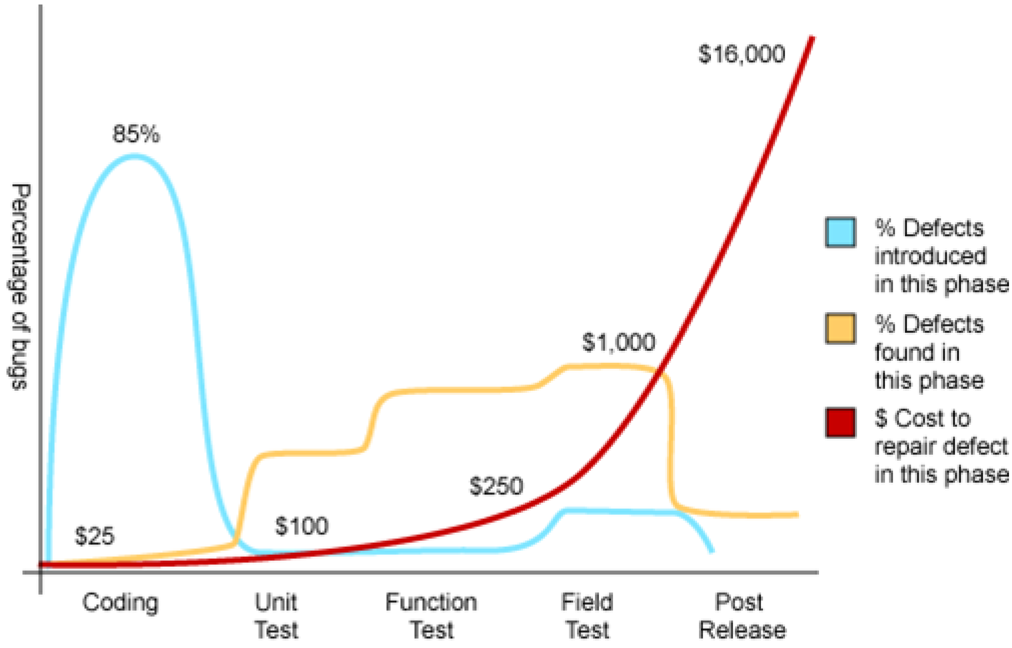

Figure 12. Bugs detected in each phase /14/

The approach used for testing is not obvious. There are many factors that complicate the testing. Some of these are:

- Know-how: designing, controlling and performing a test requires a lot of knowledge
- Process: The tester must master to adjust testing according to the project and situation
- Resources: Everything can't be tested, focus on the most important functionalities
- Schedule: Tests often start too late, lack of time and performing the test at the right time makes the testing harder
- Attitude: The tester must be realistic, not optimistic
- Importance: The importance of the testing is often misunderstood

The testing process can be figured as an own process, but it is linked to the R&D process from the beginning to the end. By initiating the test project in the beginning of the R&D project, errors and bugs can be corrected before the project has proceeded too far. This means that nothing needs to be redone. Only the errors will be corrected and the project can continue. If the testing is done only on a finished project, the product will have to be redesigned for every error and if the worst comes to the worst, be redesigned from scratch.

At least three kinds of testing are needed to show that modules of the software are interoperable. These three basic testing are unit testing, integration testing and system-level testing. Unit testing is a systematic testing of the individual components. Integration testing is a search for faults caused by integration of different modules. In system-level testing, the software is tested in its own system, to verify its functionality. System-level testing should imitate as well as possible the environment that the software will be used in.

Testing is complex and hard to perform. There are no correct ways to design a test that works every time and solves all quality problems. The primary role of software testing is to reveal bugs in the critical parts of the software. Effective testing is necessary to produce reliable, safe and successful products. /12/

3.2 Integration testing

Software is composed of modules. A module is itself a system of smaller modules or components. Integration is the definition for a process by which modules are collected together to create larger modules. Integration testing is testing done to show that even though the modules were individually tested, the combination of these modules can cause some problems. Integration testing should not be confused with testing integrated objects, which is just higher level module testing. /11/

As an example of integration related errors, the following fictional scenario will be presented. Two different modules, module A and module B, use the same input value. This value could be the current measurement, which the modules then use for different purposes. Both modules are individually tested and functionality verified, but in the integration testing one of the modules doesn’t work as expected.

When analyzing this error the following bug is found. One module is programmed to use comma “,” as separation of integer and decimal. The other module uses full stop “.” separation. This error wasn’t localized during the module testing. After the integration there is only one input and therefore one of the modules can’t handle that input value, because it is not programmed to separate integer and decimal with full stop. This scenario is presented in Figure 13.

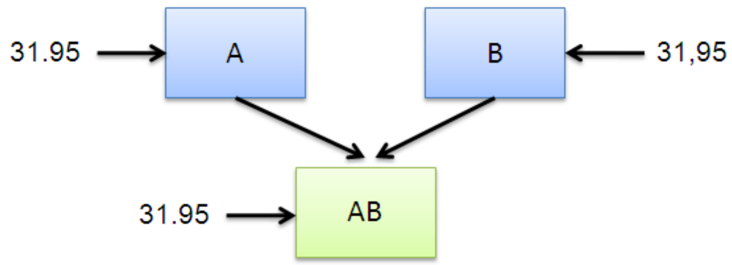

Figure 13. Example on integration related error

This example shows that all errors can't be located only with individual module testing. Some errors can only be located when the integration is done. According to Robert V. Binder, most of the faults revealed in integration testing are interface-related. These errors could be configuration and version control problems, missing, overlapping or conflicting functions. Also wrong methods used in the function call can cause some integration related faults. /12/

One of the most important questions in integration testing is when to perform these tests. Should all modules be integrated before any testing or should some modules be integrated and tested before the integration of the remaining modules? This question leads us to integration strategies. /21/

3.2.1 Integration test strategies

The selection of integration testing strategy is controlled by the architecture of the product. If the wrong strategy is chosen, bugs and errors will be detected too late. A general principle in integration is to integrate small parts and perform testing before further integration. This principle is however more time consuming and in some cases this is not the best way to perform integration. /21/

- **Big Bang**

Big Bang is an integration strategy where all parts are integrated before any testing. This method is very effective for time saving in the integration testing process and can be chosen when the main task of integration testing is to detect errors, not to localize the components that caused the errors. /21/

Unfortunately, there are a lot of disadvantages of using the Big Bang method. If this method is chosen, it requires a lot of analyzing to localize the components that cause the error before any correction actions can be taken. Debugging is therefore much harder when no clues are given about the fault locations. There is also a high possibility of missing some defects which might appear later on, when the product is used.

If the Big Bang method is used as the integration testing strategy, the following requirement must be fulfilled. Only a few components can be added after the last time that the software passed the testing. If this is not the case, the Big Bang method will create more problems than it solves. /12/

- **Bottom up**

A better strategy is to progressively integrate a few modules at a time. This leads to easier debugging because there are fewer modules to search through when trying to locate the error. Bottom up is an integration testing strategy, where the lowest level components in the hierarchy are tested first. These low level tests are then used to facilitate the testing of components at a higher level. This process is repeated until the highest component level is integrated and tested. /21/

Because of the lack of higher level components at the beginning of the test process, there is a need of some type of test driver that will replace the higher level components. The driver must be developed before any testing. This integration strategy is very useful when low level errors need to be detected at an early stage of the integration process.

- **Top down**

Like the bottom up method, the top down method is also an integration strategy where components are progressively integrated and tested. The top down method has the same benefits as the bottom up method. The debugging is easier because there are fewer modules to search through. /21/

The top down method is the opposite of the bottom up method. In this integration method the test starts with the modules at the highest level. This method allows high level logic and data flow to be tested early in the process and thus minimizes the need for test drivers.

The disadvantage of this method is that low-level components are often tested too late in the integration test process.

3.2.2 Entry and exit criteria for integration testing

The main entry criterion for integration testing is the completion of unit testing. If individual units are not properly tested for their functionality, the integration testing should not be started. All the bugs and errors detected in the unit testing must also be fixed before any integration testing can take place.

Integration testing is complete when you make sure that all the interfaces where components interact with each other are covered. All the detected errors and bugs must be fixed before this test level is complete. It is important to cover negative cases as well, to ensure that the integrated modules don’t make wrong assumptions with the data. /12/

3.3 Regression testing

Every time changes are made in the implementation of the software, regression testing should be done. The regression testing is done to make sure that a change, such as a bugfix, did not generate new errors. Bug fixing can have the negative effect that new bugs are generated in another part of the software. A common method for making regression testing is to run existing tests that have been run before. This is done to check whether the behavior of the software has changed or not. /21/

3.4 Manual vs. automated testing

When a software tool is developed to automate the test execution, the strengths and weaknesses of the human being should be considered. The strengths of the human are that he can evaluate different situations, get an overview of the situation and see the connection between different elements. The human can’t handle different situations at the same time. Time consuming tasks can reduce the concentration of the human, which affects the work that he or she is doing. Details are also easily forgotten and a human can’t handle stress so well. /15/

A properly designed software tool should replace the human in the tasks that the human being can’t handle as well as a computer. The strengths of the human should also be taken into use by letting the human do what he or she does best.

3.4.1 Manual testing

When testing manually a test engineer executes actions on elements of the system under test, either directly or through various testing hardware or software. These actions are based on a test specification which is a step-by-step instruction on what to do in order to perform the test. The test engineer needs to monitor the behavior of the system during the test. Finally, based on the behavior of the system, the test engineer evaluates the results to verify if the system under test works correctly or not. In case of a failed test, the test engineer is supposed to find the problem by some troubleshooting. /1/

The advantages of manual testing are anyway quite a few. There is no wasted time or money on trying to design a software tool to automate the testing. It is also a fact that, no matter how decently a software tool is developed, all tests can't be automated. There is still a need for a good test engineer. It is also easier to adjust the test from case to case if the test specification just needs to be updated.

The disadvantages of manual testing are also quite a few. As said before, the human has his weaknesses in forgetting details. External factors like stress, lack of time and tiredness can affect the test execution negatively. Manual testing is also more time-consuming, as the test engineer needs to execute, monitor and evaluate the testing.

3.4.2 Automated testing

With a software tool time-consuming tests can be automated. With this software tool the test engineer's primary task is to define the test scripts, based on the test specification. Once the test script is defined it can be executed multiple times. A properly designed software tool can replace the human in executing the test, monitoring and evaluating the behavior of the system. When the test fails the test engineers do troubleshooting to find the problem. The test report created by the software tool helps the test engineer find the problem. Because of the fact that a proper design software tool can execute the tests, all testing can be done at night time and the test engineer can do troubleshooting at day time. /1/

The advantages of automated testing are many. Actually it is just how well designed the software tool is that sets limits on what can be automated. The weaknesses of the human don't affect the test result and a lot of time is saved.

A disadvantage of automated testing could be the fact that if the product changes, it is not enough to update the test specification. All the test scripts also need to be updated, which can be very time-consuming.

It is not worth trying to automate all tests. A well planned test process includes both manual and automated testing. When planning the test process for a product, one should focus on exposing the advantages in both manual and automated testing. After that one should choose the software tool to execute the tests that can easily be automated. All hard and complicated tests should be executed by a test engineer.

4 Results

The task of this Bachelor's thesis was to investigate the possibilities to automate the integration testing. Pretty soon it became clear that all integration tests can't be automated. The reasons are partly because it would be too time-consuming to automate the complicated tests and partly because these tests would lose their flexibility. Automated test cases will be used only if they are easy to use and flexible so that they can be applied to any relay type. Therefore, the focus was on generating simple test cases that test and verify the functionality of the IED. These generated test cases are meant to be executed both in the integration testing and in the regression testing.

SATEEN was used as the software tool for the testing. The advantage of using SATEEN in the integration testing is that it is developed for testing ABB's protection relays. To use internally developed software has several benefits. If there is a need for new functionalities in the SATEEN, these will be developed. If a third-part software tool had been used, new functionalities to the software tool would have been harder to get.

A total number of 13 test cases for integration testing with SATEEN were made. These test cases will verify the functionality of inputs and outputs of the IED, protection functionalities and parameterization. This is a good proof for the fact that it is possible to use SATEEN in integration testing.

5 Conclusions and discussion

This Bachelor's thesis work has been a very interesting project. It was an interesting challenge to independently lead a project. In the beginning of this project a time table was made. This time table has been kept. Despite this there has always been a little lack of time. Therefore, the decision was made to use only the IEC 61850 standard in the test cases. This is a very common procedure in projects, i.e. due to lack of time and resources some functionality must be left out.

This project had several demanding parts. The practical work, generating test cases, included a very demanding task. To constantly try to generate as automated test sequences as possible was both difficult and time consuming. The work to document these test cases was also challenging. A test catalog is meant to help the test engineer to execute the tests, therefore all steps in the preparations and execution need to be systematically documented. A little more time for this task would have been useful.

The main assignment, to investigate the possibility of using SATEEN in integration testing, has been carried out and completed. It will be very interesting to follow up if this Bachelor's thesis work will speed up the integration and regression testing.

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