A STANDARDS-BASED SERVICE ORIENTED ARCHITECTURE DESIGN FOR SUBSTATION FAULT DETECTION

Ebrahim Yassir Said

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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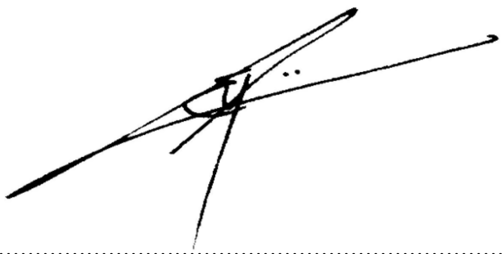
DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



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ABSTRACT

Reliability and security in power supply is a measure of how well an electrical load meets the needs of a consumer at a given point in time. Achieving high levels of reliability requires large capital expenditure. A power system is therefore required to operate at optimal capacity in order to create a return on capital investment. In order to attain a high level of reliability in these operating conditions, there is a need to implement protection processes in power systems to reduce the number and severity of failures to protect components connected to the grid. In South Africa, the power grid has aged and traditional infrastructure that has historically supported consumers is unable to support future requirements. To ensure the continued growth and refresh of grid technologies, industry bodies and committees have established standards and guidelines that challenge the traditional approach to substation systems architecture. Reference process architectures, substation communication and information exchange standards have gained support from utilities and technology vendors over the last decade. A growth in the number of implementations of these standards is proving that the demand for systems integration and interoperability is high and will continue to grow in the future. This demand and its applicability to emerging systems architecture approaches, like service-oriented architecture, are considered in this dissertation. This dissertation uses standards, design patterns and emerging frameworks to deliver a service based fault detection application design. In order to deliver the fault detection process accurately, a subset of UML artefacts represents the fault detection requirements. UML is a basis for model driven design in software engineering. The dissertation proposes the design of a series of software components that are flexible, extensible and manage fault detection information needed to support reliability processes in substations. A deployment model implements the final application design to indicate the placement of specific components in a reference architecture used in this dissertation.

The aim of the dissertation is to prove that an application for fault detection in substations can be modular, reusable and flexible in design by using existing software engineering methods and architecture design principles.

Keywords: TM Forum NGOSS, IEC 61850, COMTRADE, Service Oriented Architecture, Fault Detection.

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GLOSSARY OF TERMS

Term	Acronym
Business Process Modelling Notation	BPMN
Enhanced Telecommunications Operations Map ®	eTOM
International Electrotechnical Commission	IEC
Intelligent Electronic Device	IED
The Institute of Electrical and Electronic Engineers	IEEE
International Telecommunication Union	ITU
Next Generation Operating Systems and Software	NGOSS
National Institute of Standards and Technology	NIST
South African Bureau of Standards	SABS
Smart Grid	SG
Shared Information & Data Model ®	SID
Service Oriented Architecture	SOA
Tele Management Forum	TM Forum
Unified Approach	UA
Unified Modelling Language	UML
Extensible Markup Language	XML
XML Schema Document	XSD

CHAPTER 1
INTRODUCTION

1.1 Introduction

A key requirement for interoperability is that systems design should be technology neutral to support the development of bi-directional information flows for emerging initiatives like Smart Grid [**1**].

In order to meet desired levels of return on investment spending, power system components are required to run at optimal capacity. These operating levels are normally very high to ensure reliable load conditions for consumers. The nature of any system is that it consists of interacting components to provide some type of redundancy and fail over capability. However when poorly designed, it exposes the system to multiple points of failure. Protective measures and processes decrease points of failure in a system, providing the necessary reliability and redundancy.

All processes, including fault detection, require timely and accurate, data and information in order to operate correctly. Information is therefore required at a low latency to support substation protection devices [**2**]. All of these requirements need highly available, fast and redundant infrastructure as well as the automation of substation operations. The latter is required for delivering integrated functions and centralising substation data [**3**].

Legacy systems architecture is an issue when attempting to create an integrated environment. Legacy issues are resolved to an extent by the advent of smarter device infrastructure in substations. Current research shows that intelligent devices and modern networking technologies like Ethernet play a big part in automation and integration expenditures for utilities [**4**]. This indicates that there is continued interest in the interoperability of functions and processes, as well as the integration of utility information. To ensure the continuation and refresh of grid technologies, industry bodies and committees have established standards and guidelines that aim to challenge traditional approaches to substation integration. A standardisation strategies position a utility for emerging technology initiatives like Smart Grid and Cloud Computing. These initiatives have gained considerable support due to financial and environmental viabilities.

Research indicates that the following problems exist for integrating substation information [**2**] [**3**]:

- **Data Structure**: The large number of different formats of device outputs will affect the ability to integrate data into a single central or local substation data store;
- **Size**: The processing and assessment of every substation device event for inclusion or exclusion from the device function. The volumes of data will increase exponentially as more devices are introduced;

- **Quality**: Although data is generated by device, there may be instance of missing or malformed data that will adversely affect the function it is meant to support; and
- **Latency**: Substation information is required at very low latency if it aims to support protection functions, but at a higher latency for post fault analysis.

Continued demand in the area of substation integration means that more protocols and integration methods will become available. Some of these will be vendor specific, optimised to perform under specific conditions. The large number of electrical process components with an equally large number of configurations means that it is necessary for device specific protocols to support integration. Issues like tight coupling in devices, hardwired systems, vendor specific standards and protocols, and embedded device processes cause issues with replacing current systems with newer technologies. As expected, legacy systems architecture documentation that is dated has an impact on maintenance and upgrade costs. Delivering integrated substation environments must be in a measurable, effective and efficient way. This requires loose coupling, standards-based applications, common process and information interfaces.

Results of a recent global market survey indicate that an increasing number of utilities are, on average, increasing expenditures on capital assets, operations and maintenance [**4**]. Utilities aim to change spending across areas like SCADA, energy management, substation automation and integration and transmission infrastructure. ***Figure 1*** shows the average of the percentage of survey respondents are changing their spending between 2011 and 2012. The survey indicates that 49% of the utility companies engaged in the survey will increase their capital expenditure in 2012. This is a 2% increase from the number of respondents in the 2011 survey. An additional 3% of the utility companies will increase their operations and maintenance budgets. The survey also indicates that fewer utilities are decreasing capital, operations and maintenance spending from 2011 to 2012.

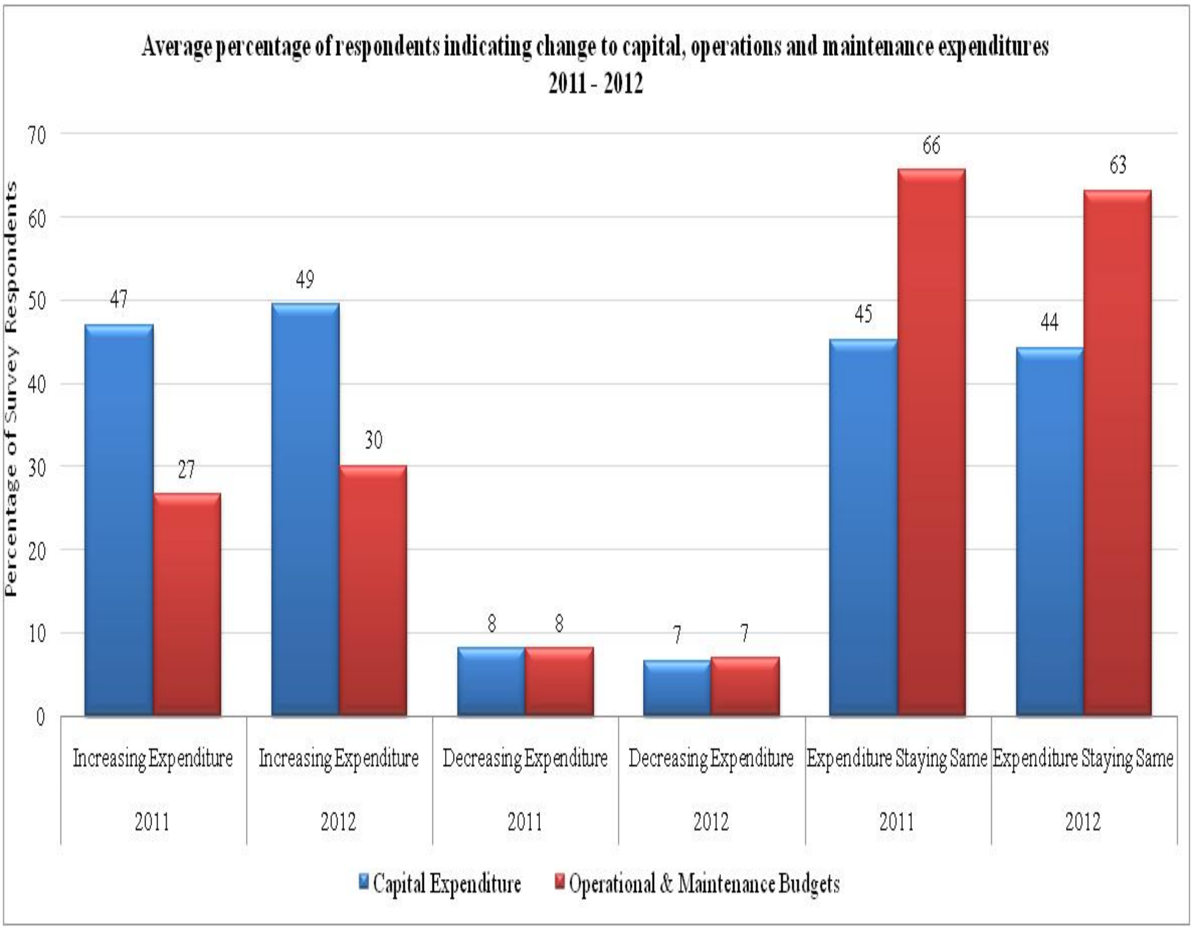

Figure 1 Power system capital, operations and maintenance spending for 2011 and 2012. Source Capital Expenditures, Operations & Maintenance Budget Outlook [4]

An investigation into the expenditures of utility companies indicates that the following categories are of interest on their budgets for 2011 to 2012.

- Advanced metering;
- Distribution automation;
- Distribution infrastructure;
- Protection and control;
- SCADA/energy management systems/operations management systems;
- Substation automation/integration; and
- Transmission infrastructure.

Figure 2 indicates the percentage of survey responses from utilities for the areas within focus of this dissertation. The survey result shows a weighted view of the spending status movement for substation automation and integration, protection and control. The report categories are:

- The percentage of utility companies *increasing* spending between 2011 and 2012;
- The percentage of utility companies *decreasing* spending between 2011 and 2012; and

- The percentage of utility companies *having the same* expenditure pattern between 2011 and 2012.

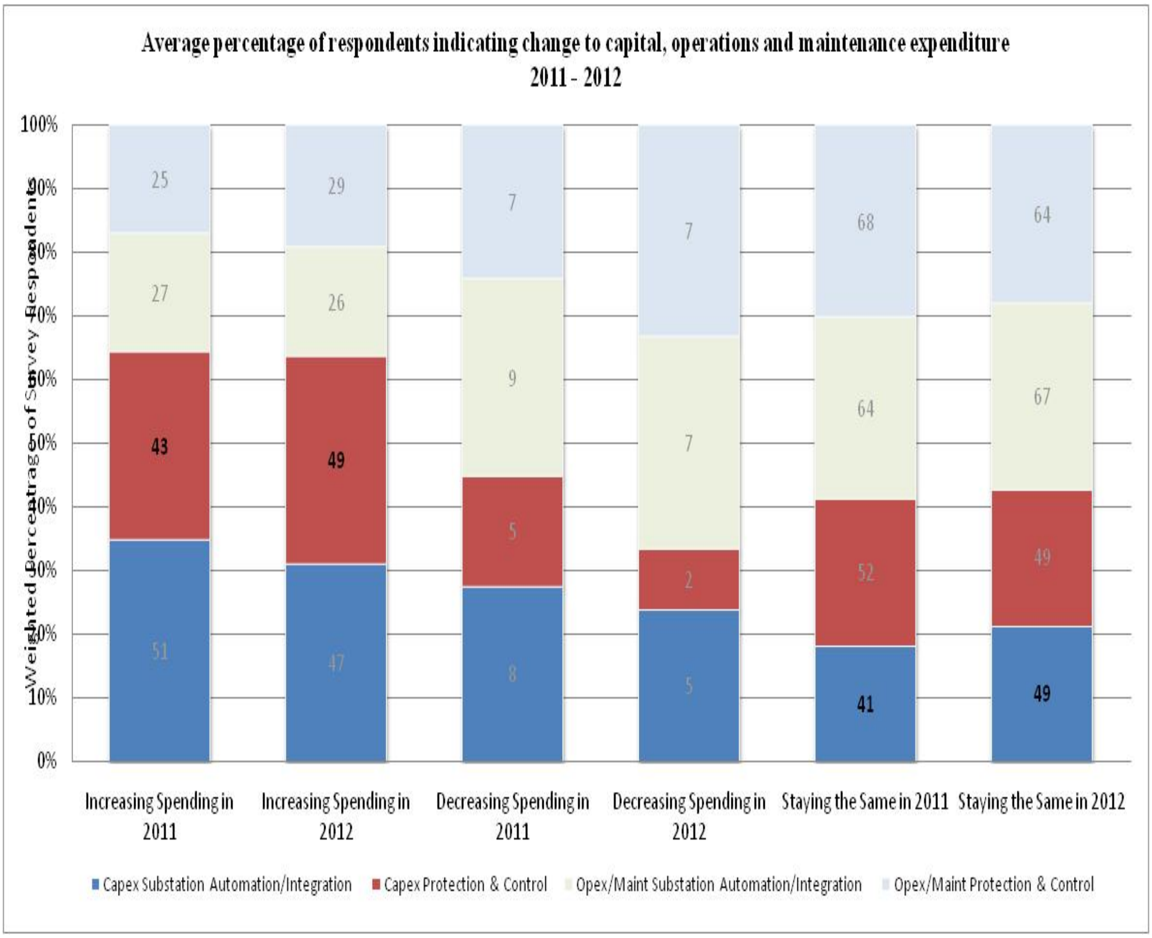

Figure 2 Capital, operational and maintenance expenditure for automation, integration, protection and control. Source Capital Expenditures, Operations & Maintenance Budget Outlook [4]

An increase in the number of survey respondents indicate that capital spending for protection and control will increase from 2011 to 2012. A 7% increase of respondents to the 2011 survey indicates this. 8% more respondents also confirm that their capital expenditure for substation automation and integration will stay the same. The survey also indicates that fewer utilities will be decreasing their expenditures on automation, protection and control initiatives.

The survey shows that technology, software and other items that can be capitalised will have focus in most utilities over the next two years. These reflect the physical assets in substations, and not workforce.

Researchers are currently engaged in delivering automation through standardisation and modelling of interoperable environments. This is found in work by several researchers most notably *Mladen Kezunovic* et. al. from Texas A&M University [**3**][**28-30**][**32**]. The area of fault analysis - specifically detection - that is of particular interest in this dissertation has always been a key research topic due to its inherent overlap with protection and control activities. Topics like data management and seamless wide access to data and information supports fault analysis research as the growth of data and information for grid operations is creating some activity in the utility industry.

As expected, the systems engineering industry has undergone changes as well and introduced different approaches for designing and implementing software systems. The rise of service orientation and cloud computing have gained considerable interest by both academics and vendors as a wave of information that has previously been embedded in utility operations now face the paramount task of being exposed to consumers and other interested stakeholders.

The aim of this dissertation is to propose an application design framework for delivering reusable software components needed for creating and consuming integrated substation data. Analytics are considered for issues like alarm processing and event analysis. Stokes-Waller and de Villiers indicate that data exchange through managed information and knowledge supports substation efficiencies and effectiveness [**5**]. Understanding and management of data is an actual requirement for sound management of utility infrastructures.

1.2 Scope

Effectiveness and efficiency of power flow regulation into homes and industry are performance indicators that can measure the reliability of a power system. Several standards govern power system reliability in South Africa. The network, system operation and information exchange standards for the South African Grid published by the National Energy Regulator contain national grid standards [**6-8**]. These standards include fault reporting, information access and information retention requirements. One of the key requirements for fault root-cause analysis is availability of information within 15 minutes from when a disturbance event occurs [**6**]. The substation-data acquisition process from component to substation gateway is however not greater than one second [**8**]. The position taken in this dissertation is that devices generate real time information and control signals. The application design in scope for the dissertation provides operator access to data irrespective of its latency. This means that the operator will have access to the data it once it is available.

The power grid is a network of components that operate to provide a utility service to a large number of power consumers. The analysis and design of power system processes require the knowledge of experts in the areas of generation, transmission and distribution architectures. Each of these areas has sub domains like transmission and distribution protection engineering. The inputs supplied by each area are vital to meet the power system's requirement of providing reliable, secure and available power to consumers. Economies built on these systems have many consumers that are dependant on specific service levels and are thus sensitive to changes in levels of expected service. In order to create a more reliable infrastructure and supply there is a need to protect the current investments whilst refreshing the ageing infrastructure to cater for future needs.

The aim of this dissertation is to focus on the substation, and components within its boundary, as a connecting node in the larger power grid within the context of fault detection. *The dissertation defines a fault as a set of disturbance events that constrain the means in which normal operating functions execute in a substation*. The dissertation further investigates the substation as container for a group of cohesive components that produces strategic, tactical and operational information. The aim is to provide needed visibility of externalised processes across clearly defined device functions that provide access to information in a substation disturbance scenario. The substation environment requires visibility for real time monitoring, protection and control purposes. Due to the known complex nature of substation data, the effective management of data, information and knowledge in substations is proposed as this supports the growth the data and information volumes in future [**5**].

Industry bodies have aimed to produce standards that will close the integration gap between vendors and aid the implementation of newer technologies in substations. Technical committees that have panels consisting of the same vendors that require integration guidelines drive most technical standards. This dissertation focuses on the implementation of a fault detection process using data collected from substation components. It references standards that have a direct bearing on substation design, information exchange and protection requirements.

1.3 Research Hypothesis

The previous sections present an overview of the problem and scope. The following section outlines the research hypothesis:

*"To investigate the ability of using **standards-based frameworks** from the communications and utility industries to deliver a **service-based application design** for analysing events from two ends of a **faulted transmission line**. The application performs a post-fault analysis function, using integrated substation data. To assess the flexibility of the design by changing the application requirements and driving the change though a requirements traceability process"*

1.4 Research Method

The research method for this dissertation focuses on identifying existing research, combining areas of focus of specific research topics and generating a research opinion based on this. Specific research areas are used to deduce a general design theory. A series of specific implementation scenarios are investigated together with industry research in the areas of service orientation and communication standards. The best possible method to deliver information between components involved in the fault detection process is stated.

1.5 Objectives

The objective is to define a model of information that traverses a service-enabled system. Specific design patterns implement the design for analysing integrated substation data. The outcome presents an application design containing a model driven approach for analysing information between substation components within the context of fault detection. This is done at a power system node level. Nodes are power system components that interconnect the power system network.

1.6 Layout

Chapter 2 discusses the standards that are important for this dissertation. The standards provide the correct levels of coverage without extending the objective beyond what is envisioned as critical to fault detection process. ***Chapter 3*** explores the architecture and components required to deliver the analysis. This chapter positions the building blocks that will constrain and enable the delivery of the software components. ***Chapter 4*** outlines an implementation use case of the fault detection process. The chapter also delivers the deployment view with an alternative use case to demonstrate the flexibility in the design. ***Chapter 5*** provides concluding remarks on the method and future work efforts in the area of substation information integration.

1.7 Conclusion

This chapter is an introduction to the research that has been performed. It outlines some of the problems with integrated substation environments. ***Chapter 1*** positions the research effort as being a key driver in substation integration and automation plans by a large number of utilities. The objective and research method proposed will result in the delivery of sustainable architecture components using flexible software engineering patterns.

CHAPTER 2
STANDARDS

2.1 Introduction

Standards are a result of combined efforts by organizations to drive interoperability and accessibility agendas for technology and infrastructure implementations. Standards are a set of mutually agreed guidelines, procedures and processes that achieve a specific outcome if applied in a specific sequence [**9**]. Standards bodies orchestrate interaction between organizations that have a common set of goals. Examples of these bodies are the Tele Management Forum (TM Forum) [**10**] and the International Electrotechnical Commission (IEC) [**9**]. Consortia like the Tele Management Forum have led the development of process and information standards for the telecommunications industry. The forum has recently branched out into areas other than communication service providers. For example, the area of military and defence has shown some activity, but more specifically utilities and energy are the focus of some activity over the last year. Similarly, the IEC, established in 1906, has developed a range of standards for the electronic devices and communication of information between these devices.

The standards produced by these bodies play a pivotal role in the delivery of the software components of this dissertation.

2.2 Standards

2.2.1 Tele-Management Forum NGOSS

The Tele Management Forum (TM Forum) is a company located in New Jersey in the United States of America. The TM Forum produce, train and consult on standards for the telecommunication service provider industry. The TM Forum launched in 1988 to provide standardisation frameworks for interoperable network management systems. The forum released its first protocol specification soon after being established and in 2004 its process framework was accepted by the International Telecommunication Union [**10**]. The forum currently has more than 700 members.

Over the last decade, the TM Forum and its partners have developed frameworks to enable interoperability and standardisation across enterprise business and technical operations. The frameworks are currently in use in the areas of business process re-engineering, information architecture and enterprise integration. Over time, the frameworks have undergone changes, however the fundamental ideas introduced as part of the original designs still hold valid for a majority of processes that are present in most organisations.

Due to increasing requirements for organisations to become socially and financially accountable for the delivery of services, many organisations have looked at ways of streamlining operations by leveraging existing business and technology assets. It is important to govern these assets to provide an accurate basis for decision and governance processes. Consortia like the TM Forum have helped by developing mechanisms for standardising processes and information.

The TM Forum manages a set of interacting frameworks labelled the Next Generation Operating Systems and Software (NGOSS®) specification. The forum defines this as an industry wide "*set of frameworks, methods, guidelines and definitions*" [**11**].

NGOSS contains four domain specific "sub" frameworks. These are:

- The Enhanced Telecommunications Operations Map ® (eTOM) defines a framework for business processes;
- The Shared Information and Data Model ® (SID) defines a information framework;
- The Telecommunications Applications Map ® (TAM) defines an application function framework; and
- The Technology Neutral Architecture ® (TNA) defines an integration framework.

Figure 3 references an online version of TM Forum's frameworks [**12**]. The figure indicates the interaction between the domain specific frameworks. The focus of this dissertation is the process and information components of the framework indicated by the dashed arrow between process architecture and information architecture. These are specifically selected due to the ability of the frameworks to act as a coverage map for the defining and specifying the scope of a design.

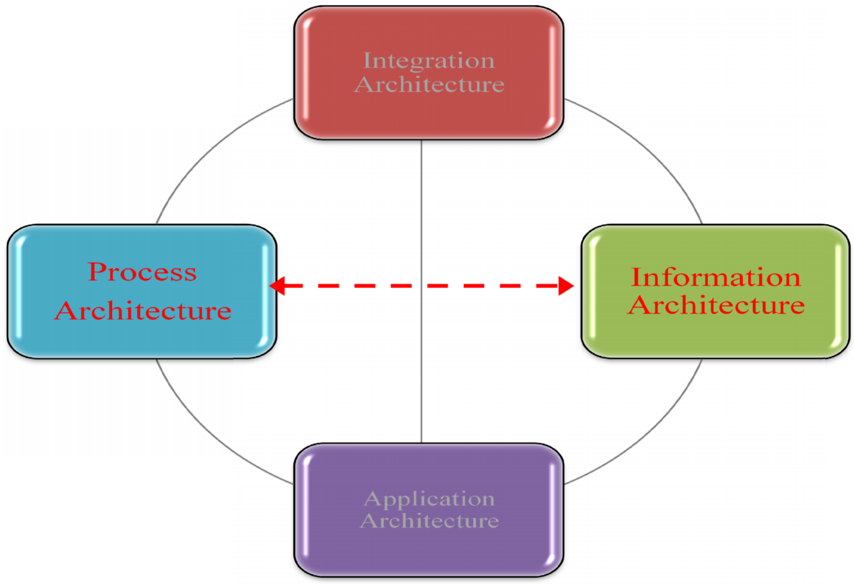

Figure 3 Interacting framework models from the TM Forum. Source TM Forum Frameworx [12]

In addition to these frameworks, the TM Forum manages application-programming interfaces (APIs), which support the creation of applications that are compliant to the semantics of the frameworks. The latter APIs are purposefully ignored due to the specific scoping capability enabled by the process and information frameworks.

The structure of the selected frameworks enables multi entry points for systems analysis. This supports the ability to keep focus on the primary definitions of the each specific framework. For example, analysts with a strong preference for process modelling can use the process framework to determine processes that control specific information entities. An analyst with a preference for information modelling can use the information framework to determine a comprehensive process hierarchy. For this dissertation, the implementation scope is a fault detection process. This means that the process framework is the point of entry.

The TM Forum process framework consists of number of vertical, horizontal and intersecting components. By the very nature of the frameworks, it is a set of reference models. Vendors and organizations that aim to implement any of the process standards do so by using the sections of the reference model that are specific to their own implementation requirements. Vendors like AMDOCS publish versions of the TM Forum's frameworks on their company website [**13**]. ***Figure 4*** presents a simplified version of the business process framework from an online publication.

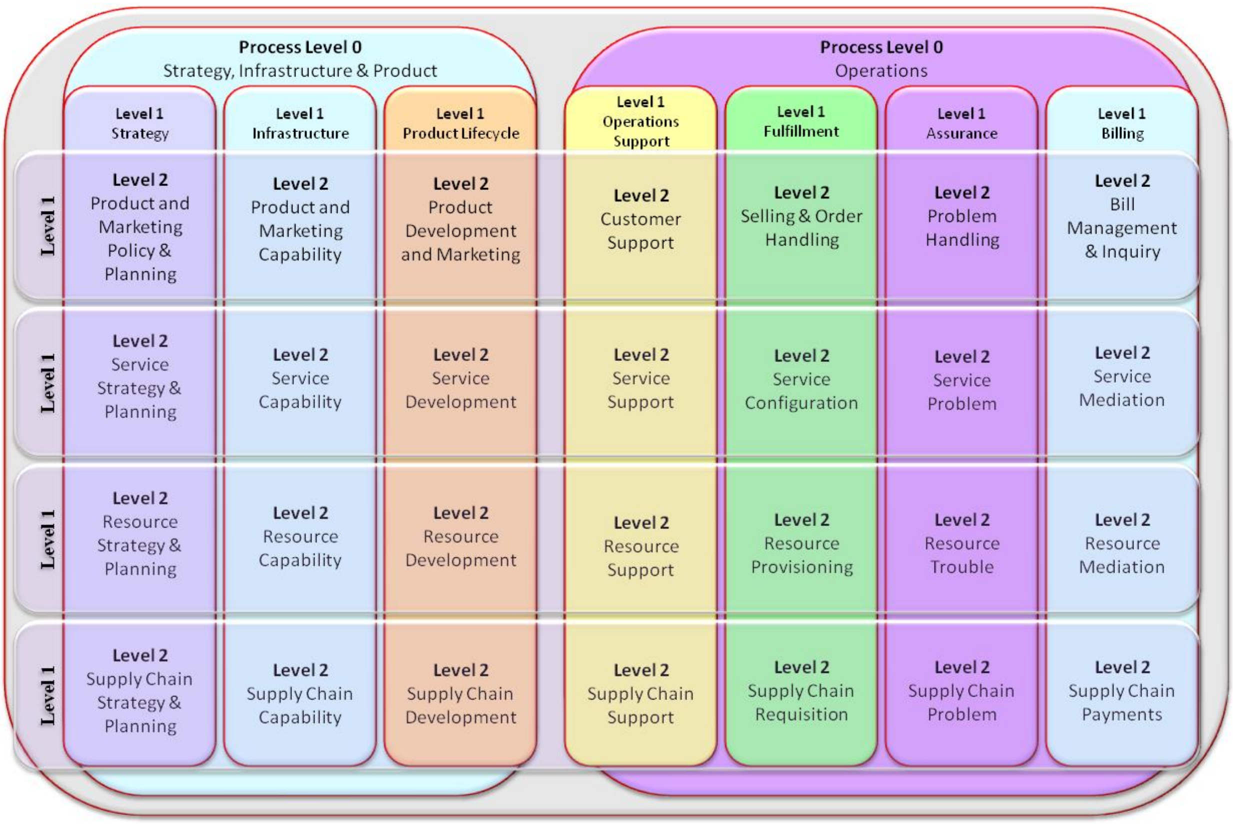

Figure 4 A simplified view of the TM Forum's process levels published by AMDOCS. Source AMDOCS Online Posters [13]

The process reference model enables vendors, implementers or analysts to assess the coverage of a project or implementation that they are engaged in. It aids in identifying gaps in requirements as well as areas where they may be a possible implementation impact. The reference architecture contains levels of abstraction that makes communication of its content easier based on who the audience is. In ***figure 4*** there are several process levels. The first level is labelled Level 0 (zero). It has two distinct process areas namely:

- **Strategy, Infrastructure and Product**: These processes deal with the creation and management of the strategic products and services delivered by a service provider.
- **Operations**: These processes deal with the enablement and billing of the products and services delivered through a product, service and resource (equipment) lifecycle.

The process framework delineates strategic, tactical and operational processes. The remainder of the process levels stretches from level 1 to level 3. Examples of a level 1-process are those that traverse all vertical or horizontal process groupings. In the figure, level 1-processes are the vertical grouping Product Lifecycle, Assurance and Billing processes. Level 2 processes are located at the intersection of a level 1 vertical and level 1 horizontal process groupings. Examples of these are the processes found for Bill Management & Inquiry or Resource Trouble. Level 3 processes are omitted in ***figure 4***. At the time of writing, the TM Forum are engaged in creating level 4 descriptions of key processes in the reference model [**14**].The presence of this work is acknowledged and ignored purposefully as the process and information frameworks selected for this dissertation use a definition map of available process documentation to classify the fault detection requirement for substation equipment specifically.

The TM Forum has recently extended its reach into the area of smart grid through its member driven initiatives called catalyst programs [**15**] [**16**]. Smart grid requirements use the vertical and horizontal layers of the process framework to outline scope as smart grids have both systems and communication requirements. One of the advantages of using a reference model for smart grid is that users of the model are able to clearly delineate the scope within which a project or initiative operates. The reference model also provides a means to check for gaps in the delivery model for smart grid projects.

This dissertation aims to reference the process framework in order to provide a classification for the fault detection process and does not attempt to change the levels or content of the pre-defined processes stipulated by the TM Forum.

2.2.2 International Electrotechnical Commission: IEC 61850

The International Electrotechnical Commission (IEC) is a standards body that produce standards for electronic, communications and information devices. The commission has a member base of 81 countries with 60 full members and 21 associate members [**17**]. South Africa, represented by the

South African Bureau of Standards (SABS), has full membership status that allows the SABS voting rights on standards and access to technical documentation and IEC management activities.

Technical committees and technical sub committees produce IEC standards. Each of the committees develops and manages a series of publications through structured workgroups. The standards required for smart grid equipment interfacing is handled by technical committee 57 (TC 57). The standards published by TC 57 focuses specifically in the areas of:

- Tele-Protection and Control Equipment;
- Distribution Automation;
- Communication Networks and Security; and
- Application and Energy Management System Integration.

This dissertation uses the IEC 61850 standard due to the applicability of this standard in analysing substation disturbance scenarios. The IEC 61968 network operations interface is the only other standard produced by TC 57 that deals with fault isolation. The IEC 61850 is a multi-part substation communication standard that has been in existence since 2003 [**18**]. Each part of the standard contains specific requirements for IEC 61850-project management, substation configuration, interface modelling, data modelling, mapping to other IEC standards and conformance testing. ***Table 1*** indicates the publication structure extracted from the IEC standards list [**19**] for TC 57.

Table 1 IEC 61850 document structure. Source [19]

Reference Parts	Domain	Short Description
IEC/TR 61850-1	Substation	Introduction and Overview
IEC/TS 61850-2	Substation	Glossary
IEC 61850-3	Substation	General requirements
IEC 61850-4	Utility Automation	Systems and project management
IEC 61850-5	Substation	Communication requirements for functions and device models
IEC 61850-6	Utility Automation	Substation Device Configuration Language
IEC 61850-7-1	Substation	Principles and models for substation and feeder equipment communication
IEC 61850-7-2	Utility Automation	Abstract Communications Service Interface
IEC 61850-7-3	Utility Automation	Information Model (Common Data Classes)
IEC 61850-7-4	**Utility Automation**	**Information Model (Logical Nodes and Data Objects)**
IEC 61850-7-410	Utility Automation	Monitoring and control communication for Hydroelectric power plants
IEC 61850-7-420	Utility Automation	Information Model for Distributed Energy Resources
IEC/TS 61850-80-1	Utility Automation	Guideline for Information Exchange between substations and control centres

IEC 61850-8-1	Utility Automation	Communication Service Mapping - Mapping to Other ISO/IEC Standard
IEC/TR 61850-90-1	Utility Automation	Use of IEC 61850 for the communication between substations
IEC 61850-9-1	Substation	Communication Service Mapping – Sampled values over serial unidirectional multi-drop point to point link
IEC 61850-9-2	Substation	Communication Service Mapping - Mapping to Other ISO/IEC Standard
IEC 61850-10	Substation	Conformance Testing

The need for a data model and associated interfaces exists due to a multitude of vendors delivering devices that serve somewhat blurred functional boundaries. Devices sold in the past by vendors have complex integrated processes that require specialist skills to operate [**20**]. The aim of the 61850 standards is to provide needed visibility to externalised processes and definitions that cut across clearly defined device functions. This is accomplished thought the creation of logical classes and a set of abstract services components.

The dissertation references 61850-7-4 that deals with logical node and data classes required for information exchange between components. Researchers use a meta-model to communicate the dependencies between 61850 model concepts [**21**]. ***Figure 5*** extends current model representations by including constraints for data types though the introduction of attribute domains. The figure shows that a data attribute has one domain. This means that the data is of a specific type.

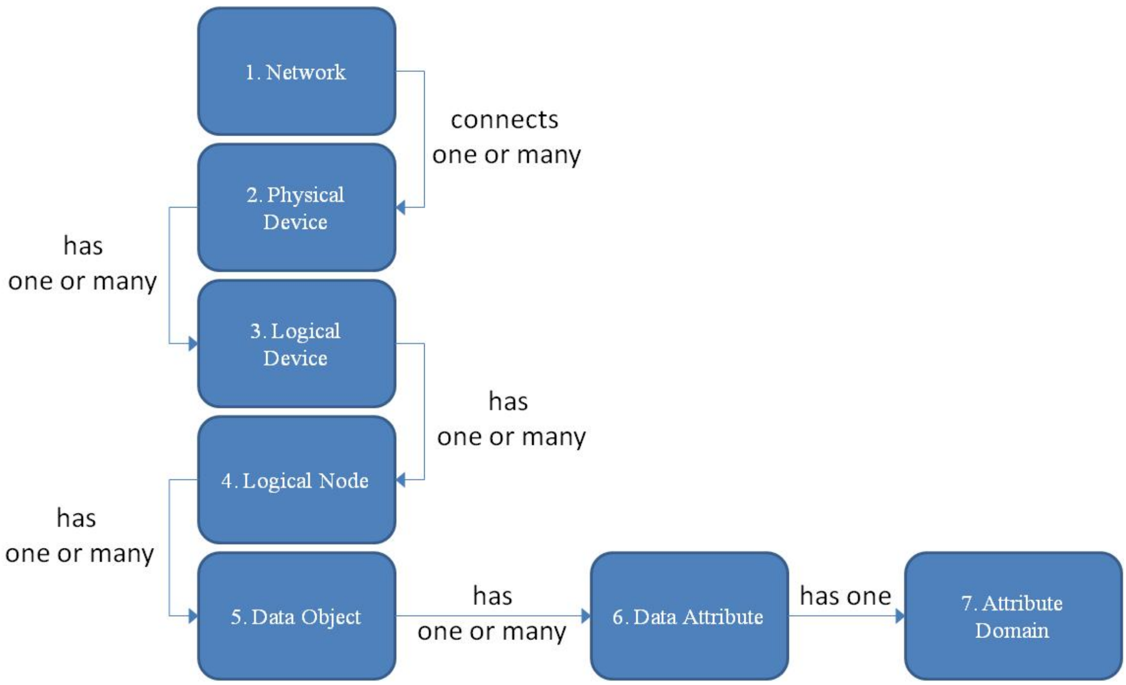

Figure 5 A Meta model for the IEC 61850 information model. Source IEC 61850 Class Model [21]

The following definitions apply to ***figure 5***:

- **Network:** This refers to the physical transmission medium over which control signals are sent;
- **Physical Device:** This refers to a physical substation device that is connected to the communications network
- **Logical Device:** This is refers to a function that is present in specific physical devices.
- **Logical Node:** This is representative of a sub function or logical split of the function supplied by the logical device.
- **Data Object**. This is a collection of attributes that describe the overall state of a logical device
- **Data Attribute**. This is single characteristic of a data object.
- **Attribute Value**. This is a specific range that describes the data attribute. For example, a Boolean attribute value will have one of two possible values, Yes/No or True/False.

Logical Nodes in the IEC 61850-7-4 standard include Protection Functions, Control, Generic References, Interfacing and Archiving, Automatic Control, Metering and Measurement, Sensors and Monitoring, Switchgear and Instrument Transformers. This effectively means that transport of standardised information between equipment of these categories is possible.

2.2.3 IEEE Std. C37.111-1999: COMTRADE

The Power Systems Relay Committee of the IEEE Power Engineering Society has developed a common file format used for transient fault information exchange. The standard, known as the IEEE Standard Common Format for Transient Data Exchange (COMTRADE), deals with persistent data storage and not transported data as in the case of 61850 [**22**]. This largely means that the standard can be used to create optimized physical data structures to support the storage of fault information. The format contains four key files used for storing fault information:

- A header file which was the. HDR file extension;
- A configuration file which has the .CFG extension;
- A data file which has the .DAT extension; and
- An information file which has the. INF extension.

Table 2 C37.111-1999 data file distribution. Source [22]

Name	Type	Target	Requirement
Header	Optional	Plain Text	Data file information and comment
Configuration	Mandatory	Plain Text	Defines data file format
Data	Mandatory	Plain Text or Machine Readable	Contains sampled event data
Information	Optional	Plain Text	Contains access requirements

The standard explores multiple representations of each file with each file named according to a set format. Based on the file types and requirements, some these files become candidates for reporting and monitoring input, which defines suitable structures for analysing data. ***Figure 6*** indicates the information classes that form part of the COMTRADE configuration files.

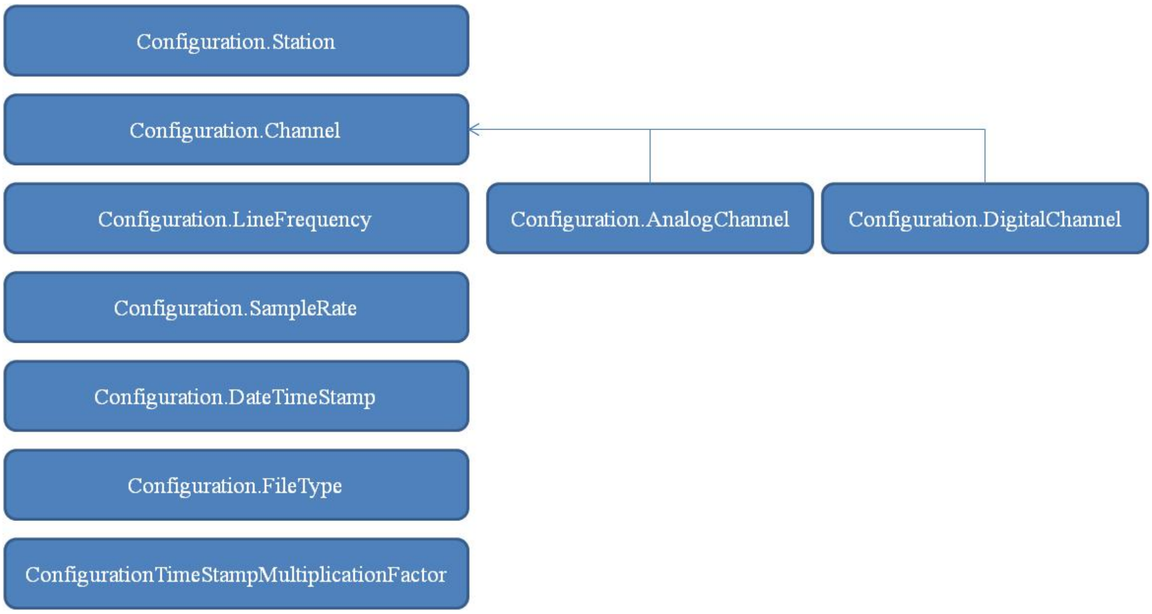

Figure 6 Information Entities for COMTRADE configuration files. Source [22]

2.3 Conclusion

Standards are a result of combined efforts by organisations to drive interoperability and accessibility agendas in technology and infrastructure implementations. Standards-based implementations for classification, transient and persistent information is defined using process and information architectures from the TM Forum, and information architectures from the IEC and IEEE. The implementation of standards are important to the align efforts for driving robust architectures of telecommunication and utilities infrastructure. The harmonisation of standards that form part of daily utility and communication operations is vital in that there is an inevitable convergence of these standards. The success of standards convergence is measured by the ability of interoperable models to be associated with each other by placing little or no constraint on the standards to which they plan to align.

The dissertation uses three diverse standards to enable a coherent implementation across power, information systems and communication environments. The position taken in this dissertation is to harmonise sections of each standard in order to deliver a set of a tangible components within the specific guidelines set out by each of the standards.

CHAPTER 3
ARCHITECTURE

3.1 Introduction

This chapter deals with the scope, requirements and architecture patterns needed to deliver a service-based solution that enables flexibility and agility in the area of substation fault detection.

3.2 Wide Area System Requirements

In the United States, the National Institue of Standards and Technology (NIST) provides a view of a smart grid architecture outlining information and electrical flows. This is seen as a suitable means to state the boundary of the applications that serve specific functions. The models used by the NIST provides context only and does not represent how the proposed architecture will be deployed. In addition to the power flow from a utility's generation to distribution infrastructure, smart grid networks are linked to users that are internal to the utility as well as consumers that are external to the utility. This means that the smart grid connects all users of the power value chain. ***Figure*** *7* is derived from a conceptual model proposed by the NIST [**1**]. The model indicates that there is a secure information flow between all parties engaged in the power value chain over a shared network. Smart Grid models in current research shows that there is a need for extending the reach of analytics through the integration of data and information from disparate sources found in Generation, Transmission and Distribution environments [**2**].

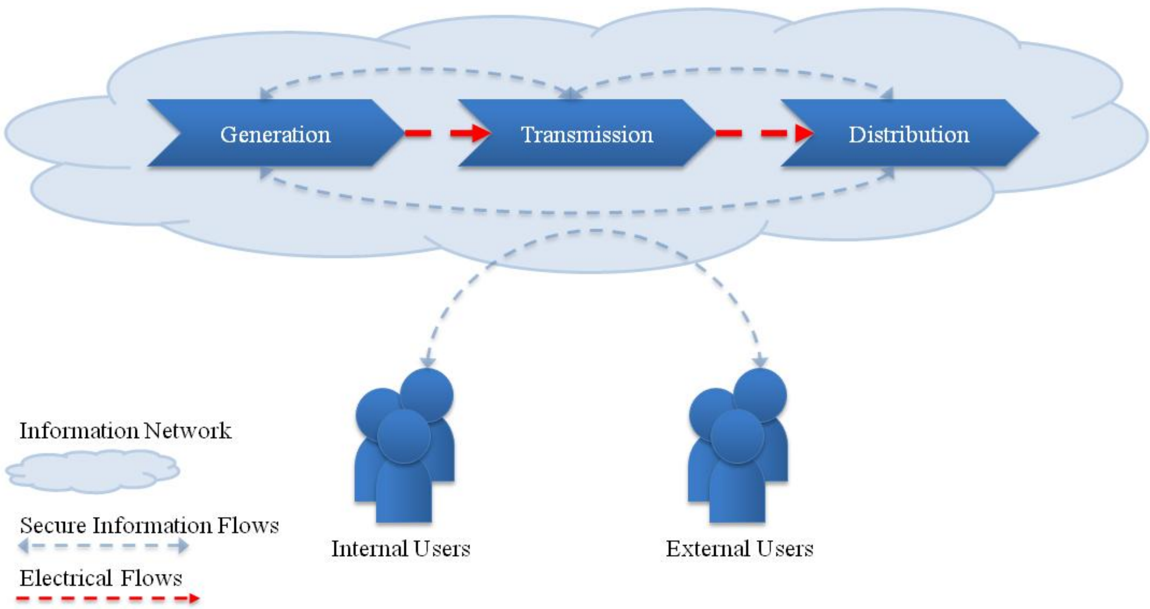

Figure 7 A conceptual information network for exchanging power system information. Source NIST Smart Grid Framework [1]

In the US, the NIST have outlined requirements for the implementation of a wide area monitoring protection and control environment. A key infrastructure component in the wide area protection and control environment are substation systems that enable fast communication and information exchange. A centralised substation control computer system, or data concentrator, is a system that is able to communicate with the control centre that monitors substation activities [**2**]. The substation systems and communication links between the substation and the control centre therefore require redundancy and high availability in order to meet low or medium latency information exchange requirements. For example, a non-functional requirement of this system is to deliver information to specific substation devices within threshold ranges.

In order to certify the integrity of the information across substation systems, synchronisation methods that comply with IEC standards are deployed to substations to ensure correct timing and structure of information propagation [**2**]. The IEC standards support substation process-bus communication. This communication is sensitive to delays due to the role of the bus in connecting primary device equipment in the substation together. A network station wide bus connects substations to the outside world over a wide area network via a secure gateway appliance. The latency requirement for communication of this bus is marginally slower than that of the equipment bus. A wide area monitoring system should support two types of information stored and requires synchronization across data stores. Synchronisation occurs at all affected nodes on the network. Data stores can be of two types:

1. Localised to the substation for low latency processes, activities and tasks. For example, trip signals sent from a relay to a breaker.
2. Decentralised to the substation for higher latency processes, activities and tasks. For example, post fault analysis processes for fault trending and equipment failure prediction.

There are constraints placed on distributing data for substation integration. The NIST explores areas of contention for deploying different classes of storage [**2**]. The NIST compare the use of disk versus file access methods with the former storage mechanism suffering from I/O contention issues. Files provide faster access but come with a large management overhead. Certain standards do however aim to reduce the identified overhead through specific file extension and naming requirements. These standards are used to check for the absence or presence of specific files on the substation file system. An example of this is the COMTRADE file format that follows the xxxxxxxx.yyy naming standard [**22**].

In order to support either local or distributed data storage patterns, a requirement exists to produce data access components that offer reuse and are polymorphic. The dissertation focuses on positioning function call patterns in a multi-layer architecture to meet specific non-functional requirements.

Function call patterns are common function call paths that execute to deliver the fault detection process.

3.3 Substation

Lusby defines a substation as an interconnecting component of the power system grid [**23**]. Substations are nodes that provide isolating, transformation, control, corrective functions to the power grid. They are important to the dissertation as they generate data and information required to manage the grid. There are several substation design patterns in use today. Cost, reliability, location, and safety factors are some of the variables that affect decisions relating to substation design. Substations are very complex entities that have multiple configurations, tooling, processes and management requirements. In addition, they require specialised skills to manage and design.

An analysis process to decompose the main functions and information that enable effective substation operations must be used to understand the exact requirements and impact of any new technologies into the substation environment.

3.3.1 Equipment

The generation and dissemination of timely information is vital to support accurate decision-making. In substations, the provision of accurate and quality information is needed to increase reliability whilst decreasing safety and security risks [**5**]. Substation monitoring and control devices have evolved from hardwired analogue interfaces to digital interfaces and microprocessor based equipment [**20**]. Intelligent Electronic Devices (IED) generate information in substations. An IED is defined as a processor-based unit which has at least one communications port capable of receiving and sending control signals to enable specific functions [**24**] [**25**]. Standards that govern inter-substation process and information flows create a logical to physical mapping of the core functions that these devices enable [**26**].

Within the scope of the dissertation the information produced by Digital Fault Recorders (DFR), Digital Protection Relays (DPR), and Circuit Breaker Monitors (CBM) are considered to be the main sources of data for the creation of fault detection information. Each substation device provides a clear set of functions that supplies a set of information used in the analysis of component condition and operations. These device types interface with other components in the substation via direct connection or via feeds onto the file system of device with which it is interacting.

Figure 8 is derived from a substation automation architecture indicated by Kasztenny *et. al.* [**27**]. The figure indicates that the area of intended purpose for the data defines the placement of the data and the relationships between different buses in the substation. It indicates the control flows between substation sub systems, and by definition, the information flows between these systems. The access requirements for each of the buses have a varied latency.

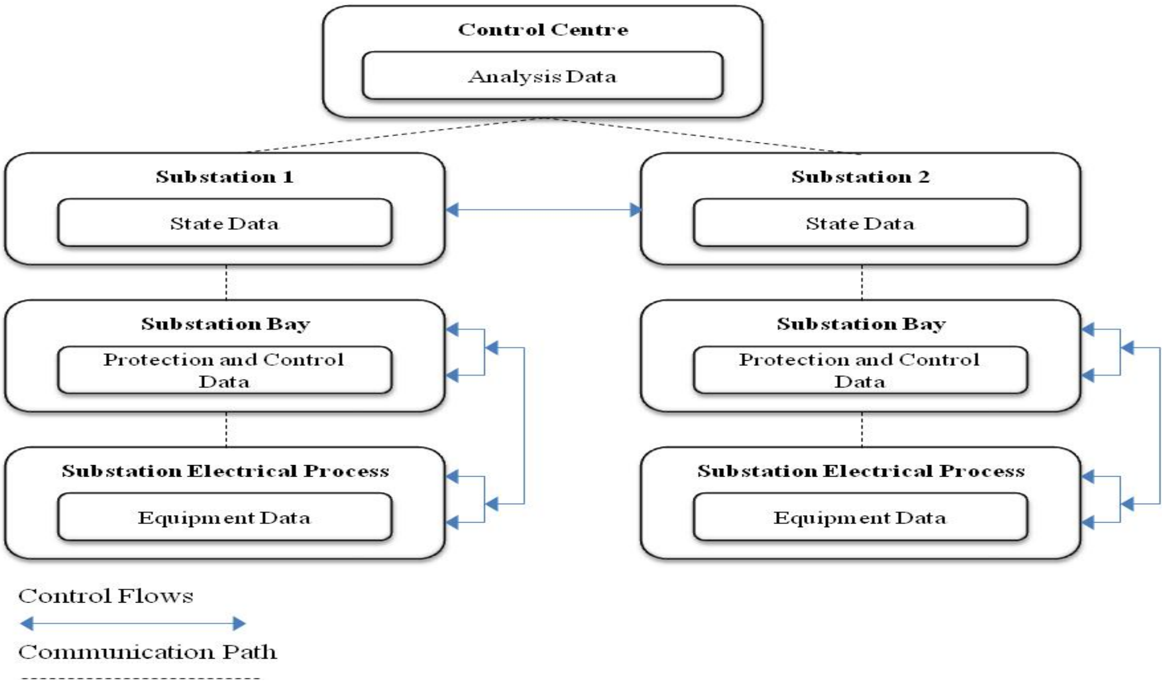

Figure 8 Substation protection control flows and data placement. Source IEC 61850 Substation Automation Interface Model [27]

In ***figure 8***, the substation nodes (substation 1 and 2) contain the substation wide operational and condition state data and information. Moving lower down the chain of data stores the requirement for availability of data increases to a real time view as the data needed at lower levels support electrical process real time action. It should be noted that the control and data flows between different components in ***figure 8*** occur simultaneously. It is not a serial process. Due to the nature of these components normal operations generate both related and unrelated data thus increasing the volume of data that can be processed and analysed.

3.3.2 Substation Operational Data Store

A substation operational data store is a local data store that holds data pertinent to the equipment and devices that operate within the substation boundary. Depending on the requirement, data can be stored in databases or as flat files. Most databases are, however, file-driven with well-designed access and management protocols and user interfaces. For example, Microsoft Sequel Server either stores data files in .mdf format locally or distributed across a storage cluster.

A problem of varying data formats is a known issue in current research [**2**] [**3**]. The standardisation of data structures are required in order to integrate substation data effectively. Standardisation, also known as transformations, can occur in the following scenarios [**28**].

1) Transformation could happen close to the intelligent electronic device. This means that the conversion to a common substation information model will occur via embedded device

software or software supplied by the device vendor. The device would deliver a common format onto the substation file server or substation master computer.

2) The transformation could happen after the device has delivered a non-standardised file onto the substation file server or substation master computer. This means that the server or master computer would require a client service call to load the file, transform and automatically export a file formatted in the common file format onto the server or master computer.
3) The substation device will use its native format in executing normal substation operations and only transform the file to the standardised format if the substation needs to communicate with transmission substations or directly with the control centre.

Certain design uses a "triggered" event to indicate the presence of a file or data in the substation computer [**29**]. The application design proposed in this dissertation considers an event as a published information message rather than continuously checking whether a file is present in a specific file system location.

The second and third scenarios are of particular interest as these are the scope of post-fault analysis processes. However, each of the scenarios needs to be investigated for performance, usability and reusability. Standardised file formats should be compliant to COMTRADE for Power Systems. The area of substation data concentration is the topic of many research efforts. Researchers discuss centralisation and classification of information in [**24**] [**29**] [**30**]. This is by no means an exhaustive list of references as the use of integrated substation data cannot be understated at this stage of substation device evolution. Determining the type of warehouse or operational data store, which is a subset of the broader enterprise warehouse, is driven by the latency and performance needed to fulfil basic protection or reporting.

An influx of information for analysis purposes caused by an increase in the number of electronic devices in substations, and on the power grid holistically in cases of smart grid implementations, requires that a forecast is calculated on the growth of data and information stores. Simple calculation methods provide a means to forecast growth. Data store calculations can use an 8-bit calculation to create a size forecast model as proposed by Inmon [**31**]. The model in ***table 3*** can be used for calculating individual table sizes, however, this could include multiple table and variant growth rates to be more accurate. The numbers used in the calculation in ***table 3*** are indicative of a 256-byte record and a 10-byte primary key, for a period of 1.5 years for a single table.

Table 3 Calculating data store sizes for an 18-month time window. Source [31]

	byte	kilobyte	megabyte	gigabyte
Row Size	256 b	**0.25 Kb**	**0.0002441 Mb**	**0.00000024 Gb**
Annual Row Count Min	500 000 000			
Annual Row Count Max	510 000 000			
# of Years	1.5			
Key Size	10 b	**0.01 Kb**	**0.0000095 Mb**	**0.00000001 Gb**
	Minimum		**Maximum**	
Row Min/Max	**750 000 000**		**765 000 000**	
Total Minimum for 1.5 year(s)	199 500 000 000 b	194 824 219 **Kb**	190 258.03 **Mb**	185.80 **Gb**
Total Maximum for 1.5 year(s)	203 490 000 000 b	198 720 703 **Kb**	194 063.19 **Mb**	189.51 **Gb**

3.3.3 Architecture Boundary

Protection functions enable the grid to run at high capacity for a maximum time-period by implementing necessary safety and security controls to protect equipment and personnel. In order act on fault alarms, or to initiate protection resolution procedures, engineers and technicians require access to accurate information. This information must reflect the detailed state of components connected within the substation boundary. Researchers indicate the use of file systems and warehouse databases to retrieve and store event information. File systems and data warehouses are known design patterns used for substation integration [**3**] [**32**]. The modernisation of automated substation functions requires that integrated data is available for use by peer components housed in the substation boundary. Generated event information by multiple substation devices is available to applications via a file system or database link.

Using a process reference framework it is proposed that fault detection functions form part of the *Resource Trouble Management* processes found in the *Operations* core process grouping. This is a level 2 process indicated in ***figure 4*** of ***Chapter 2***. The dissertation later discusses the definition of this level 2 process.

The application design proposed by the dissertation allows operators, analysts and planners to analyse disturbance data in the substation. Knowing that a fault has occurred allows the efficient dispatch of technicians to the correct physical location minimising downtime and as well as supporting reliability goals of the grid. However, multiple devices in the substation can send the same information that affects the integrity of the data [**28**]. Based on a numbers of possible duplicate events generated by devices in the substation the focus is on establishing and querying a master source of data for the fault detection process. Fault analysis can be delivered as a set of applications that run on the substation master computer [**29**]. Composite fault detection services are created to execute on a shared environment within the substation.

The federation of data sources provides a way to decentralise data placement whilst still supporting consolidated information views. In future, the need to federate smart grid information from various sources will increase due to an increased number of information providers. These views are required to support dynamic pricing, demand and supply modelling as well as other tenets of smart grid operations. The data and information supporting fault analysis play an important role in these operations and are justified as dependant variables in the calculation of these tenets.

Currently requirements for data integration span three specific classifications of data. SCADA, Phasor measurement and intelligent device data are applied to different analysis requirement categories [**30**]. Research in the areas of integration data still focuses on delivering some kind of source to target transformation. This actually means that warehouses must support real-time loading and reporting which in turn require stringent availability and quality of service requirements. The database structure of a warehouse should be de-normalised to enable the ability to query information with sub second response times. The design of data structures for substation information should consider the questions of flattening records versus records that have a high referential integrity.

The application design classifies data into four broad categories:

- Data that needs to flow between two devices in order complete a specific function;
- Data that will be written to a file system or database;
- Data that will be retrieved from a file system or database; and
- Data requirements for transient calculations.

The standards selected must support the following requirements:

- Mapping of the device outputs to the substation data store source and/or target structures;
- Standardise the target load process; and
- Increase clarity in analysis process by reducing complexity.

Table 4 indicates how the standards selected for the fault detection process supports the stated data requirements.

Table 4 An alignment of the selected TM Forum and IEC standards to support fault information requirements

Requirement	Standard	Preferred nomenclature used in this dissertation
Substation device mapping	IEC 61850-7	Device Information Architecture
Standardized file system or database landing format	COMTRADE	Fault Information Architecture
Enterprise wide utility business process and activity visibility	TM Forum eTOM	Utility Process Architecture
Enterprise wide utility definitions	TM Forum SID	Utility Information Architecture

The fault detection process is a business process. A mapping between the TM Forum and IEC standards create a common understanding of the fault process from both a top down and bottom upper perspective. The following reasons support the selected mapping approach:

- The utility process architecture will not require a remapping to the utility information architecture as both of these architectures are actively maintained by a single standards body;
- The IEC 61850-7 Standard will undergo minimal change;
- Mapping of the utility information architecture (SID) definitions to the IEC and IEEE Standards ensure that standards are coupled only as tightly as their relevant transformations. Changes to any of the standards do not affect other standards directly.

The area of common information models is currently a well discussed topic as seen by standards like IEC 61850, IEC 61970 and IEC 61968. Wherever a number of software and hardware vendors implement similar technologies, the need for common information is always present. Centralised and decentralised warehousing models, and access to warehouse information, is the subject of known data integration activities. The implementation of common utility information access through common infrastructure is supported by the creation of physical common information platforms [**33**]. Technology implementations like the Common Information Data Platform System (CIDPS) at Central China Grid Company Limited, is one such example. Even though the authors of the CIDPS use the 61970 standard for energy management, the principle regarding common information for automation and integration within the substation boundary is evident.

3.3.4 Architecture Patterns

An architecture pattern outlines a set of constraints used to solve a common recurring problem. Patterns exist for most systems engineering problems. The decoupling of business logic and presentation is such a pattern in many Object Oriented programming languages. For example, a layered approach to software development indicates a three-tiered architecture pattern that decouples components in an application design [**51**].

In the world of data management, software vendors focus on two distinct patterns of data integration, namely batch and real-time. Conventional data warehouses use the process of extracting data, transforming the data into information and finally loading the data into a target data structure. The difference between moving data for warehousing versus application processing is that the latter executes in real time whereas the former requires batch loading. Data integration in the context of this dissertation focuses on all processes that are required to acquire, transform, store and retrieve data to support the fault detection process.

A clear distinction in the architectures of data acquisition, transformation and analysis is required [**28**]. Each of these categories has specific issues and need to be resolved separately to ensure no overlap or dependencies exist. An extension to the collection, transformation and analysis requirement is to include a storage, retention and access methods for data collected through substation operations.

The architecture patterns indicated in ***figure 9*** is derived from the wide area monitoring and substation communication views indicated in [**2**] and [**28**]. In ***figure 9***, there is a requirement for multiple communication links within and between substations. One of the most important links is the substation to the control centre link. The interface and data model required for energy management systems should conform to the IEC 61970/968 standard. A second communication link occurs between substations. This will likely be a fault recorder communicating to another fault recorder via a secure gateway appliance on the substation boundary.

Both of these communication links may exist over a wide area network. There is a need for fast incoming and outgoing control centre links, with low data contention ratios, if a requirement to route communications between substations via a control centre exists.

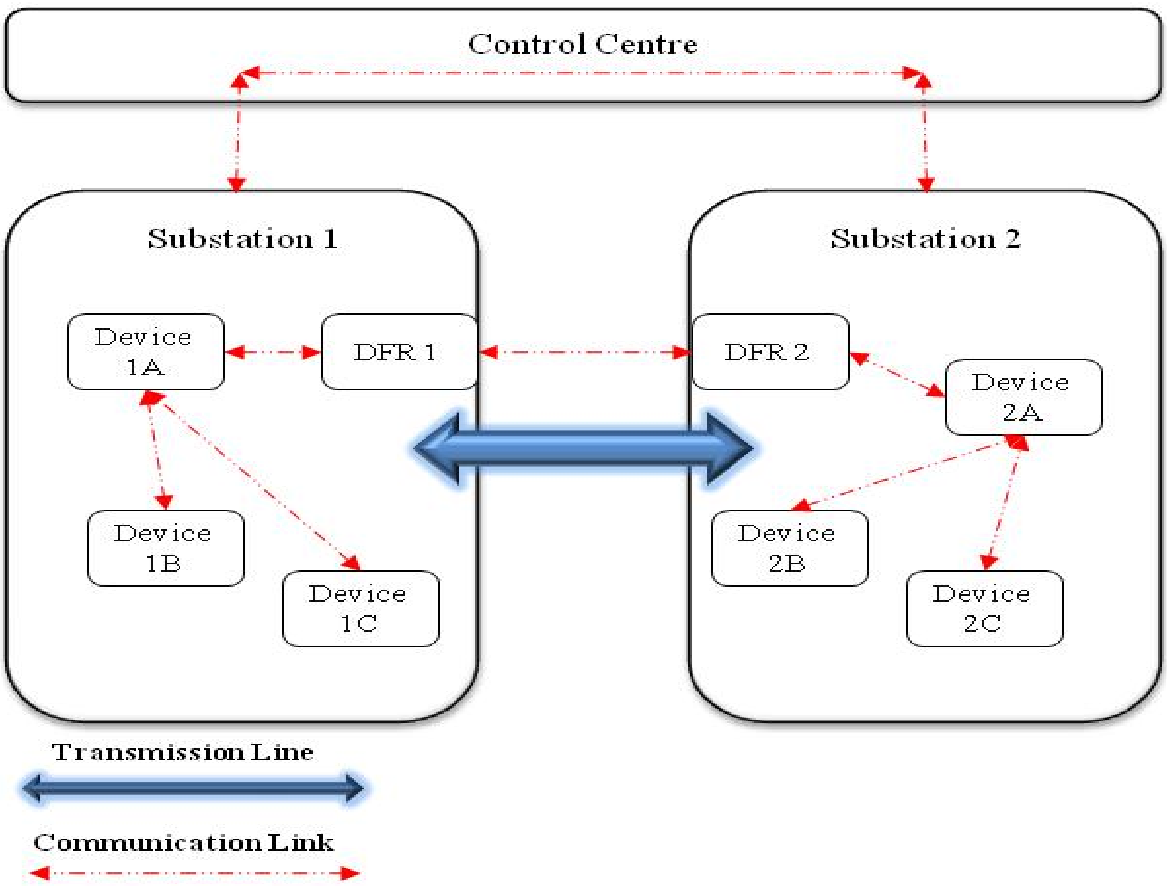

Figure 9 A substation fault information collection pattern. Source Wide Area Monitoring System [2] and fault event records capture [28]

Information collection paths in the figure can occur between Device 1A and Device 1B or between Device 1A and Device 1C. In order for communication to be complete, and successful, these devices have to support the same protocols. Similarly, in the event of a disturbance, Device 1A will broadcast information to DFR1. Substation 1 will communicate the disturbance information to the control centre. Within the control centre, internal communications can ensure that all necessary parties are notified and event analysis performed to ensure that the fault does not affect other parts of the grid.

Figure 10 *extends* ***Figure 9*** to create a fault information storage pattern.

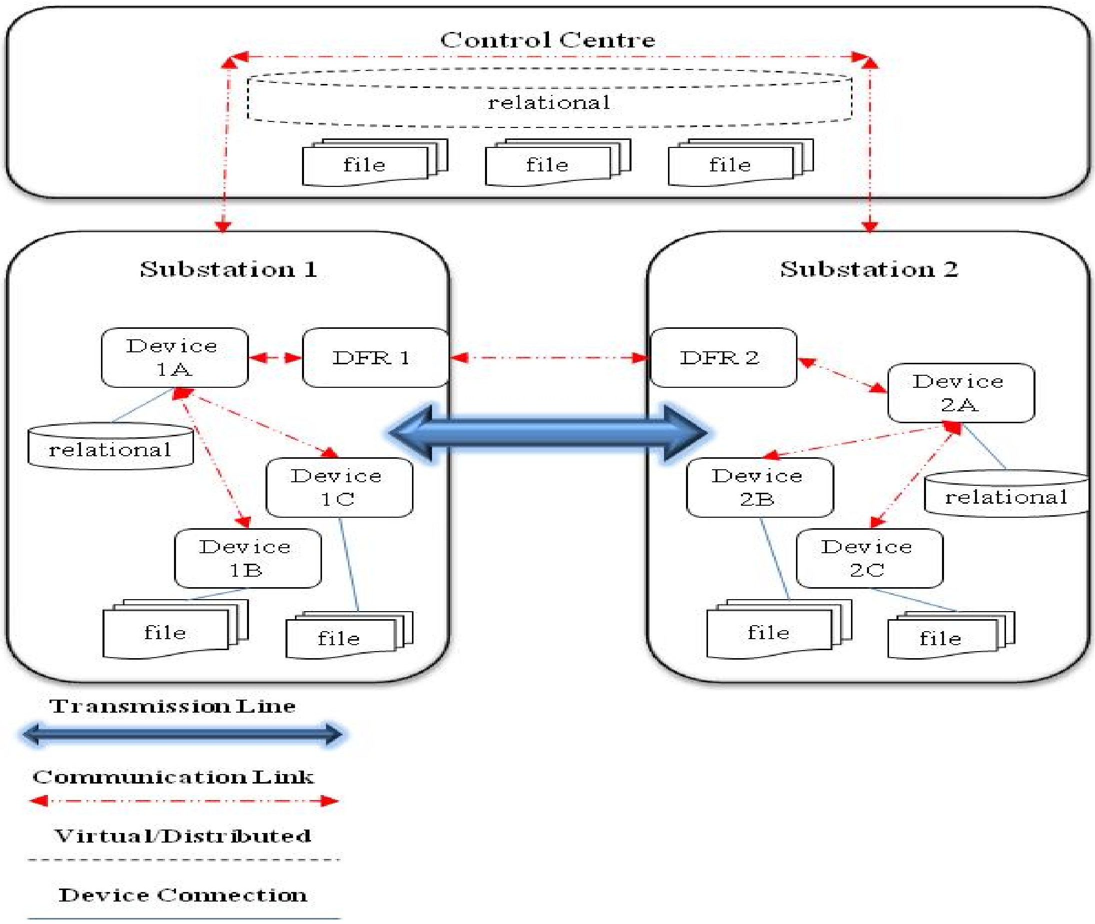

Figure 10 A substation fault information storage pattern. Source Wide Area Monitoring System [2] and fault event records capture [28]

In ***figure 10***, the fault-information storage pattern indicates that each device can store its own data. Data can be stored in a relational database or the file system local to the device. In systems design, this can be both an advantage and a disadvantage. An advantage is that devices can function more effectively by not transmitting or requesting information to and from an external source for its internal device processes. A disadvantage is that integration of this device may be extremely difficult due to tightly integrated internal device processes.

Due to the distributed nature of the substations and control centres, it may be beneficial to create a clustered database environment to aid in reliability and performance of information retrieval. An example of this would be the creation of a database that contains device information indexed by device identifier or event data that would support analysis of recent events for specific zones of a substation.

Figure 11 enhances ***figure 10*** to indicate the access methods for stored disturbance information.

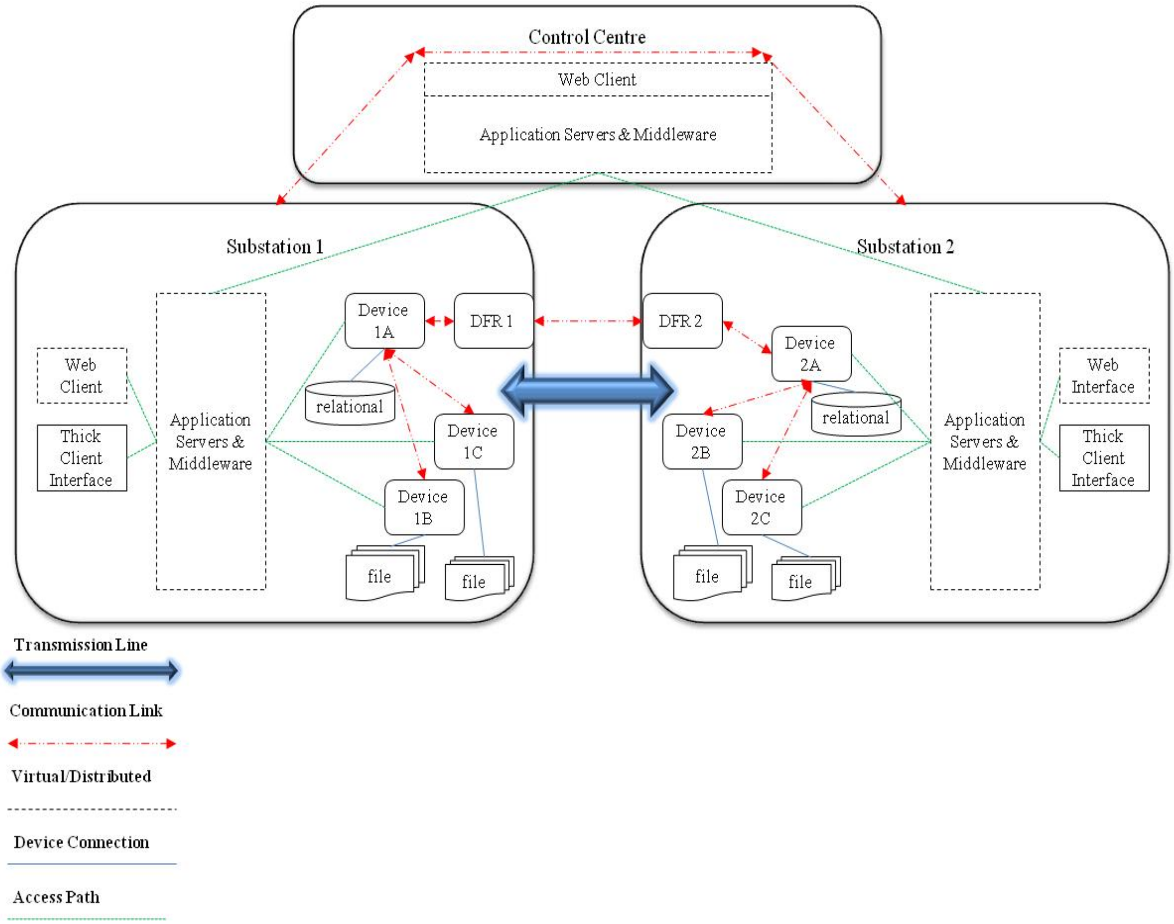

Figure 11 A substation fault information access pattern. Source NIST Conceptual Reference Diagram [1] and fault event records capture [28]

Figure 11 introduces access paths to the data that is required for fault detection. The pattern uses the domain communication paths indicated by the NIST [**1**]. Depending on the documentation available and knowledge of the device interfaces, access paths may or may not access device data stores directly. In the control centre, a web client that has its deployment components distributed may aid in accessing information more efficiently. Application servers and middleware like enterprise service buses will aid in the routing of control and information to provide effective access to information.

The collection, storage and access architecture patterns indicate a means to rationalise the process of performing fault detection. A fault detection method that uses two ends of a transmission line is the problem to which the collection, storage and access architecture patterns are applied. It is assumed that the data has landed at a specific location after the notification of a disturbance has occurred. Two ended fault location analyses makes use of time stamped event samples also used in power relaying and control [**34**].

Reports by the NIST indicate that standards for storage and access do not yet exist [**2**].

3.3.5 Architecture Alignment

The mapping of the models selected for the dissertation ensures that the application design does not expose itself to the changes that affect individual models and also allows more purpose driven information to be supplied to power system staff. The nature of standards implementation however is such that industry bodies may not necessarily look at all models outside of their domain of interest due to the vast number of models and standards that exist. It is important that all models are considered, however certain model mapping are already underway and the dissertation does not aim to redefine any of these mappings. The dissertation references the best practise instituted by the individual standards bodies where a model mapping already exists and proposes mappings where they do not exist.

Figure 12 indicates the scope of the model harmonisation requirement.

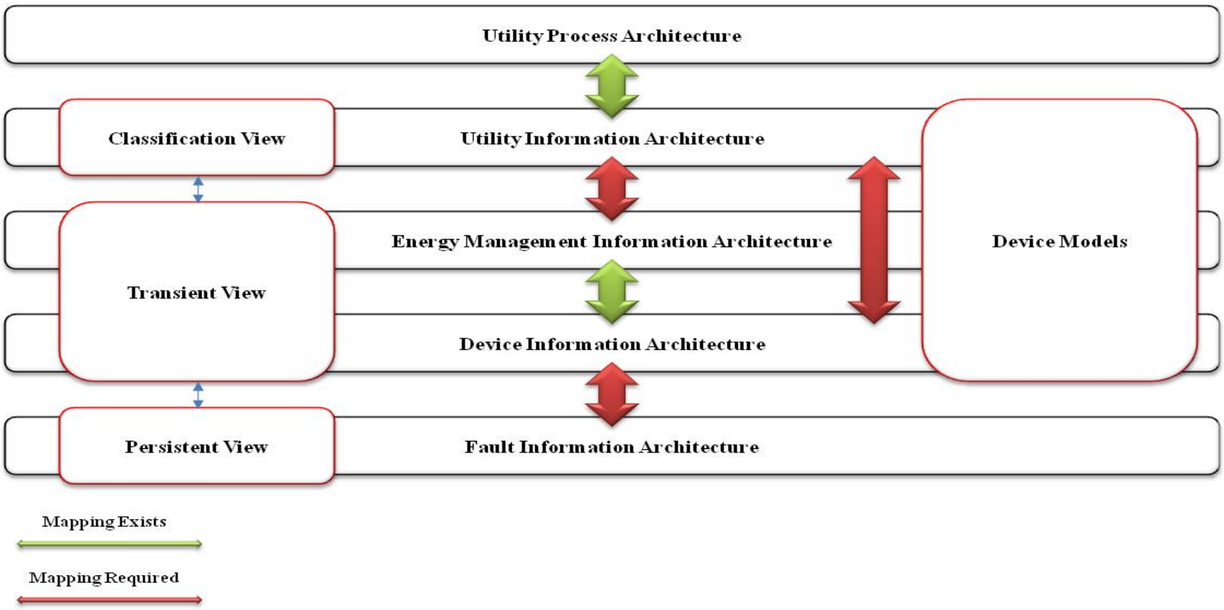

Figure 12 The process and information model mapping requirement for selected TM Forum and IEC standards

In ***figure 12***, the preferred nomenclature is used as indicated in ***table 4*** of ***section 3.3.3*** of the dissertation. ***Figure 12*** indicates where mapping exists and where mappings do not exist. The utility process and utility information architecture mapping already exists. The same standards body, namely the TM Forum, manages these standards. The energy management and device architecture mapping exists and uses a model driven approach to create the mapping between these standards [**35**].

A mapping between the utility information architecture and the device information architecture is required.

A point of departure for model mapping is to use the fault detection process. Using ***figure 4*** in ***Chapter 2***, the *Resource Trouble Management* level 2 processes are defined as the processes that are used to "*detect, analyse and report resource failure events*" as well as for "*fault localisation analysis*" [**36**]. A *Resource* is defined as a *"physical and non-physical components used to construct services. They are drawn from the application, computing and network domain, and include for example, network elements, software, IT systems, and technology components*" [**37**]. These process and information definitions form the basis of the mapping exercise.

Table 5 contains several definitions that will also be used to align the information required. The table contains an extract from the IEC 61850-7 model that was donated by ABB to the IEC TC57 Workgroup [**38**].

Table 5 Selected IEC 61850 logical node groups. Source [38]

Group	Type	Logical Node	Usage
P	Protection	PDIR	Decision to trip based on relays surrounding faulted component
R	Protection Related	RFLO	Fault Location
I	Interfacing and Archiving	IARC, IHMI	Human/Computer Interaction
M	Metering and Measurement	MMXU	Measurement
X	Switchgear	XCBR	Circuit Breaker
T	Equipment Transformers	TCTR, TVTR	Voltage and Current Sampling

Figure 13 indicates a map between previously unmapped architectures. By analysing the key entities found in the model definitions, a model mapping between the utility information architecture and the device architecture is possible.

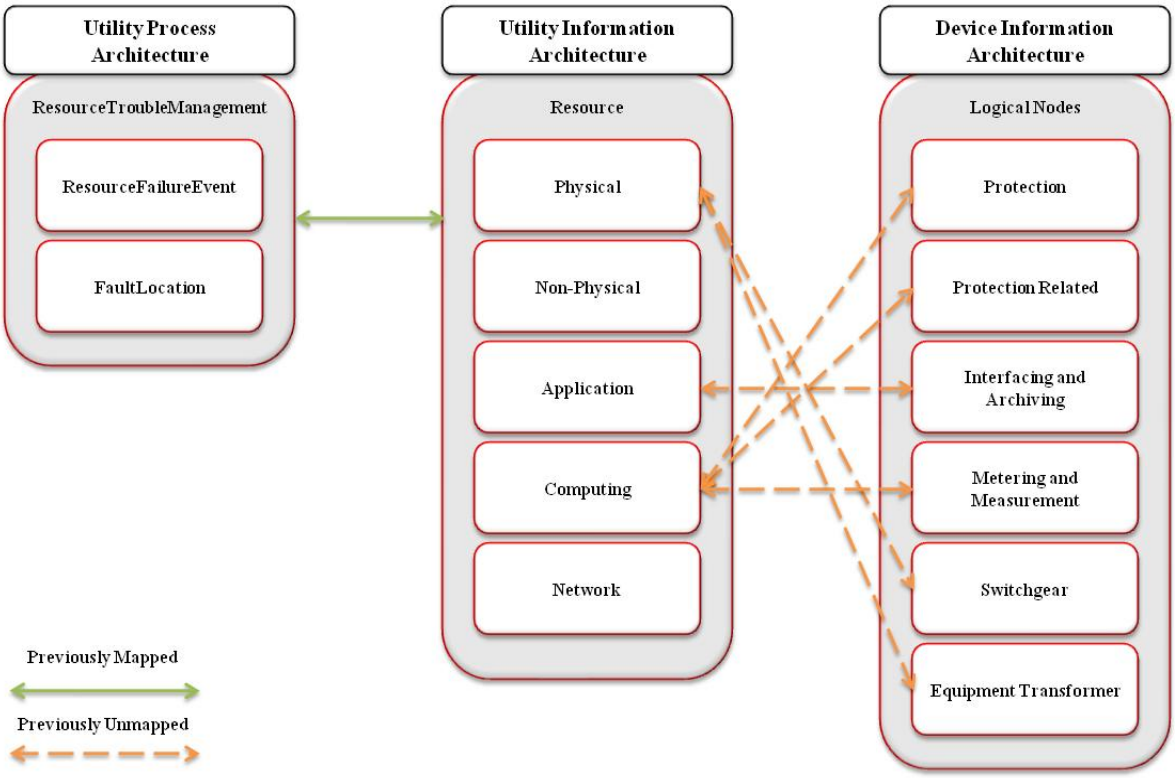

Figure 13 A TM Forum and IEC information model mapping diagram

Figure 13 indicates that switchgear and equipment transformers are physical equipment. Interfacing and archiving nodes map as application types. This definition holds true based on the usage of these applications in human-computer interaction in substations. Computing is assumed to be a processing capability enabled by a substation device. Trip decisions, fault location, metering and measurement are data centric computing processes that generate information.

The mapping performed in this section provides a conceptual viewpoint on how the input and output information will be structured. It also provides a high-level view of the information transformation or information re-structuring requirements.

3.4 Service Oriented Architecture

The proliferation of system engineering methods and architecture patterns over the last decade have aimed to resolve design flaws like tight coupling and low cohesion in legacy information and network systems. Software engineering textbooks all send the same message – produce software that is easy to deliver and manage. The flaws in systems design are present in most industry verticals, including power utilities.

In order to integrate legacy systems, service-oriented architecture (SOA) implementations are proposed [**39**] [**40**]. Technology companies also note the usefulness of service architecture in advanced metering management [**41**]. A service-based architecture is used for the same goals that software engineering aims to achieve, namely abstraction and component decomposition.

An SOA views a system as set of components, known as services that interact in order to provide a specific piece of functionality. Functionality delivered by these systems can be business focussed or provide some type of technical administration function. The role that the service plays classifies the service in service design to maintain design consistency. This is per the requirements laid out in a services framework. ***Figure 14*** references a smart grid reference framework [**1**], middleware reference architecture [**42**], and an SOA reference model [**43**] to derive a common service design pattern. The NIST reference framework indicates that there are several consumers of information and several providers of information distributed across domains [**1**]. The reference architecture diagrams on *page 4* and *page 7* of the JBOSS reference architecture also contain consumers and service composition layers [**42**]. The consumer layer could have multiple access points - like electronic data interchange and web interfaces - into the service architecture [**43**]. Mention is made of the process orchestration in the middle layer of the service architecture across the reference architectures. ***Figure 14*** is therefore representative of the service layers used in this dissertation.

The reference list used in indicating this architecture in ***figure 14*** is by no means an exhaustive list of references as every major software vendor in the software industry deals with service-based architectures in some form or the other. For example Microsoft, IBM, Oracle all have architecture frameworks that conform to a layered service architecture pattern. Services classified into specific layers of a framework may follow a pattern indicated in ***figure 14***.

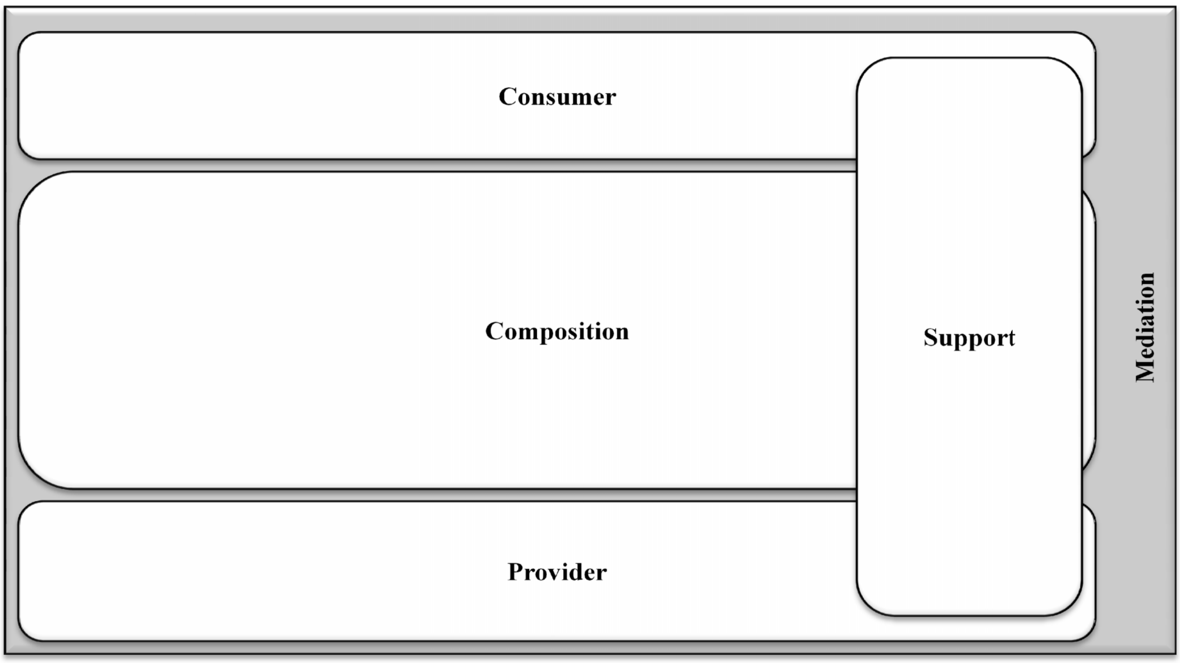

Figure 14 A layered service architecture pattern. Source Smart grid reference framework [1], middleware reference architecture [42], and an SOA reference model [43]

The general pattern is that specific layers indicate the context of the functionality offered by the service. Service description tables are used to derive these classifications [**43**]. Mediation of control and messages though an enterprise service bus (ESB) or another type of mediation platform underpins an SOA.

At times, low latency information requirements are not fulfilled due to increased response times caused by an increase in the number of handover and transformation points through the layers of the architecture. This occurs when services are very granular and causes high execution overhead. Granularity of services balances reusability and performance requirements [**43**].

Most development languages and systems development lifecycles are enabled to deliver an SOA. However, the delivery of services via web services has been the most prominent over recent years. By means of smarter information system infrastructure, the deployment, management and reuse of services are a current reality. Advancements in systems engineering methods leverage off existing methods by increasing the coverage of the artefacts that the current system engineering methods deliver. For example, the Unified Modelling Language (UML) delivers concepts like abstraction, encapsulation and polymorphism [**51**]. Service oriented architecture uses business processes to aggregate and decompose processes into web service implementation units. Service oriented architecture also encapsulates functions and information structures into service description units. In the case of contract-based services, a single service with multiple methods used in different ways is a form of polymorphism. In the scope of this dissertation, the SOA architecture pattern uses a process classification approach to derive functional units delivered as singular or multiple web service units.

Composite applications are composed of one or many web services [**43**]. These composite applications serve a specific purpose and the grouping of web services into logical or physical units aid in delivering a discrete piece of functionality. The activities indicated above can be either fine or coarse-grained services. This study opts for fine grained in order to increase flexibility in the design of the fault information access pattern discussed in ***Figure 11***.

SOA offers a means to re-structure operations and provides the necessary patterns to integrate operations. The IEC standards specifically aim to deliver open systems architecture for inter and intra substation systems integration efforts.

3.4.1 Services

Services are functional components that have defined inputs and outputs. Services can expose native application information or they can be used to create a standardised view of information in cases of common information model requirements [**33**]. Services can be fine grained which means that they have a few specialised methods or operations that delivers a very specific function. Alternatively a service can be coarse grained which means that the service can deliver more than one function either of the same or similar functional requirement. This is termed service granularity [**43**].

Figure 15 indicates a simple web service implementation.

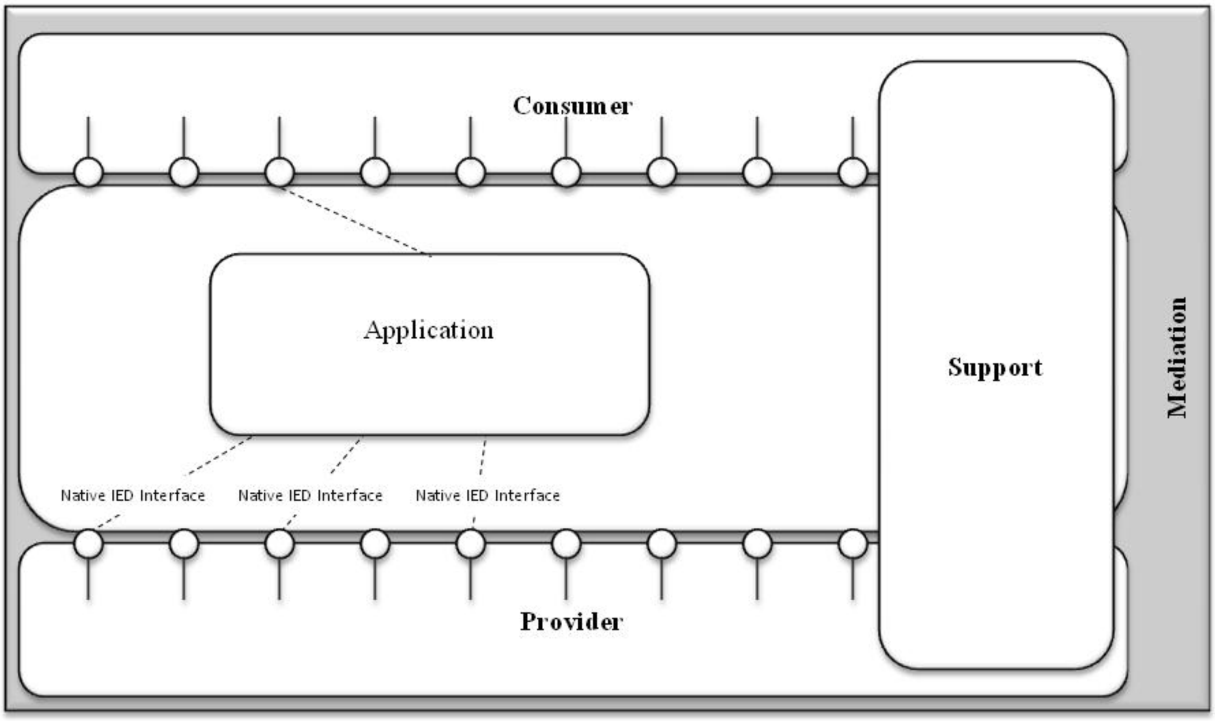

Figure 15 A simple web service application interfacing with service consumers and providers

As indicated in ***figure 15***, providers supply native device interfaces. These are the built-in processes that form part of the standard implementation for the device and its application software. Standard device interfaces may write data to a file system or to a set of database tables. These may or may not be in a standard format like the fault information architecture based on COMTRADE [**22**]. File writes can occur as automated file downloads or direct publishing of data values to a common information platform. The services that use data from source devices are *Data Services*. Data Services are atomic units that provide data without any context. For example, a service that uses the data manipulation capability of device or device firmware is a Data Service. Bahrami indicate this capability as being "*access and manipulate*" functions [**51 p.243**]. These services expose primitive values like current or voltage values. *Information Services* generate the semantic context to data. The definition of data and information services are aligned to that of the data providing and information processing services used in [**39**]. It is proposed that data sources are wrapped into a framework, like the Web Services Resource Framework, that provides the necessary reliability for the services implementation [**39**]. The Web Services Resource Framework (WSRF) provides the capability of the services infrastructure to test if an information resource has undergone any changes in state. For example, if the database or data store value has changed, the native WSRF interface would alert the application. It is further mentioned that the centralised storage of data is a poor architecture decision. The application design used in the fault detection architecture in this dissertation proposes that specific information is placed closest to the information access point for the intended web service functionality. ***Figure 16*** indicates the scope and domain for either service classification.

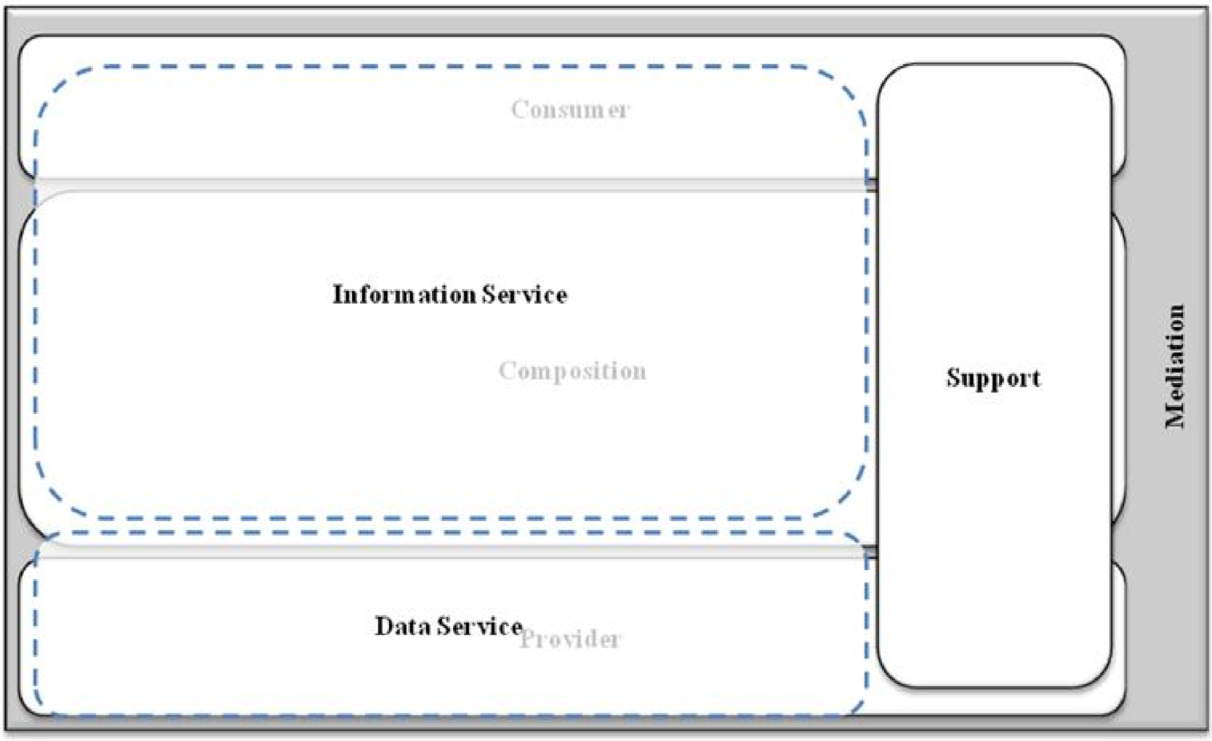

Figure 16 Fault detection information and data service domain. Source Data Providing and Information Processing Services [39]

The consumer and composition layers of the architecture works on the premise that data has been processed into information and may also perform the actual processing for data to information. The Web Services Description Language (WSDL) specifies the functions required for Data and Information services. A WSDL contains the interface names, messages structures and network protocol identifiers that form part of a service implementation [**44**]. A WSDL is an Extensible Mark up Language (XML) document schema. A fault information service can be implemented using single or multiple WSDL documents depending on the availability of data from specific devices.

3.4.2 Mediation

A service bus is an application that mediates communication in a service-oriented architecture [**45**]. In a service oriented architecture the service bus accepts, transforms or translates, and routes messages. It therefore serves as a key software application in integration environments. Design considerations like machine core and memory processing are standard requirements when calculating scaling metrics for any enterprise grade software application. The application design consideration must also include the ability to federate buses, message handling and message growth. Researchers use a number of metrics to define the ability of an ESB to fit into existing architectures [**45**]. The metrics are based on:

- The ability of the service bus to interoperate with technologies or protocols;
- The ability of the service bus to be extended by increasing basic machine capacity and by allowing machines to operate in a clustered environment;
- The ability of the service to deliver secure and reliable messaging;
- The extent of familiarity with the ESB application interface; and
- The availability and failure recovery mechanisms of a service bus.

In this dissertation it is assumed that the service bus infrastructure will house the service design in its current form. Load testing of the application design on any specific infrastructure is not in scope for this dissertation.

3.4.3 Schemas

Data schemas provide a structured view of the messages exchanged in a service-enabled environment. Schemas contain element, data types and its associated structure. Schemas are Extensible Markup Language (XML) documents having an Extensible Markup Language Schema Definition (XSD) file extension. Elements in the XML document structure can appear as single elements or as multiple elements that are grouped by a specific context in the XML document structure. These are simple and complex types respectively. Schemas provide much needed flexibility and scalability in data structure design.

Modelling tools like IBM Rational Software Architect provides the functionality to model schemas as UML class models and generate an XML Schema directly from the UML representation [**55**]. This is useful as you can leverage off the UML modelling patterns like generalisation, composition and aggregation.

3.4.4 Processes

Processes are defined a set of activities that deliver a specific objective [**46**].

A process executes in a specific order and generates information from data using defined inputs and outputs. An opportunity therefore exists to create and reuse functional components and design agile application architectures. The Business Process Modelling Notation (BPMN) [**47**] and Business Process Execution Language (BPEL) [**48**] supports the composition and ordering of process activities. Each process step contains a series of pre and post conditions, triggers and other valuable meta data that describes the purpose that the activity fulfils. BPMN is used for the orchestration of power system processes [**40**].

Figure 17 indicates key BPMN components in a simple process flow.

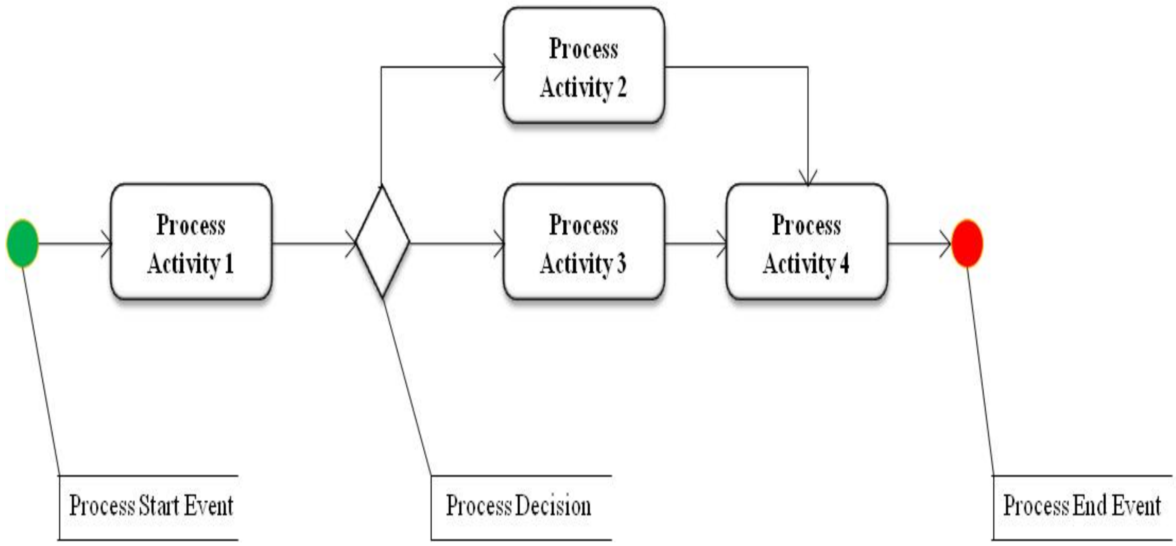

Figure 17 Basic business process modelling notation (BPMN) components. Source [47]

Figure 17 indicates that process activities connect together in an ordered manner. Arrows indicate the connections and flows between process activities. The process has a defined start and endpoint. Process activities can have single or multiple input requirements. For example, Process Activity 4 accepts inputs from Process Activity 2 and Process Activity 3. A decision component in the process controls the process flow. Process activities can also be decomposed into granular structures that are more granular [**43**]. Control within these granular activities can execute using BPEL. Functions like variable assignment, error throw and catch constructs as well as *If* and *While* programming constructs can be implemented in BPEL [**48**]. Less granular control can be accomplished using BPMN. Typically, BPMN drives the activity level flows, whereas BPEL implements the lower level web service control.

Business process notation and execution languages are significant components in service-oriented architecture. They support the ability to build applications that are monitored at a function level higher than that of known application server logging. Server logging is meant for application support personnel to aid in the application support process. It is important to model the correct process hierarchies to ensure correct process engineering and measurement at the correct process level.

Figure 18 shows how the processes relate back to the total process coverage map shown in ***figure 4*** of ***Chapter 2.*** Additional process groupings appear in the definitions accepted by the ITU [**36**] which are not shown in ***figure 4***. These processes are *Resource Performance Management* and *Resource Data Collection and Processing*.

Figure 18 presents the level 1 and level 2 process grouping within the context of the larger process framework.

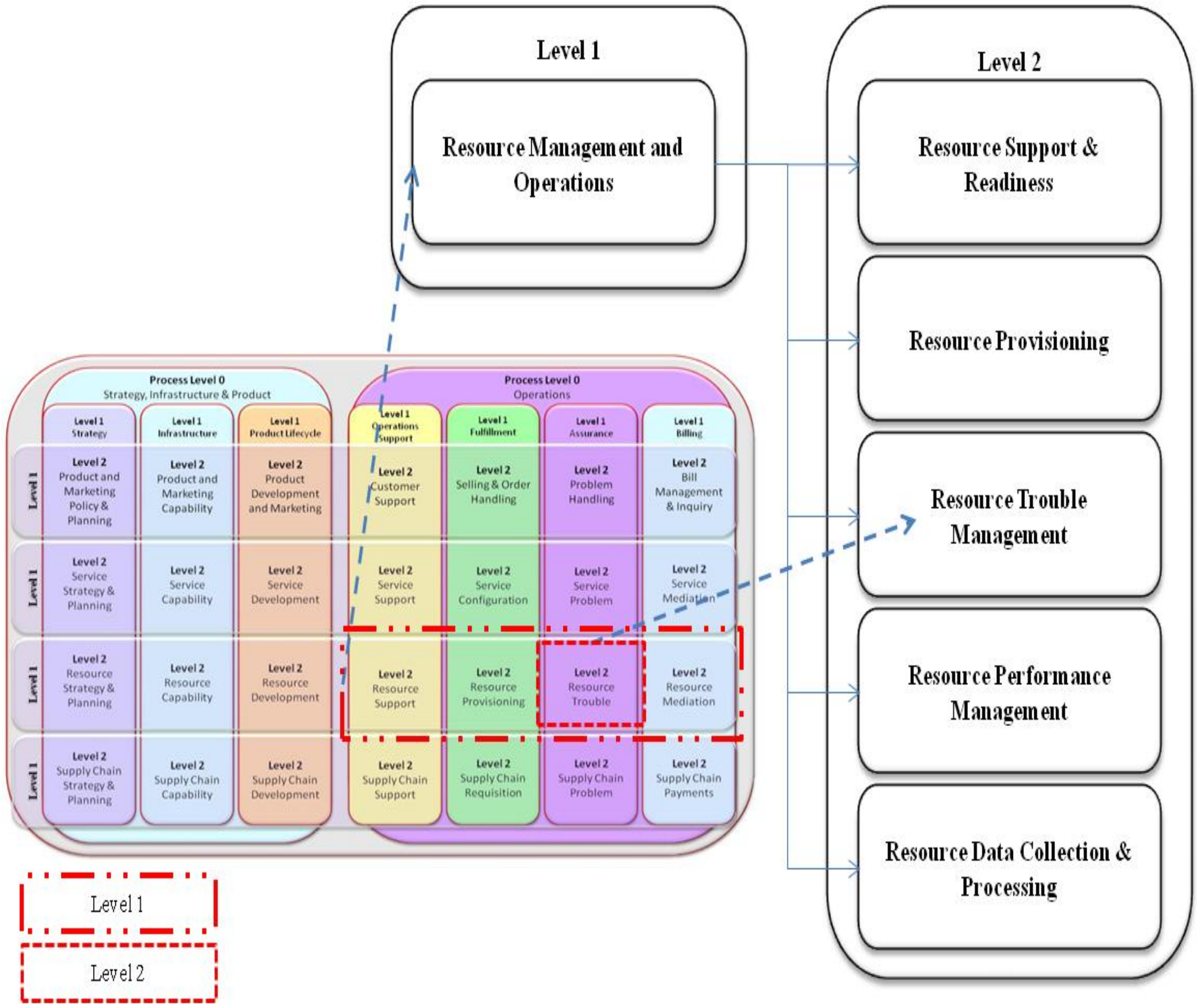

Figure 18 A defined process hierarchy that supports fault event reporting. Source Resource Management & Operations Process Decomposition [36] and AMDOCS Online [13]

Figure 18 indicates two process levels. Process levels 1 and 2 are standard TM Forum processes adopted by the ITU. In this dissertation there is no attempt to redefine these process definitions. An advantage of using the selected process reference architecture from the TM Forum is that it places no constraints on the order in which the process activities execute. The power utility determines the order in which the process should execute to best suit the utility's internal operations and policies. ***Figure 19*** provides an example of an end-to-end Resource Management & Operations process by combining the notation from f***igure 17*** and the process activities from ***figure 18.***

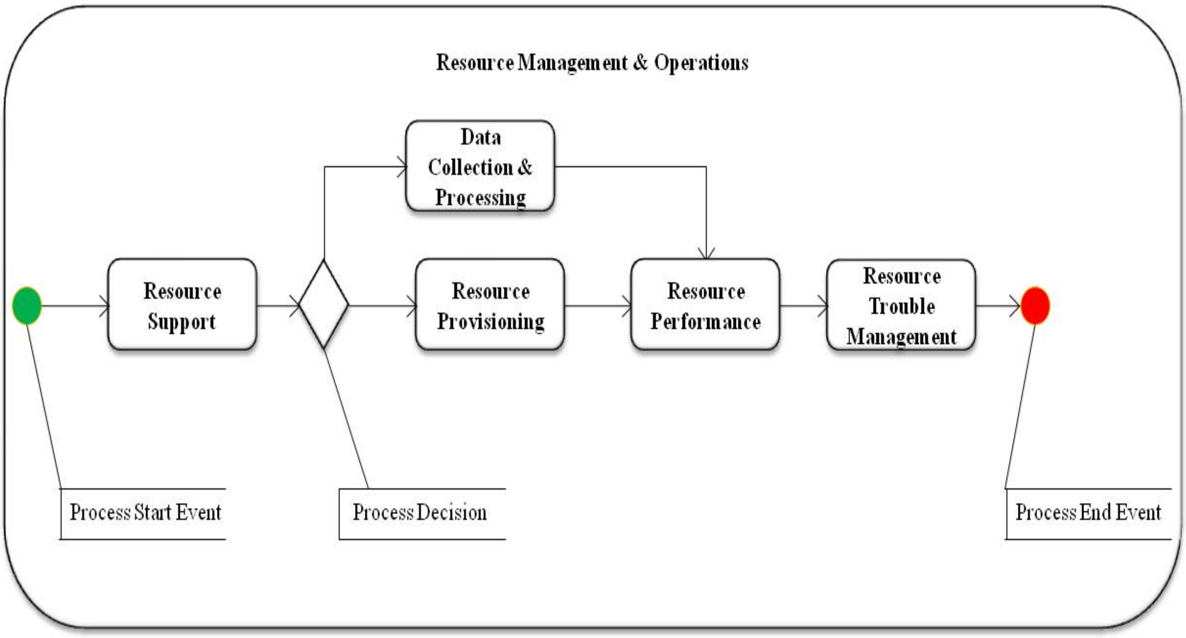

Figure 19 An end-to-end Resource Management and Operations process modelled in BPMN

Figure 19 contains the process flow that is modelling in BPMN. If the process pattern indicated in ***figure 19*** is reusable, then the utility can also deploy this as a composite application. This provides automatic reuse of the process definition. A more granular service structure is however missing in ***figure 19.*** The decomposition of the process forms the next level of design required to deliver the fault detection services. This additional decomposition will break down the processes from level two, indicated in the figure, to level three and lower.

3.4.5 Integration Overview

In order to achieve suitable levels of automation in the substation, integration of both substation functions and information is required [**3**]. The use of patterns for this integration is important as these patterns solve recurring problems [**51**]. By their very nature, patterns support the development of modular and reusable components. For example, a decoupling pattern enables the abstraction and decoupling of the logic and presentation components of the system [**51**]. Thus, the layered architecture presented in ***figure 14*** is a pattern for integrating service consumers and service providers by abstracting each of the layers away from the other. The pattern indicated in ***figure 14*** provides the necessary abstraction but may pose a problem if the number of transmission handover points from consumer to target is greater than one. The service call pattern and management of services must allow for low latency control and information exchange. Research shows that protection requires sub-second response times [**2**].

Integrating data can also make use of a pattern. A data integration pattern may result in the federation of decentralised data or centralisation of data based on functional and performance and security requirements. Theoretically, substation integration is the creation of functional boundaries and the placement of the existing device functions into the appropriate classified groupings within the substation systems hierarchy. The extraction of the function out of the existing functional area decouples the function and places it into the boundary where the function belongs. Depending on the requirement this could be done either physically or logically. Once all functions are classified, the functions form an atomic unit that accepts instrumentation inputs and provide specific outputs to the device functions.

The grouping of functions is seen in the design of an IEC 61850 compliant substation, which includes station, bus or process layers each serving a specific functional area [**21**].

3.5 Network Topology

A network is as a series of connected computers, systems or devices [**1**].

Notwithstanding the issues relating to fault tolerant network infrastructure, researchers see these technologies as vital in the interconnection of substations and other nodes on the power grid. Activities in the area of network standardisation are undoubtedly in the interest of smart grid initiatives. Network research outlines key requirements, such as interoperability, integration and accessibility of local area, wide area and home area networks. ***Figure 20*** is derived from a conceptual reference model used by the NIST [**1**]. The figure indicates the connection types for communication between control centres and substations. The figure excludes home area networks, however the NIST indicate that these connect to the field networks and in turn to substation gateways or operations. A consumer's request for information may need to traverse multiple network switches, and hence information frequency and latency is a consideration in the application design.

A recommendation provided earlier is to place well-structured data closest to the function that needs the data to ensure less overhead and contention.

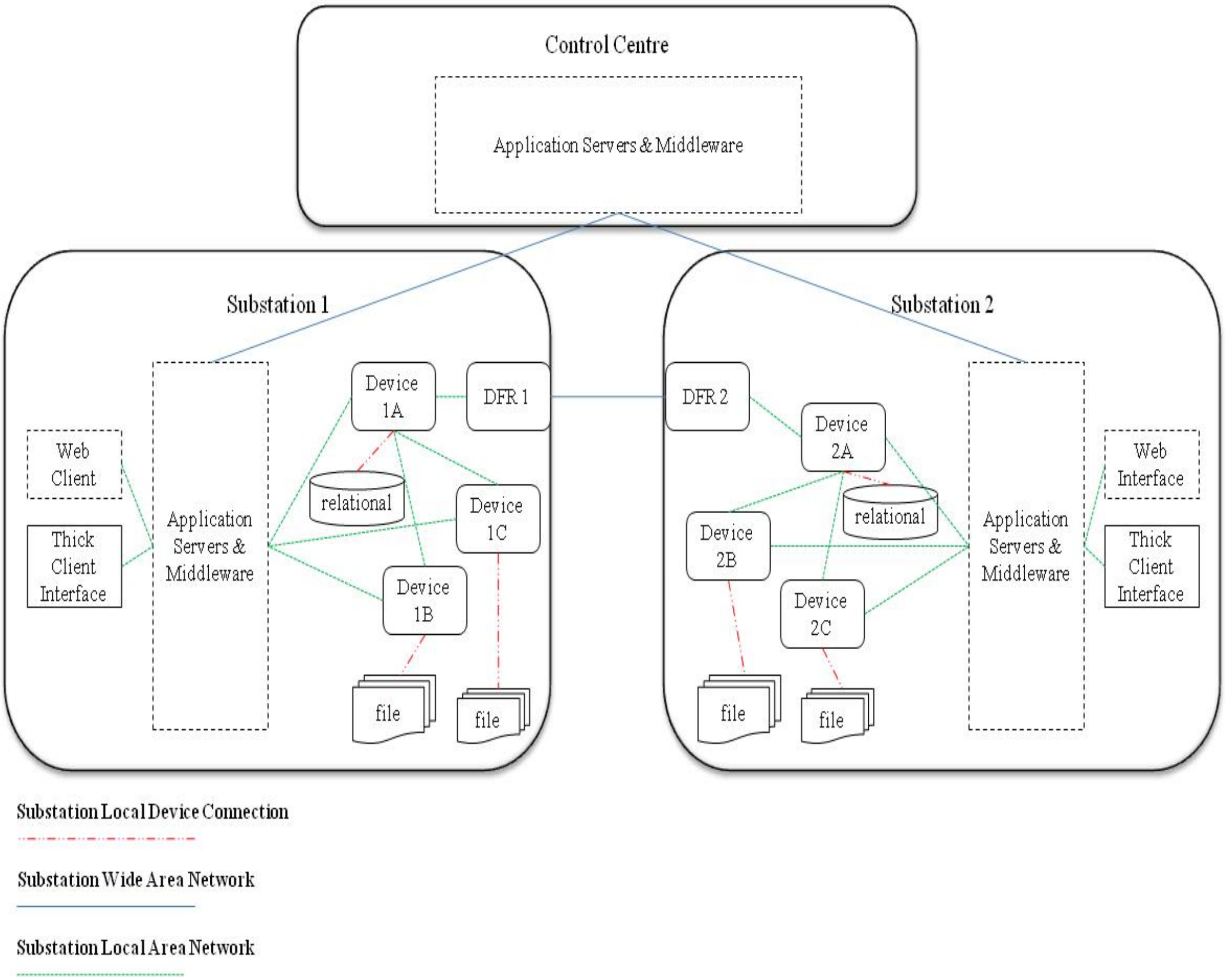

Figure 20 Substation network connectivity requirements for fault detection: Source NIST Framework and Roadmap for Smart Grid Interoperability Standard Conceptual Reference Diagram [1]

Figure 21 is derived from a known substation architecture that represents the IEC 61850 standard [**25**]. The figure indicates a faster communication requirement for the electrical equipment connected to relay and metering devices at ten Gigabit per second. Substation communications across bays are enabled through one Gigabit Ethernet switches that connect to the substation gateway appliance. Station buses enable substation-to-substation communications over wide area networks. ***Figure 21*** represents the substation communication subset of the smart grid reference model proposed by the NIST in ***figure 20***.

The need for fast processing and application interfacing guides the placement and deployment of application on this infrastructure. The processing applications indicated in ***figure 21*** would require a more robust network as this has an immediate impact on safety and security. The ability to report on post event analysis is not as demanding as real time action required for disturbance clearing.

Figure 21 Communication requirements for fault detection. Source IEC 61850 Architecture [25]

Networks are required to support multiple categories of data namely operational, non-operational and control data [**49**]. The network scoped for this dissertation supports multiple information categories however, the operational and non-operational data is used specifically as sources of data for the fault detection. Control information is information sent by an operator to initiate a control action in the substation.

Recommendations in the report by the IEEE indicate that fibre optic channels are more suited to deliver protection-based functions in a substation environment. The recommendation outlines benefits and disadvantages of both serial and IP based communication mediums citing response times, maintenance and scalability as characteristics that can be used to measure effective choice [**49**].

3.6 Conclusion

This chapter deals with the information needed for wide area monitoring. The core of the chapter's detail relates to specific information requirements for substation devices. Device information volumes will grow due to increased device functionality and vendor interest in the areas of smart grid. The chapter also discusses the strategies relating to the effective placement and access of integrated substation data. A simple data store forecast model is presented, however this model can be extended to cater for multiple device inputs within the same substation.

The chapter further discusses a common mapping of process and information architectures to support service classification. A generic SOA reference model is derived from industry and technology vendor models. The reference model positions devices as providers of data, which is processed into information in the upper layers of the reference architecture. The components of an SOA are presented to provide context to the implementation requirements of the fault detection process. Services, data structures and description languages are the components that enable flexible design and deployment units in an SOA.

The chapter finishes with a future view of communications. Intelligent networks are the future of communication in power networks [**50**]. An increase in the volume of data means that industry will need to react by developing standards for management and analysis of extremely large data sets in real time using existing network topologies and technologies. The delivery of smart grid power infrastructure can only be successful if the communication network compliments the power network's delivery of reliable and secure power, through fast and accurate information exchange.

CHAPTER 4
UA ANALYSIS AND DESIGN

4.1 Introduction

The previous chapters of this dissertation motivate for the use of a specific architecture patterns, data and information access methods within which a fault detection solution should be delivered. This chapter focuses on the analysis, design and implementation aspects of the solution within the given architecture constraints. The delivery of the required artefacts and deployment units of this dissertation uses the Unified Approach (UA) as a guiding framework.

In software engineering, an object oriented systems development lifecycle uses a requirement-driven approach to model and deliver software [**51**]. The Unified Modelling Language (UML) supports the view that software is modular in design and independent of the implementation technology. A subset of UML artefacts are used for the delivery of the requirements analysis model. These are:

- Actor identification;
- Business process;
- Use cases; and
- Sequence diagrams.

4.2 Wide Area Architecture Concepts

The system wide architecture concepts used in this dissertation abstract the physical implementation of the system into a rich software storyboard that contains only high-level system boundaries, information and control flows. The subsequent sections of this chapter indicate how the conceptual view is decomposed into the components and physical topology that enable functions and capabilities in the proposed layered target architecture. Each interaction produces a piece of data that can be contextualised and classified as information used within one of the core power generation, transmission or distribution processes. With the entire power network seen as a "*system of systems*" as indicated in [**1**], a decomposition pattern is applied to specific nodes on the network specifically interconnecting nodes, like bulk transmission substations. Research indicates that the following equipment is amongst the most important for substation integration [**3**] [**32**]. These devices are:

- *Digital Protection Relays* which are used send trip execution signals to other devices,
- *Circuit Breaker Monitors* which receive and monitor breaker signals, and
- *Digital Fault Recorders* which record station wide disturbance information, and
- Substation human-machine computer interfaces and terminals that accesses devices attached to the substation network.

These components communicate with each other by means of device application interfaces over a common protocol via a process bus and with other substations via a station bus.

Figure 22 gives context to the control and information flows indicated in current research activities. Research in the areas of bulk data storage, classification, access and retrieval is currently underway [**2**].

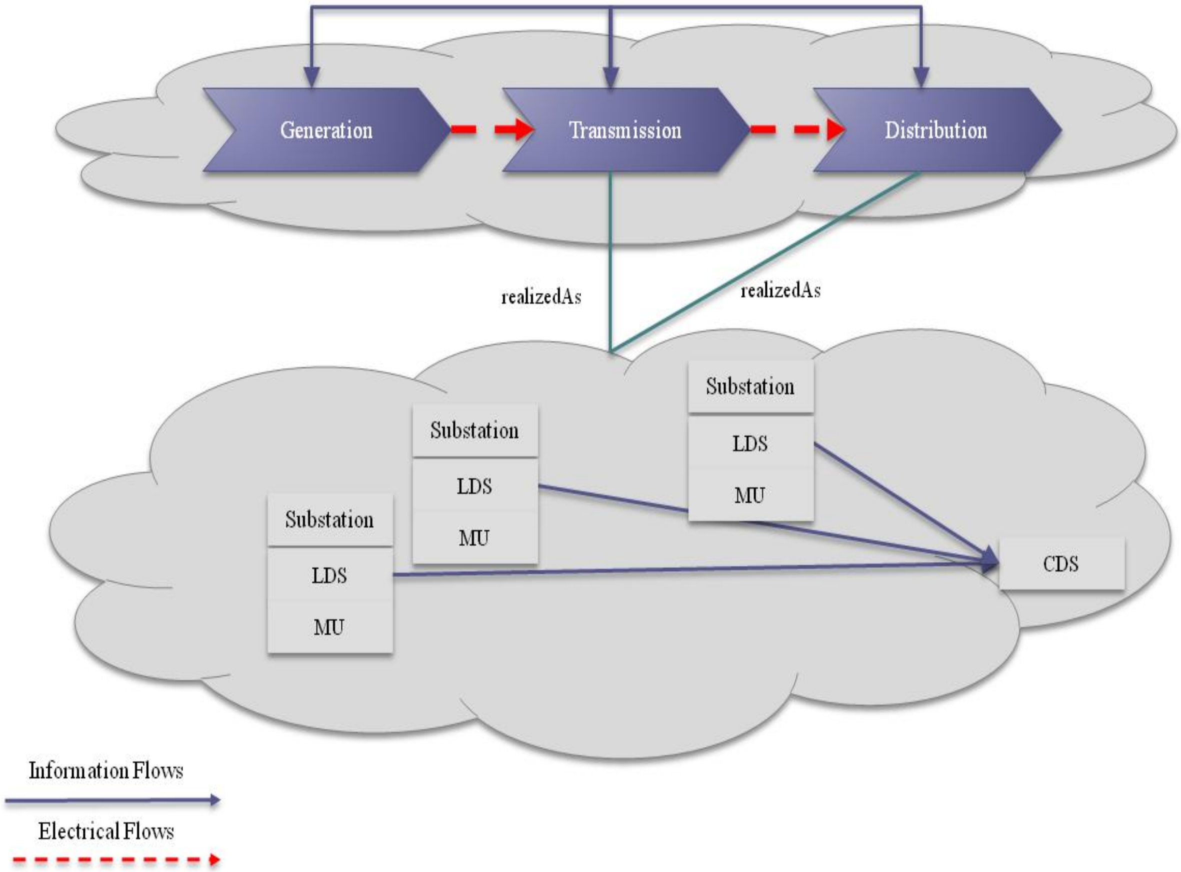

Figure 22 Substation device components for distributed information access. Source Centralised and decentralised data collection for Wide Area Monitoring Systems [2]

The figure indicates that transmission and distribution infrastructure is realised as a series of substations and Localised Data Stores (LDS) that gather data from Merging Units (MU). The collection process also feeds data to a Centralised Data Store (CDS). The essential function of an LDS and CDS is to collect and "*concentrate*" device data [**2**][**24**][**27**][**49**][**54**]. A MU is a physical device unit that accepts binary and analogue inputs from the other devices in the substation [**52**]. The MU serves as a mediation device that transforms and aggregates data from electronic devices. Transformed information can be loaded via real time batch or real time database feeds into the LDS. An LDS is a localised store that serves the substation's protection, control and monitoring requirements. LDS information propagates to a store that serves operational and non-operational requirements for other areas of the network. Warehousing, or alternatively concentrating, is a pattern for serving "different functional groups" [**29**].

4.3 System Domain

Figure 23 expands on the component architecture indicated in ***figure 22***. ***Figure 23*** uses the architecture concepts and creates the next level of detail for the systems within scope of the dissertation. A system domain context provides the necessary overview of the system as a set of interacting components.

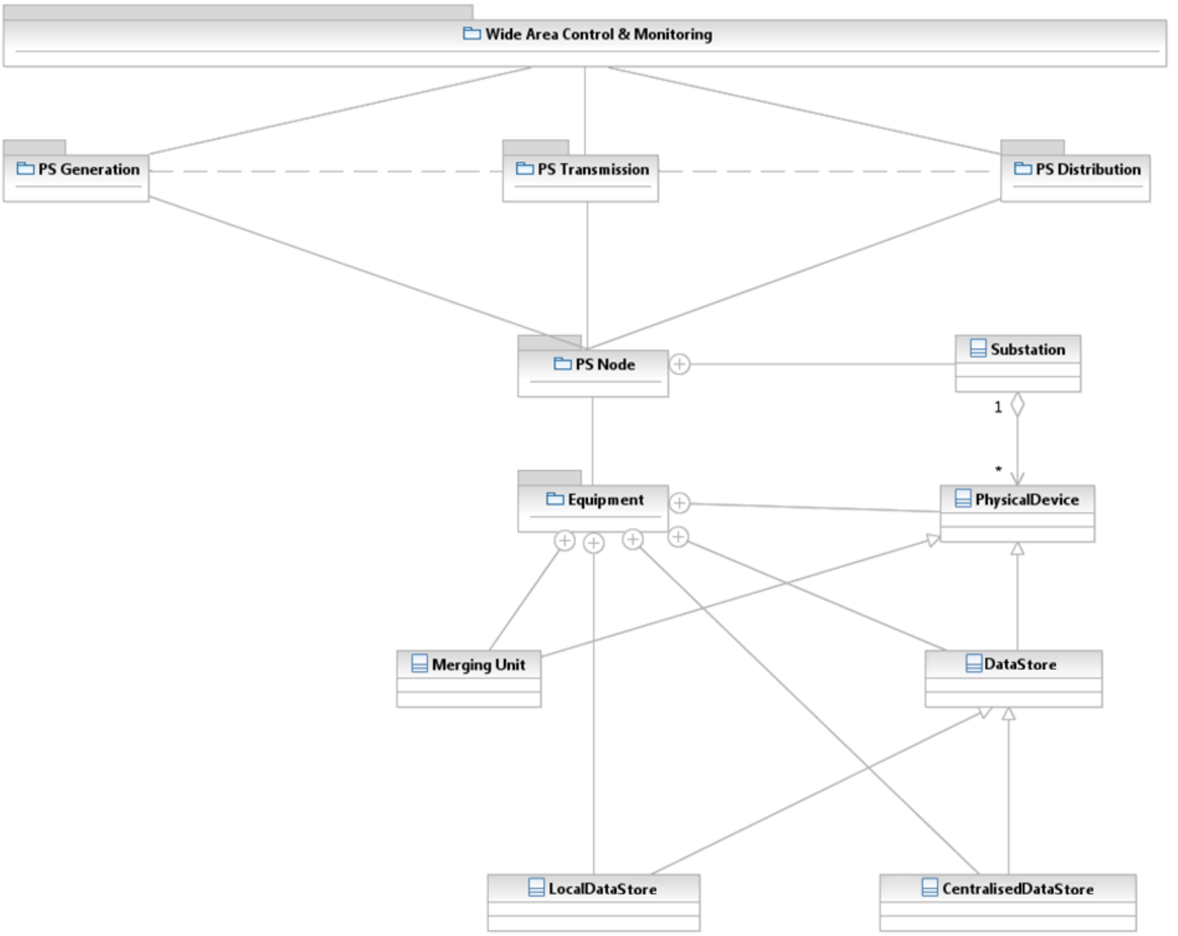

Figure 23 A system domain diagram for a wide area system based on centralised and decentralised data requirements

Figure 23 indicates the following relationships:

1. Power System (PS) Generation, Transmission and Distribution domains have components that are independent to one another, but are related under a wide area monitoring and control environment;
2. Power System (PS) Generation, Transmission and Distribution domains have nodes that are related specifically to PS Generation, Transmission and Distribution environments;
3. Substation nodes are either generating, transmitting or distributing in function;
4. Power System (PS) nodes have equipment. For example, a substation has monitoring or physical control devices.

5. Merging Units are specialised physical devices.
6. Data Stores are specialised physical devices.
7. Local Data Stores and Central Data Stores are specialised Data Stores.

4.4 Protection Use Case Actors

Figure 24 contains a view of the actors that interact with protection functions in a monitoring, analysis and operations capacity. Natural persons (humans) play the role of operator and analyst.

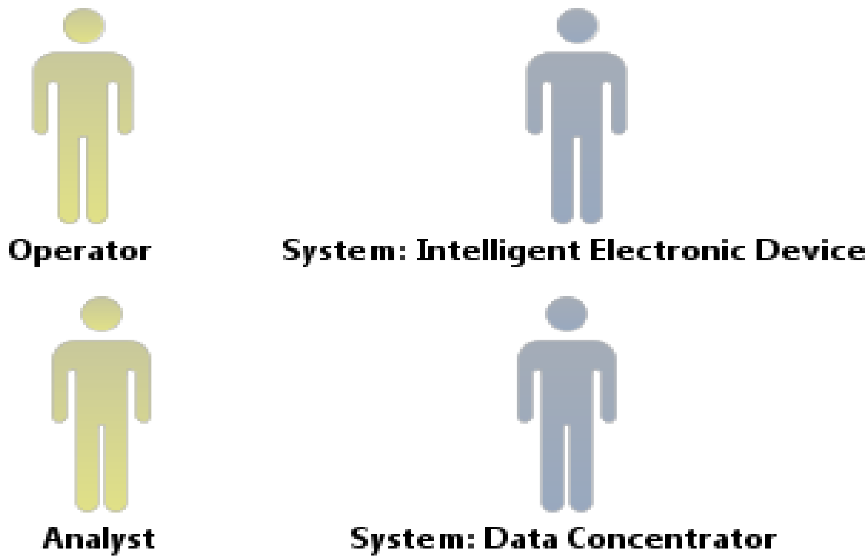

Figure 24 Power system use case actors for the fault detection process

- **Operator**: This person is the control centre operator that has the ability to view information for the stations connected to a control centre or transmission substation.
- **Analyst**: This person analyses available information in order to produce statistical information using faulted line information.
- **Intelligent Electronic Device:** This is a device that enables automated monitoring, analysis and control functions.
- **Data Concentrator**: This is a system that acts as a store of information and data.

The business process indicated in ***section 4.5*** outlines the requirements for generating and analysing data. It assumes that a disturbance occurs within the substation boundary. The human actors that interact with the system are not involved in the physical restoration that commences after a disturbance occurs. A technician manages the re-closing process once the fault is located and a trouble ticket is raised for resolution. Human actors use the data and information access methods to analyse post fault events.

4.5 Fault Detection Process

Research suggests that a fault analysis sequence uses three processes to deliver the analysis of a faulted line [**53**]. These are *Fault Detection*, *Fault Classification* and *Fault Location*. A series of activities and decisions are extracted from the fault theory for transmission line fault analysis using readings from both ends of a faulted line [**53**]. The Business Process Modelling Notation (BPMN) is used to translate this extraction into an implementation view of the fault detection process. The process does not include the actual fault classification or location once detection is completed. The focus is on making detected fault data and information available to other processes that will actually perform the fault classification and location. This method of modelling demonstrates the ability to decouple functions and provide information to other consuming processes or functions. ***Figure 25*** indicates the business process that shows the control of process activities. The figure outlines required process inputs, process outputs and the activity process control flows. The blue dashed arrows indicate the data inputs needed for each process activity. The red dashed double line arrow indicates the process outputs. The double dotted dashed line indicates process control.

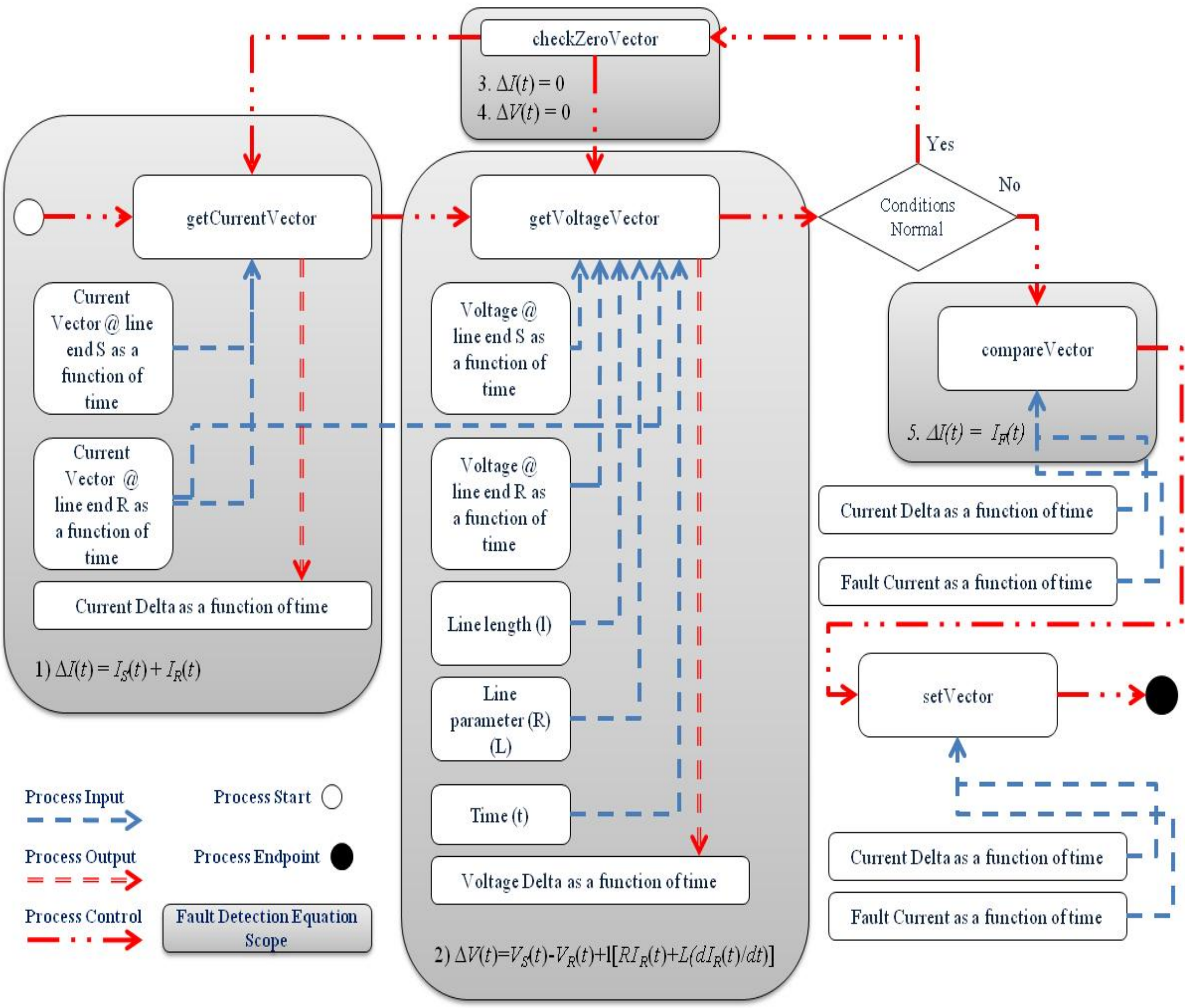

Figure 25 A business process for detecting a faulted line. Source Detection equations (1) to (5) [53]

The fault detection process scoped for this dissertation performs the following functions:

1. Uses line readings to calculate a current vector;
2. uses line readings to calculate a voltage vector;
3. compares calculated vector values; and
4. sets the appropriate vector values.

The process diagram in ***figure 25*** implements the fault detection equations indicated in ***table 6***.

Table 6 The implementation of process activities for fault detection equations. Source Detection Equations (1) to (5) [53]

Process Activity	Fault Detection Equation	Equation ID
getCurrentVector	$\Delta I(t) = I_S(t) + I_R(t)$	1
getVoltageVector	$\Delta V(t) = V_S(t) - V_R(t) + 1\,[RI_R(t) + L(dI_R(t) / dt)]$	2
checkZeroVector	$\Delta I(t) = 0$	3
checkZeroVector	$\Delta V(t) = 0$	4
compareVector	$\Delta I(t) = I_F(t)$	5

The following legend contains the variable definitions applicable to the fault detection equations referenced from **[53]** in ***table 6***.

1. $V_S(t)$, $V_R(t)$ - Vectors of Phase Voltages at line end S and R respectively
2. $I_S(t)$, $I_R(t)$, $I_F(t)$ - Vectors of Phase Currents at line end S, R, at fault respectively
3. l – Length of transmission line
4. R, L – Self and Mutual line parameters

It should be noted that mechanisms to determine equipment condition monitoring is based on defined rules that must be stipulated beforehand. For example, the creation of defined fault isolation rules using known isolation constraints should be used in the fault analysis process rather than using fuzzy logic to determine the fault isolation boundaries [**20**]. The explicit rule constraint is stipulated beforehand for security, personnel safety and in protection scheme testing cases.

4.6 Fault Detection Use Cases

The use cases indicated in ***figure 26*** do not indicate a specific implementation technology. It indicates that some type of device or system will fulfil certain functions. For example, there is a function initiated by an intelligent electronic device that generates data. The use case places a specific focus on the data produced and how to create a physical or virtual view of data for use within the substation boundary, for the purposes of initiating fault detection.

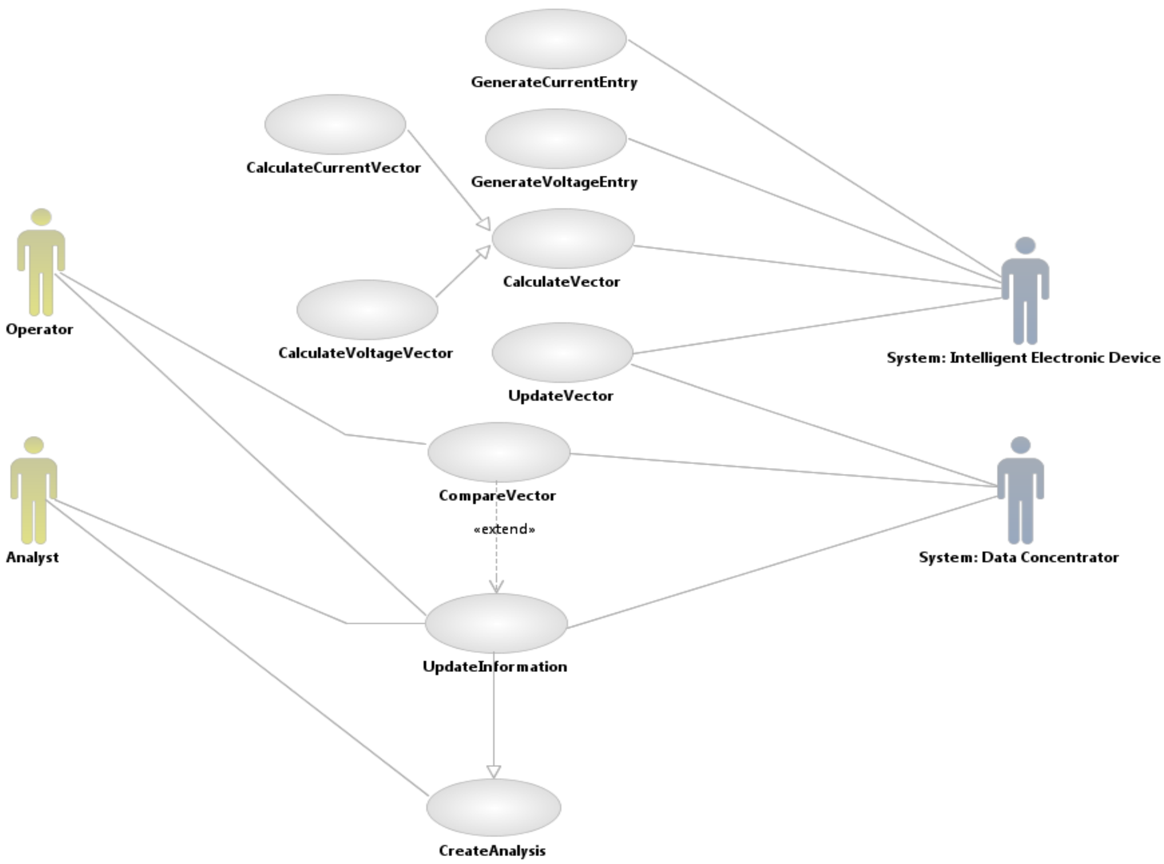

Figure 26 A fault detection use case diagram based on the fault detection process

The diagrammatic representation provides some clarity on how the analysis process will be structured, and which actor will be engaging in the process. The requirements in ***section 4.5*** are a basis for the use case diagram and include the scope of the analysis sequence and the components required. Two additional use cases are included that allow operators and analysts a means to access information. These are updating information and creating new analysis from data or information found in the data store or concentrator. A diagrammatic representation is an important view when clarifying the functionality and boundary of the system. A textual view of the use cases provides additional information for the detection process. This dissertation also requires the textual description of the use case in order to map the use case to the selected process framework. ***Table*** *7* contains the additional use case attributes descriptions.

Table 7 A set of textual use case descriptions derived from the use case diagram for the fault detection process

Use Case ID	**Use Case Name**
UC001	Generate Current Entry
Description	This use case describes the automated process initiated by a substation device to generate data for analysis purposes.
Actors	Intelligent Electronic Device
Triggers	Sampling frequency checkpoint is encountered
Pre Condition	No event record exists
Post Condition	A device generates an automated event record having line current values.
UC002	Generate Voltage Entry
Description	This use case describes the automated process initiated by a substation device to generate data for analysis purposes.
Actors	Intelligent Electronic Device
Triggers	Sampling frequency checkpoint is encountered
Pre Condition	No event record exists
Post Condition	An automated event record, holding line voltage values, is generated from the device.
UC003	Calculate Vector
Description	This use case describes the fault analysis vector calculation
Actors	Intelligent Electronic Device
Triggers	A disturbance is encountered in the substation
Pre Condition	Continuous vector calculation
Post Condition	Vector value available for use
UC004	Calculate Current Vector
Description	This use case describes the calculation of the current vector using readings from two line ends
Actors	Intelligent Electronic Device
Triggers	A disturbance is encountered in the substation
Pre Condition	Continuous vector calculation
Post Condition	Vector value available for use
UC005	Calculate Voltage Vector
Description	This use case describes the calculation of the voltage vector using readings from two line ends, as well as self and mutual line parameters.
Actors	Intelligent Electronic Device
Triggers	A disturbance is encountered in the substation
Pre Condition	Continuous Vector Calculation
Post Condition	Vector value available for use
UC006	Update Vector
Description	This use case describes the updating of the calculated vector
Actors	Intelligent Electronic Device, Data Store/Concentrator
Triggers	An alarm is processed
Pre Condition	No vector value available for update
Post Condition	Vector value updated to Data Store/Concentrator
UC007	Compare Vector

Description	This use case describes the process of comparing the fault current to the line current
Actors	Operator, Data Store/Concentrator
Triggers	An alarm is raised and notifies the operator
Pre Condition	Polling yields no change in event directory content
Post Condition	New record added to the event directory
UC008	Update Information
Description	This use case describes the update of generated information
Actors	Analyst, Operator, Data Store/Concentrator
Triggers	Notification of an event change is produced
Pre Condition	Normal operating conditions encountered in the substation
Post Condition	Abnormal operating conditions encountered in the substation
UC009	Create Analysis
Description	The use case describes the process of running an analysis on available data
Actors	Analyst
Triggers	Notify user of available data set.
Pre Condition	Analysis result not available
Post Condition	Analysis completed and results updated

4.7 Interaction

The use case diagram and use case textual descriptions are used to define an interaction process. ***Figure 27*** represents this interaction requirement as set of sequence diagrams. The red swim lanes in the figure delineate specific use case interactions.

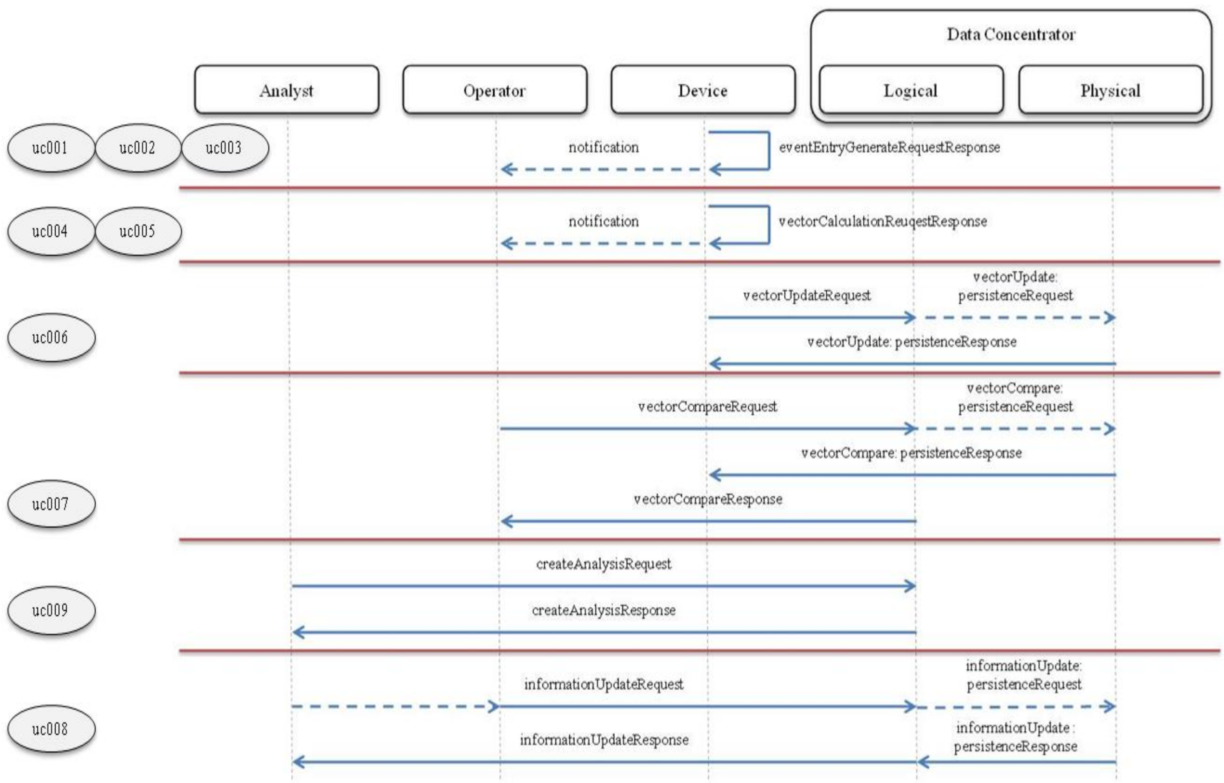

Figure 27 A sequence diagram representing fault detection use case interactions

Each use case contains the required control flows that advance the process flow from one stage to the next. The use cases contain the flows that implement the pre and post conditions indicated in ***table 7***. The sequence diagram indicates the interaction between actors and the control flows required to analyse the detected fault data. To provide a more detailed view of the interactions, the service framework classifies these interactions. ***Figure 28*** extends the defined service framework given in ***figure 14*** in ***Chapter 3***. The service framework layers now have the following definitions:

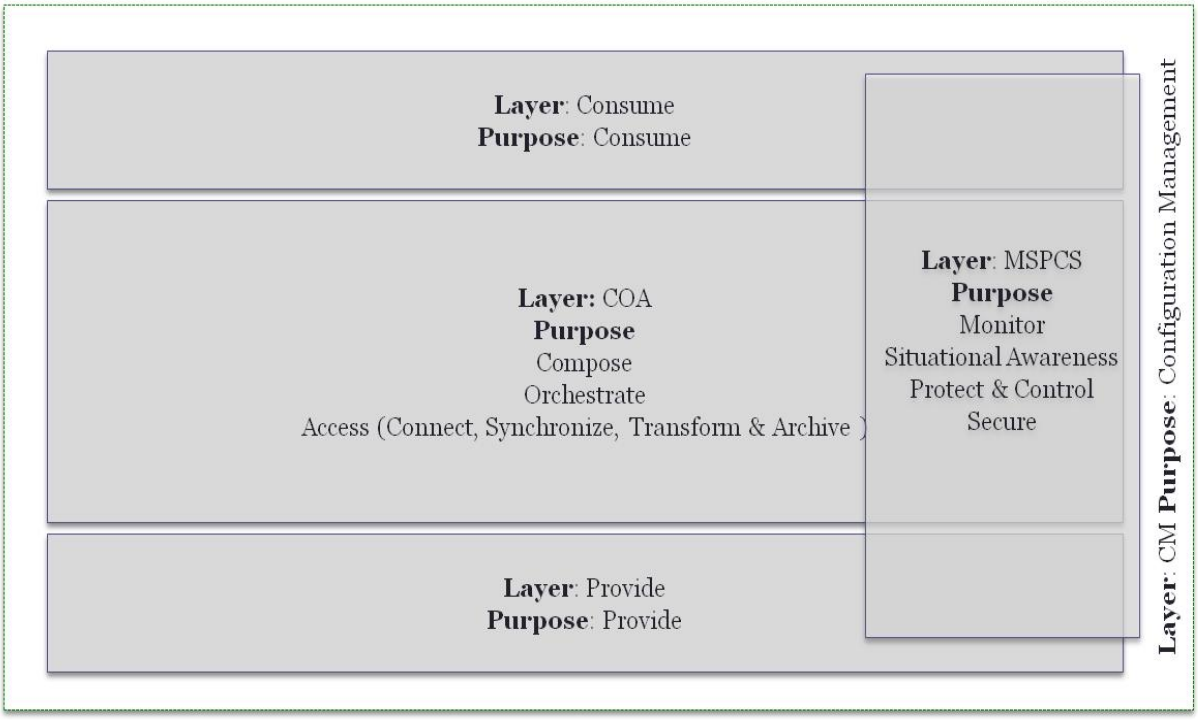

Figure 28 Service classification definitions by service layer for implementing fault detection interactions. Source Chapter 3 Figure 14.

- **The Consume Layer**: This layer provides access for human-machine interfaces to consume composite applications or processes from the lower service layers.
- **The COA Layer**: This layer composes atomic services into **C**omposite applications, **O**rchestrates atomic services into processes, connects to interfaces, synchronises, transforms and **A**rchives data [**54**] into information for consumption by the higher layers. This layer also covers the scope of warehouse update and retrieval operations. As indicated in [**29**], data warehousing principles are applied to substation data integration problems. Warehouses should be capable of either real-time processing or for batch processing. Latency and performance needed to fulfil basic protection or reporting requirements drives the real-time or batch processed warehouse requirement.
- **The Provide Layer**: This layer exposes native device or application interfaces.
- **The MSPCS Layer**: This layer is an operations management layer from where monitoring and control signals are controlled. It also covers security enablement. Data managed in this layer is

also termed as “situational awareness” data. This layer produces and is able to report time sensitive information that is termed “*Situational awareness*” [**30**].

- **The CM Layer**: This layer enables configuration management. This covers services enabling IEC 61850 Part 6: Substation Device Configuration Language (SCL) interfaces and message structures. SCL is an XML based configuration language that contains device capability and specification data elements [**21**].

Components identified in the interaction sequence, based on the use cases, are super-imposed on the service framework to derive the diagram indicated in ***figure 29.*** A recommended service interaction pattern uses the *Create Analysis* use case (UC009) as an example of how the service component interaction is defined.

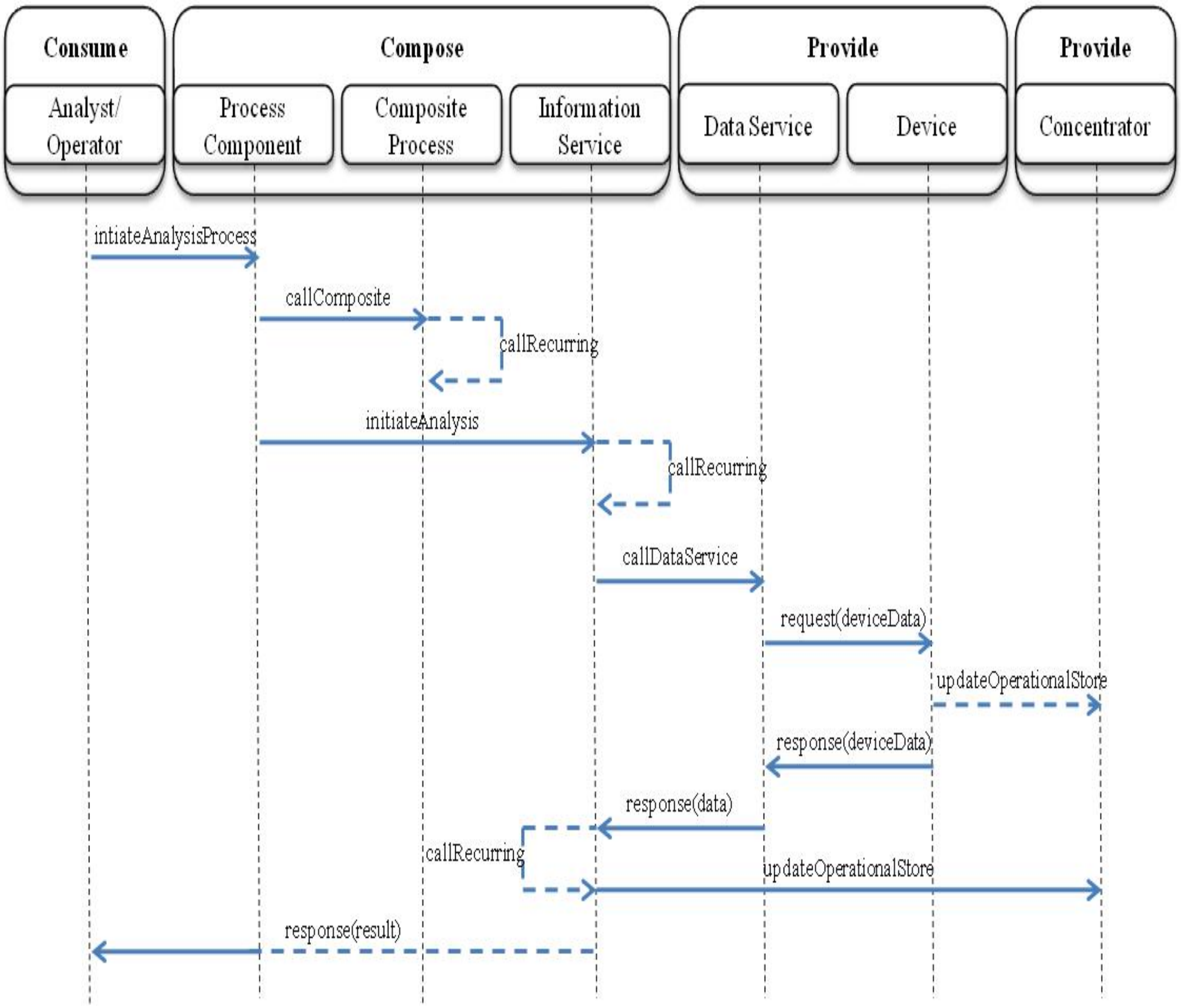

Figure 29 A recommended service interaction pattern for Use Case 009 mapped to service framework layers

In ***figure 29***, the analyst and operator actors are classified into the consume layer of the framework. This is correct as the point of entry for analysts or operators are either a web or thick client in the substation or distributed to the control centre indicated in the information access pattern given in ***figure 11*** *in* ***Chapter 3***.

When the analyst or operator requests a faulted data set sample, the consume service initiates a process component that may call a composite application if the request requires a complex set of data. If this is not the case, the process will initiate a call to the information service. The request type for an information service could require the federation of distributed device data and thus could call other information services. Alternatively, it would simply call the data service that retrieves device information. The configuration on the device database or the device file system allows the data service to query the data. Information returned from an analyst or operator request may be returned to the intermediate layers of the service framework and cached for subsequent consumption by other services.

4.8 Service Modelling

4.8.1 Process

In this dissertation, the method of modelling a service starts with identifying the requirement that the service aims to meet. This modelling is performed using a top down or bottom up approach. The approaches are defined as:

- **Top Down**: The approach uses a high-level process view to classify the requirements that the new service architecture needs to fulfil.
- **Bottom Up**: The bottom up approach ensures that specific data elements and data sets are classified first. This approach uses the fault information architecture - COMTRADE - format as an entry point to analyse coverage and availability of data to support any services. In order to relate the bottom up approach to the required services, a mapping from the fault information architecture to the utility information architecture is required.
- **Hybrid Approach:** Both process coverage and implemented functions are considered. This means that the functional requirement and the process grouping must be known.

In this dissertation, the definitions accepted by the International Telecommunications Union (ITU) align to the system actors in ***figure 24***. It effectively means that devices and concentrators are types of *Resources*. This conforms to the system domain view given in ***section 4.3*** of this chapter which indicate that an IED and a data concentrator are specialisations of a physical device that is a technology component, and in turn a type of *Resource*. The definition of *Service* in the ITU *Resource* definition does not indicate a service in the context of this dissertation. The service referred to in this dissertation is a web service, defined in ***section 3.4.1***.

Figure 30 creates a more detailed view of ***figure 18*** in ***Chapter 3***. The process followed for the modelling of services uses distinct requirement boundaries, with the requirements decomposed into finer grained requirements that lead to the delivery of services that perform non-overlapping functions. Level 3 process groups are shown using the definitions indicated in [**36**]. ***Figure 30*** creates a lower level of decomposition than that found in ***figure 18***.

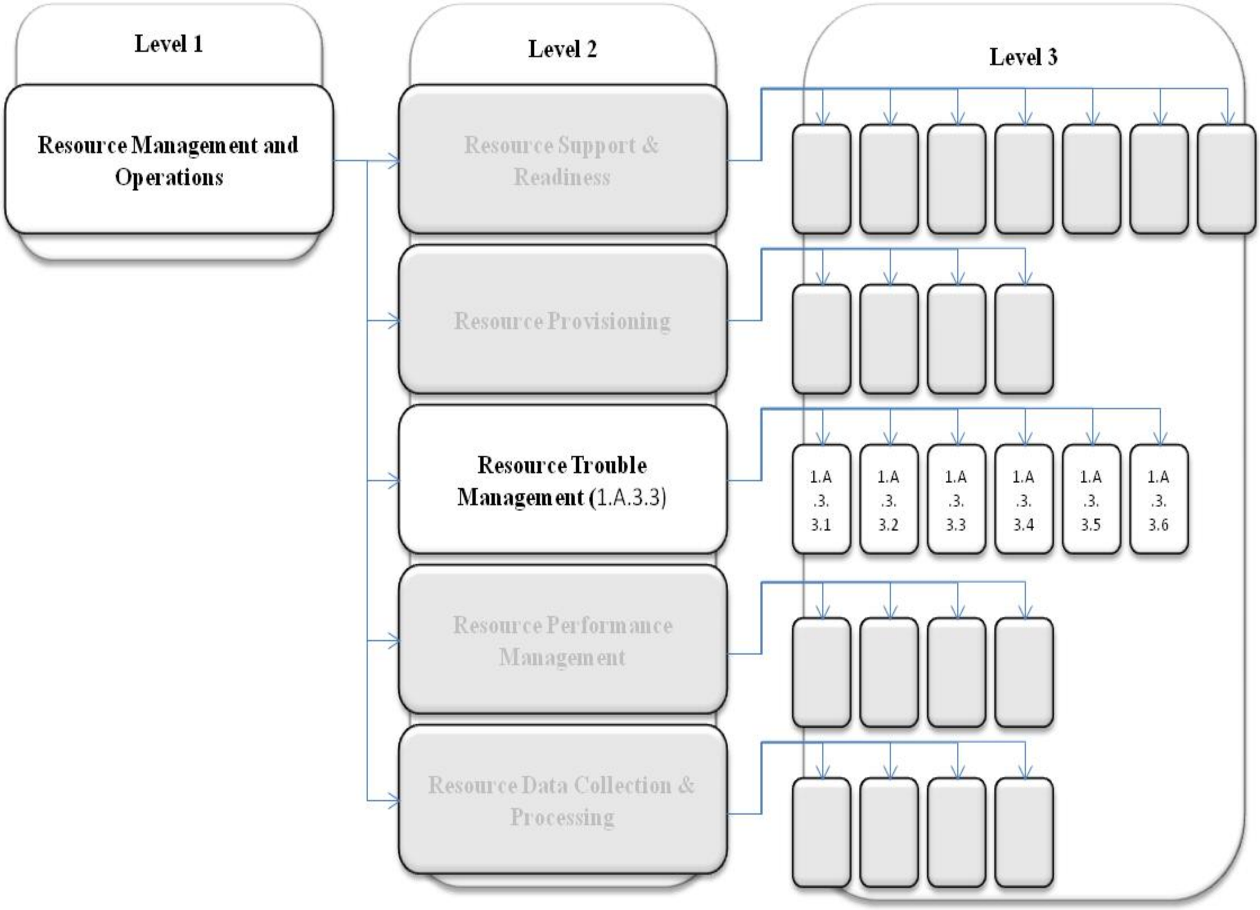

Figure 30 Resource Trouble Management level 3 process decompositions. Source Resource Trouble Management decomposition into level 3 processes [36]

Figure 30 indicates that each level 2 process group has multiple level 3 process sub groups. Each of the level 3 process groups are attached to only one level 2 process hierarchy. This makes it possible to define strict functional areas without creating unnecessary duplicate services. Depending on the granularity of functions, composite service applications can be structured using level 3-processes.

The definitions on *page 78* to *page 80* of the ITU process decompositions indicate that the fault detection process touches a subset of the larger process framework [**36**]. The table below indicates the core processes definitions published by the TM Forum and adopted by the ITU.

Table 8 : Master process definitions from the ITU contextualized to the fault detection process. Source Resource Trouble Management (RM&O – A) [36]

Level	Name	Original ITU Document ID
2	Resource Trouble Management	1.A.3.3

"Resource Trouble Management processes is responsible for the management of troubles associated with specific resources. The objectives of these processes are to efficiently and effectively manage reported resource trouble, isolate the root cause and act to resolve the resource trouble."

Context in this dissertation

This process group deals with the management, isolation and resolution of substation device trouble

Level	Name	Original ITU Document ID
3	Survey and Analyse Resource Trouble	1.A.3.3.1

"The objective of the Survey and Analyse Resource Trouble processes is to monitor resource alarm event notifications and manage resource alarm event records in real-time."

Context in this dissertation

This process group deals with the monitoring and management of disturbance events in the substation

Level	Name	Original ITU Document ID
3	Localise Resource Trouble	1.A.3.3.2

"The objective of the Localise Resource Trouble processes is to identify the root cause of the specific resource trouble."

Context in this dissertation

This process group deals with the analysis of data in order to locate and analyse disturbance data

Level	Name	Original ITU Document ID
3	Correct and Resolve Resource Trouble	1.A.3.3.3

"The objective of the Correct and Resolve Resource Trouble processes is to restore or replace resources that have failed as efficiently as possible."

Context in this dissertation

This process group deals with the initiation of actions required to correct the faulted conditions

Level	Name	Original ITU Document ID
3	Track and Manage Resource Trouble	1.A.3.3.4

"The objective of the Track and Manage Resource Trouble is to ensure testing, repair and restoration activities are assigned, coordinated and tracked efficiently, and that escalation is invoked as required for any open resource trouble reports in jeopardy."

Context in this dissertation

This process group deals with the monitoring and management of fault correction activities.

Level	Name	Original ITU Document ID
3	Report Resource Trouble	1.A.3.3.5

"The objective of the Report Resource Trouble processes is to monitor the status of resource trouble

reports, provide notifications of any changes and provide management reports.” **Context in this dissertation** This process group deals with the reporting of fault conditions to grid stakeholders.		
Level	**Name**	**Original ITU Document ID**
3	Close Resource Trouble Report	1.A.3.3.6
“The objective of the Close Resource Trouble Report processes is to close a resource trouble report when the resource trouble has been resolved.” **Context in this dissertation** This process group deals with the closing of fault trouble reports.		

The table contains the following labels used to identify specific sections of the process definition. These are:

- The **Level** of the process definition. The Utility Process Architecture - TM Forum eTOM - contains standard process definitions from level zero to level three and sometimes up to level four. Where a defined level four process does not exist in the process architecture, level four, five and beyond are indicative of the utility's own operational processes;
- The **Name** of the process defines the classification within which one or many process activities can exist;
- The **Original ITU Document ID** indicates the process references stipulated by the ITU [**36**];
- A short description of the scope of the process grouping; and
- **Context in this dissertation** provides the description of how the process group is positioned for this dissertation.

The definitions included in the table are small percentage of the total number of processes found in the process architecture. A full view of the process reference framework is published on the internet by vendors like AMDOCS [**13**] however without visibility of the process definitions the online document is rarely useful. Fortunately, the ITU publishes its decompositions [**36**] that can be used as a cross-reference.

Process classifications do not necessarily indicate a sequential flow of activities or tasks the analysis sequence requires. The document IDs included in the ITU process documentation can be used to represent an initial sequence. ***Figure 31*** represents this sequence, ordered by the Original Document ID in ***table 8*** to indicate an implementation view of a service framework.

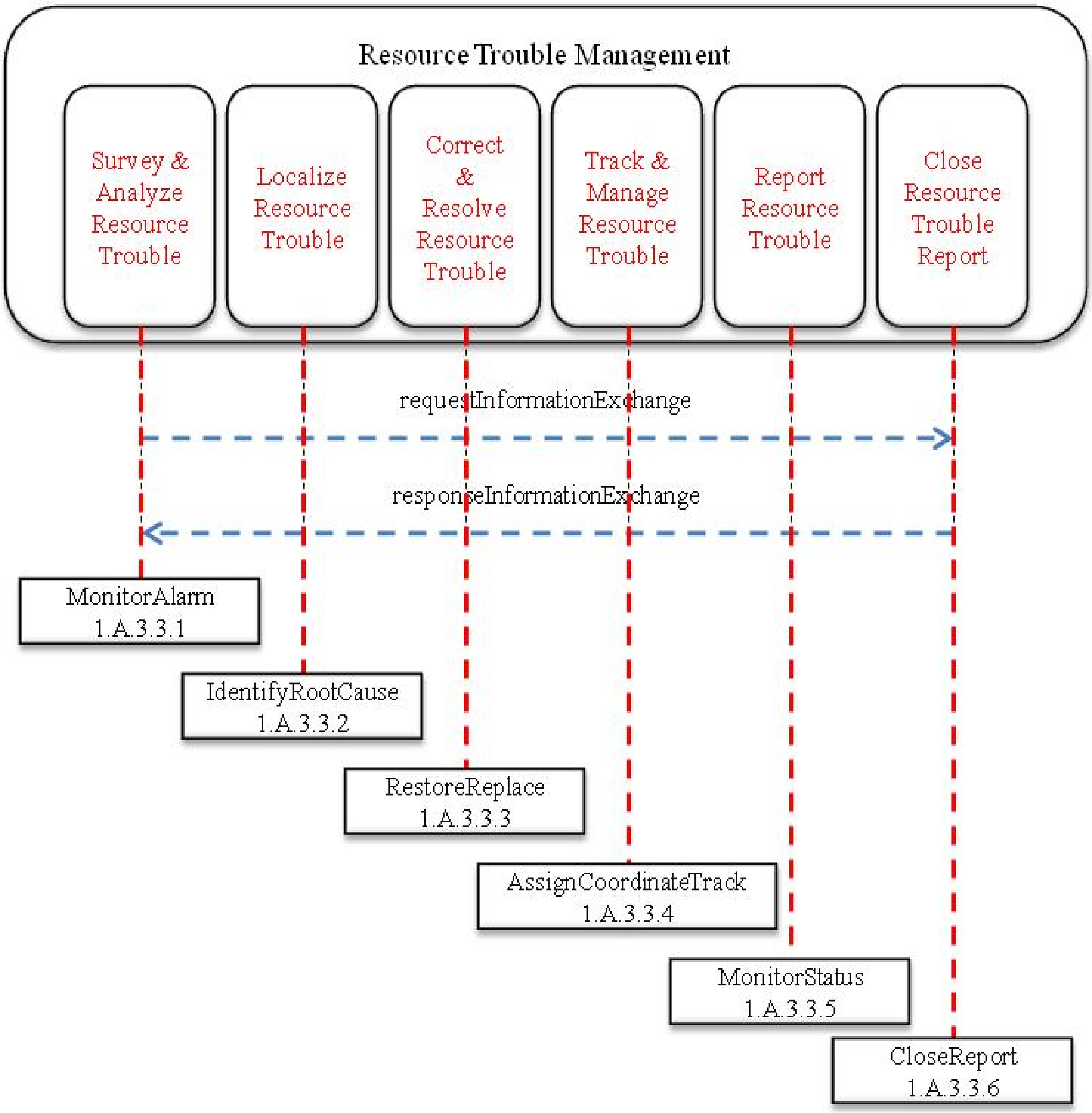

Figure 31 A business process sequence ordered by ITU process reference ID using unique service identifiers

A single text string identifier is proposed to help with the implementation of the fault detection services. The text boxes on the lower end of the red dash vertical lines in ***figure 31*** indicate this. The constructs represented by the text boxes at the end of the red dashed vertical line are possible composite applications.

Figure 32 shows that the process can be executed in some sequence based on the requirements of the service model being developed. The figure shows an entire flow of all level 3 activities attached to level 2 *Resource Trouble Management* processes.

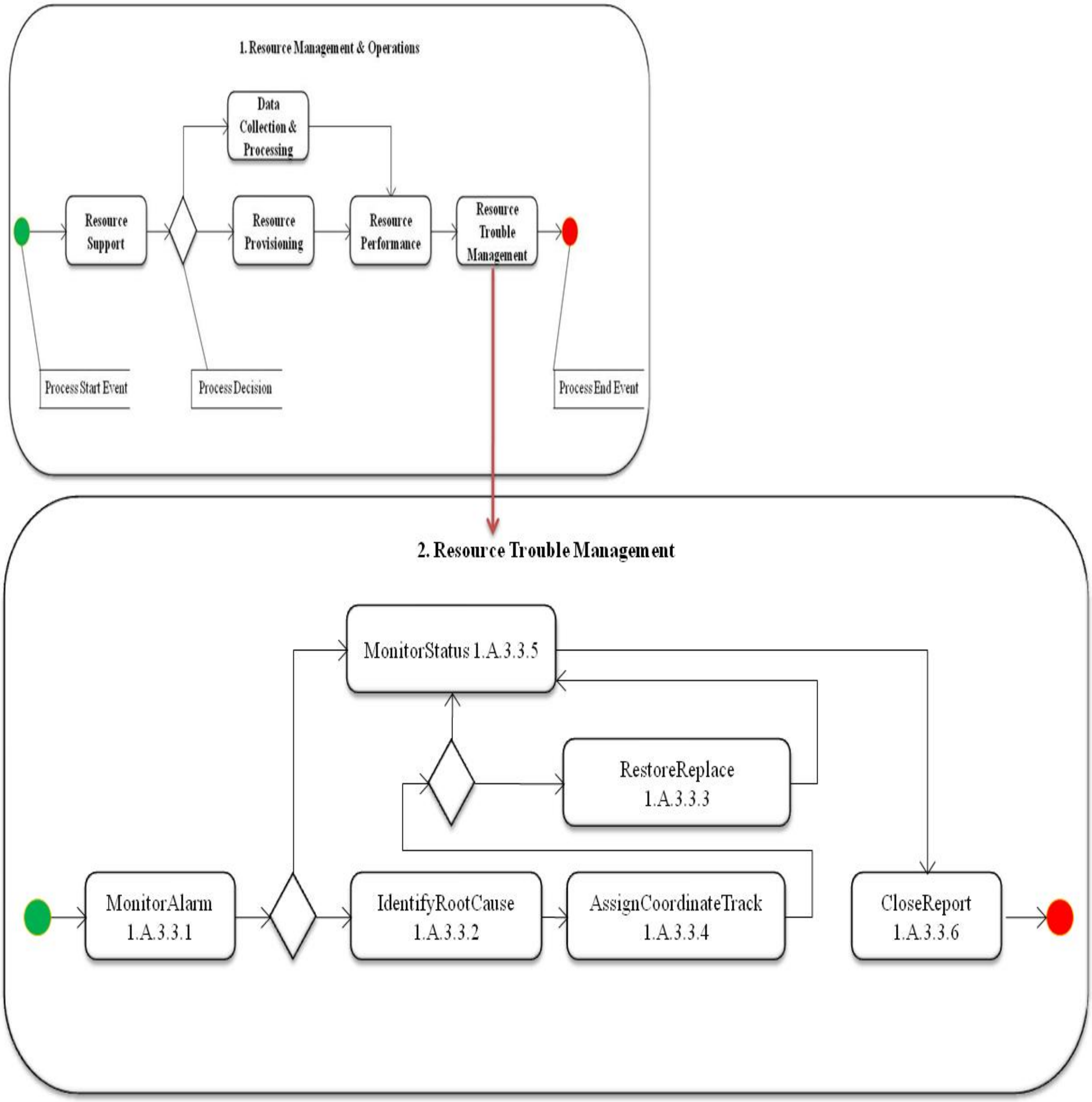

Figure 32 A level 2 BPMN process model for Resource Trouble Management including level 3 device trouble activities

Under circumstances where process reference architectures are not used, the incorrect design of service granularity may yield services that are not reusable and may become hard to manage if a large number of service operations are continually added to an incorrectly levelled service.

In order to complete the service modelling, the process for detecting a faulted line using a two-ended fault calculation is used. In ***figure 33***, the use cases derived in ***table*** *7* map to the original fault detection process from ***figure 25***.

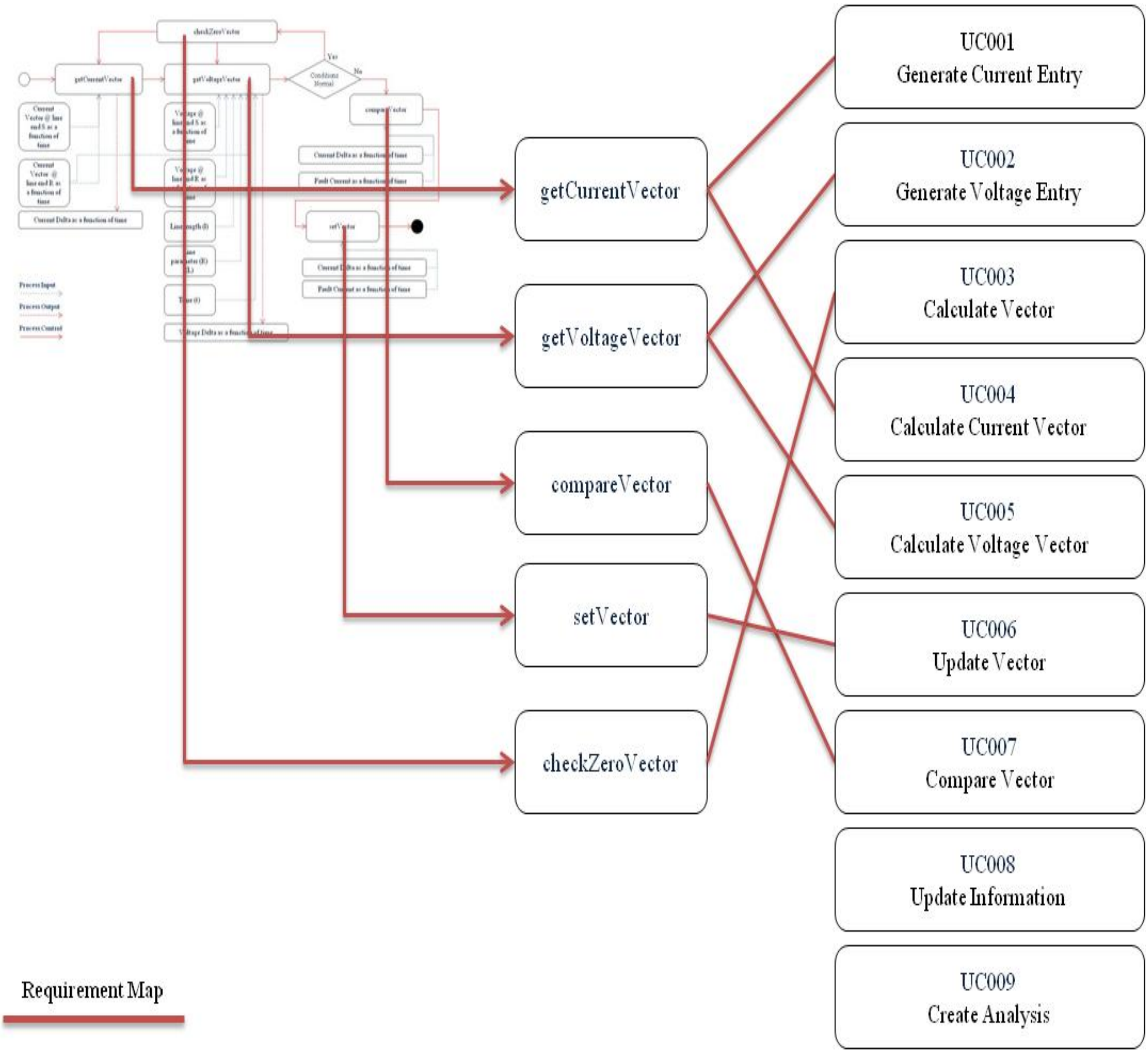

Figure 33 A requirements map between the fault detection process and the requirement use cases

All but two use cases map to the original requirement indicated in ***figure 25***. The additional Use Cases, UC008 and UC009 are included so that the creation and storage of the fault detection analysis and its associated results are clearly articulated.

Figure 34 expands ***figure 33*** by indicating the process inputs and process outputs required to support each use case. The figure shows that four out of a possible six level 3 processes from the Resource - *Substation Device* - Trouble Management process grouping are required for the fault detection process. These are;

1. MonitorAlarm
2. MonitorStatus
3. IdentifyRootCause
4. CloseReport

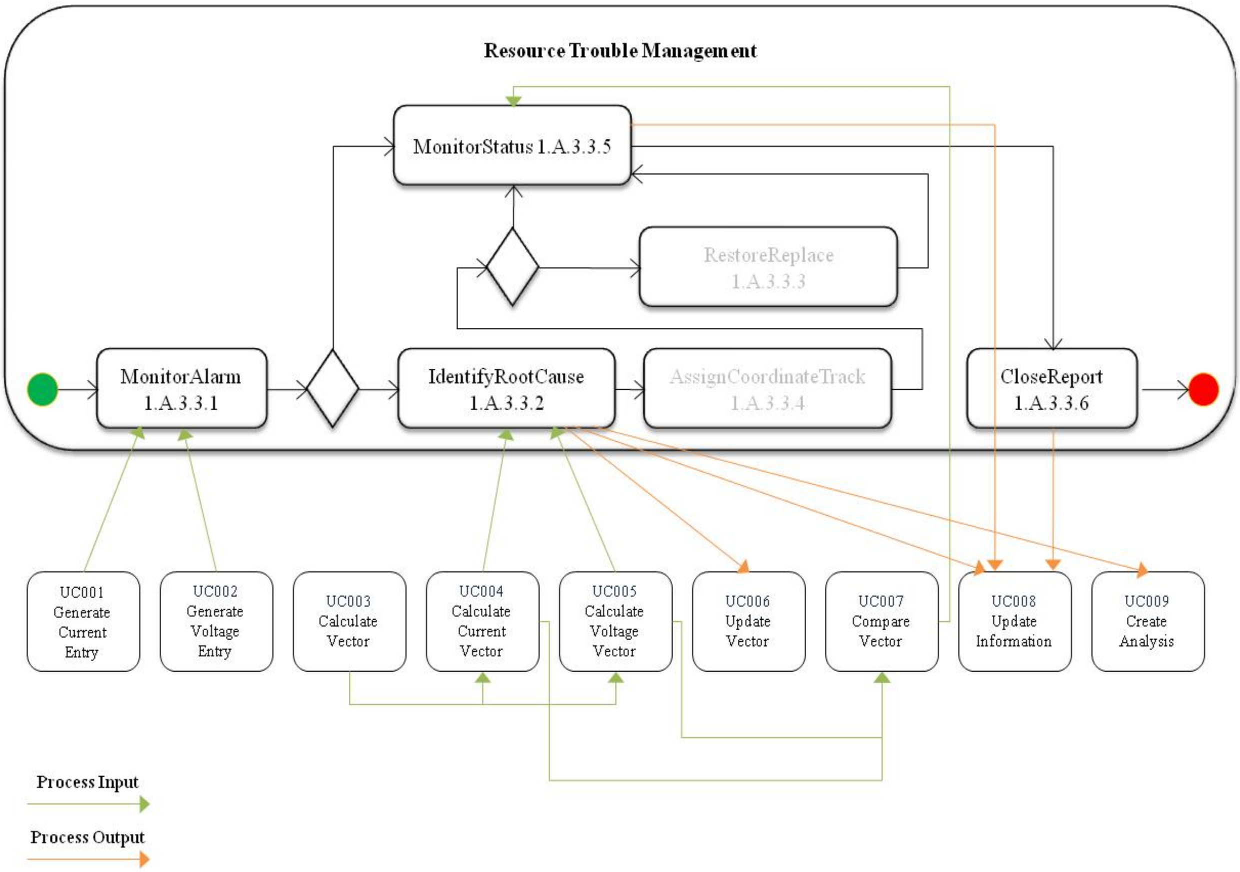

Figure 34 Mapping fault detection use cases to level 3 process activities attached to the Resource Trouble Management level 2 process

Figure 34 displays the key information and process flows. The process has the following characteristics:

1. The Monitor Alarm activity (1.A.3.3.1) accepts inputs in the form of generated current and voltage values (UC001 and UC002),
2. A decision point occurs if a disturbance has been encountered and drives the process logic to either
    a. monitor the status of the disturbance (1.A.3.3.5) and in turn update data store information for the monitored event (UC008),
    b. or continue with a root-cause identification (1.A.3.3.2),
3. Current and voltage vectors are calculated (UC004 and UC005) and used as inputs into the root cause analysis process activity(1.A.3.3.2),
4. The root-cause process activity (1.A.3.3.2) updates
    a. vector information in the substation data store (UC006),
    b. updates other supporting information (UC008) and
    c. creates the analysis outputs (UC009).

The vector compare activity (UC007) receives the calculated output current and voltage vectors (UC004 and UC005). The vector compare activity (UC007) provides input into the MonitorStatus activity (1.A.3.3.5),

5. After the root cause is identified (1.A.3.3.2), the AssignCoordinateTrack activity (1.A.3.3.4) is ignored and the process flow is directed to the MonitorStatus (1.A.3.3.5) activity in the event that no device equipment needs replacing, and
6. MonitorStatus (1.A.3.3.5) enables the final process flow to the CloseReport activity (1.A.3.3.6). Both of these activities update the substation data store (UC008) before the CloseReport (1.A.3.3.6) terminates or ends the process.

The process flow represented in ***figure 34*** is granular enough to derive the implementation of services. An additional step will be to logically group use cases that have similar functionality into a single unit with multiple methods. This is possible for UC001 and UC002. Functions required in the use case may or may not exist on the same physical device. The application design may need to consider the impact of creating a single service with multiple methods as opposed to multiple services with single methods. The performance overhead and number of service calls may increase when the number of services increases.

Up to this point of the dissertation, all required building blocks to support the deployment of a set of reusable components are in place. The UML artefact set produced creates the design traceability from requirement, or business process, through to the sequences that implement specific use cases. The next section deals with the design of the service deployment architecture.

4.9 Service Deployment

This section deals with the deployment of the classified deployment units into the services framework. ***Figure 35*** outlines the placement of the services in the service framework indicated in ***figure 14*** of ***Chapter 3***. ***Figure 35*** indicates the split of provider and consumer use cases. The provider use cases are *use case 001* to *use case 006*. These are native application functions like generating and calculating vector values. The consumer use cases are *use case 007* to *use case 009*. The human-machine interface of the consumer use cases for the fault detection process will be a data entry form deployed on the service infrastructure. This may be via web or thick client interface. The advantage of form-enabled web services is that the forms in both thick or web client derivative can reuse the same web service.

In ***figure 35***, an operation’s monitoring process without an alternative process flow is considered:

1. The provider services execute *use case 001 and 002*;
2. The operator compares the vector through the human-computer interface via web service forms that implements *use case 007*;

3. The operator updates information about the substation status in the substation data store through the human-computer interface via web service forms that implements *use case 008*;
4. The operator updates report status to close in the substation data store through the human-computer interface via web service forms that implements *use case 008*; and
5. An optional step is the creation of an analysis report using data from the substation data store. The analysis can be created by an analyst via the human-computer interface using web service forms that implement *use case 009.* A final step will be an update of the substation data store using the web service forms that implements *use case 008*

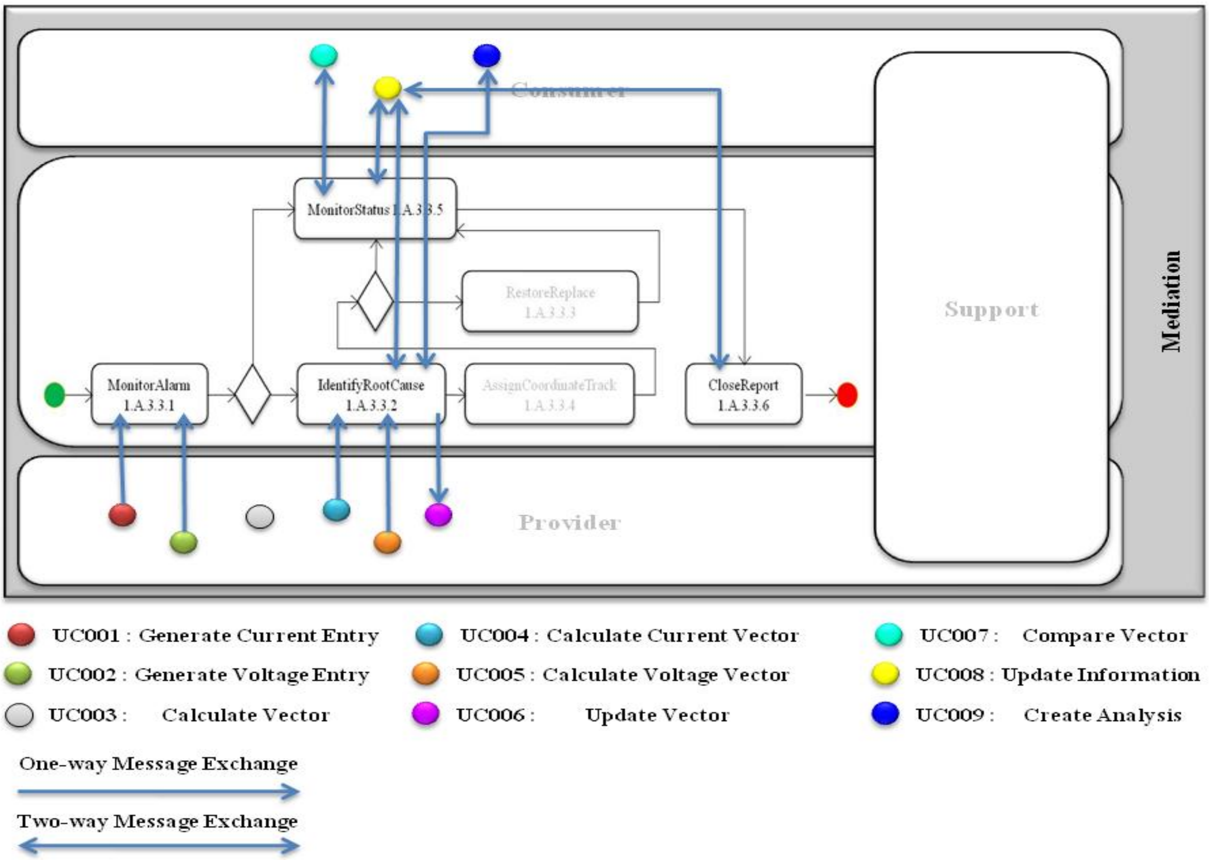

Figure 35 The fault detection web service deployment and message exchange model

The figure provides the opportunity to extend the process by increasing the number of requirements. A new requirement will translate into a use case that traces through the design process. For example, if the utility deems it necessary to include a work order for a technician to review faulted equipment, the service model would only change by enabling the required process step. Assigning a technician classifies into process step 1.A.3.3.4, AssignCoordinateTrack. ***Figure 36*** indicates a new use case called “Assign technician”.

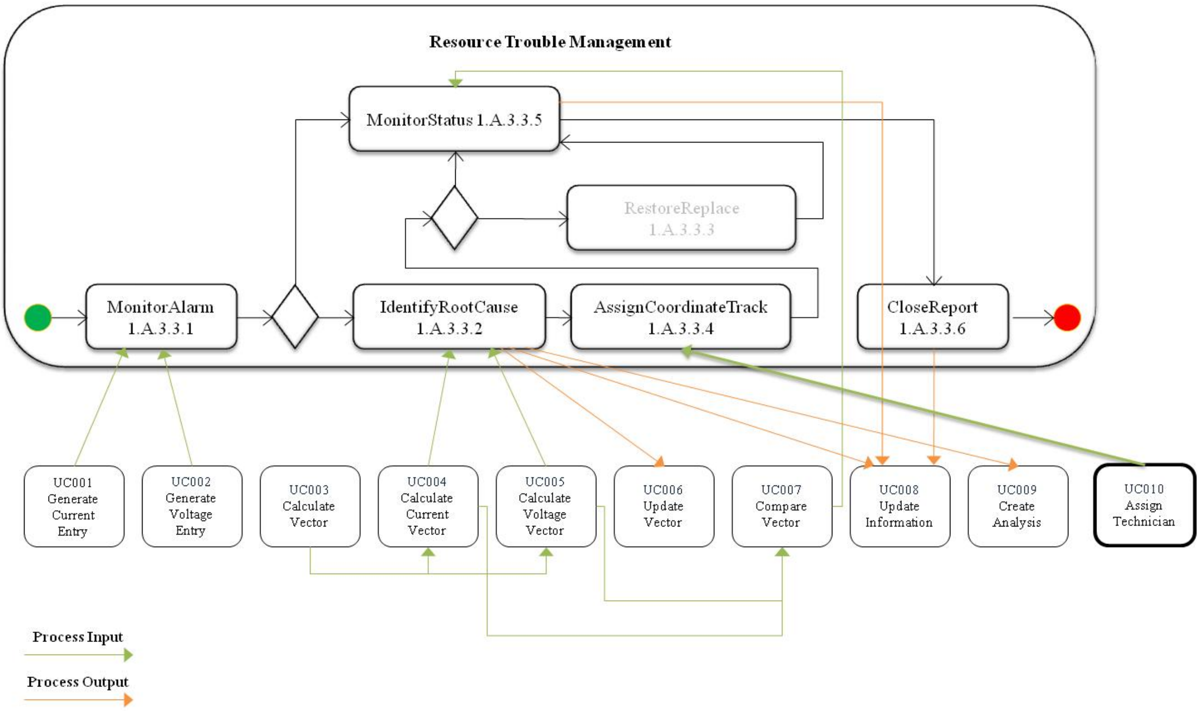

Figure 36 Assign a new use case by enabling an inactive process step in the fault detection process

Figure 37 extends the previous deployment model by including the new *use case 010*. The assignment of a technician to a problem occurs directly after the identification of the root cause. The assignment of a technician is done via the human-computer interface using web service forms that implement *use case 010.*

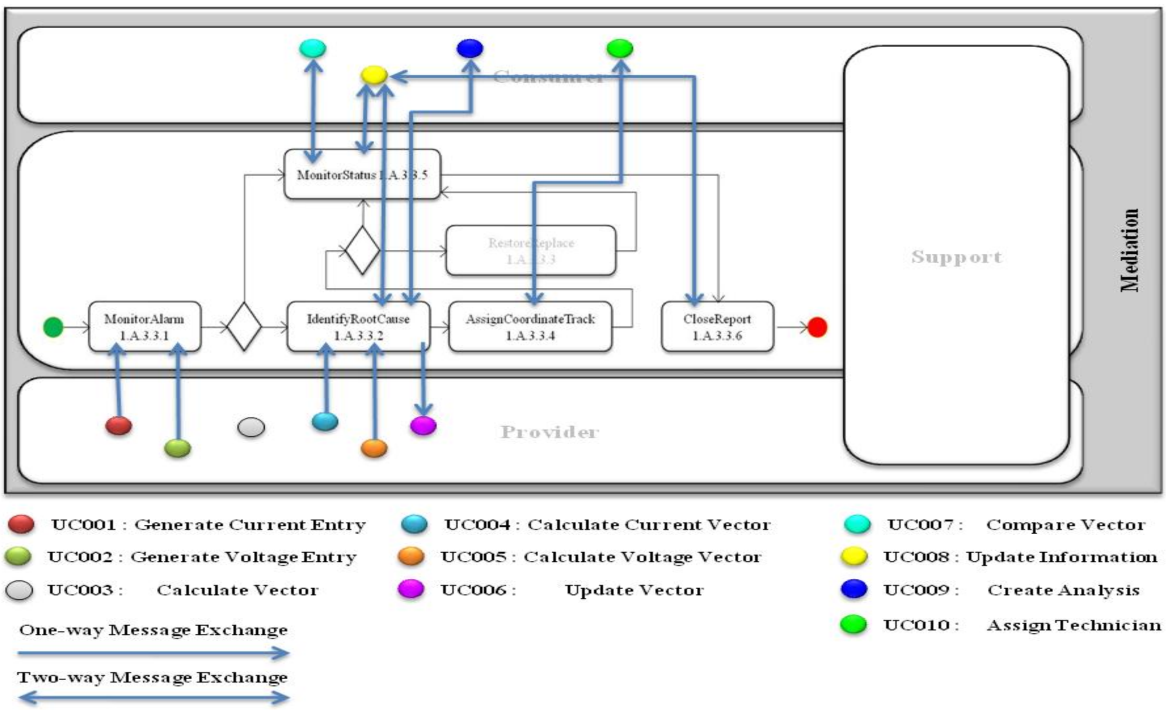

Figure 37 The fault detection service deployment and message exchange model including technician assignment

Figure 38 changes the order of the fault detection activities. The assignment of the technician now takes place before the first decision point. Previously, this process step occurred after the root cause identification step. One reason for changing the order may be to create a work order queue for a technician once the initial process starts. A point to note is that the only item that has changed is the order in which the process executes. This means that the BPM process can be re-compiled and deployed onto the mediation layer. No changes will be made to the web service, its interface or data structure unless the change of process requires new edit text boxes, or drop down status list items be placed on the data entry form. This type of change will require an update to the service interface and data structure.

Figure 38 show that the process step keeps its original process identifier but has shifted after the monitor alarm step and before the first decision point in the process.

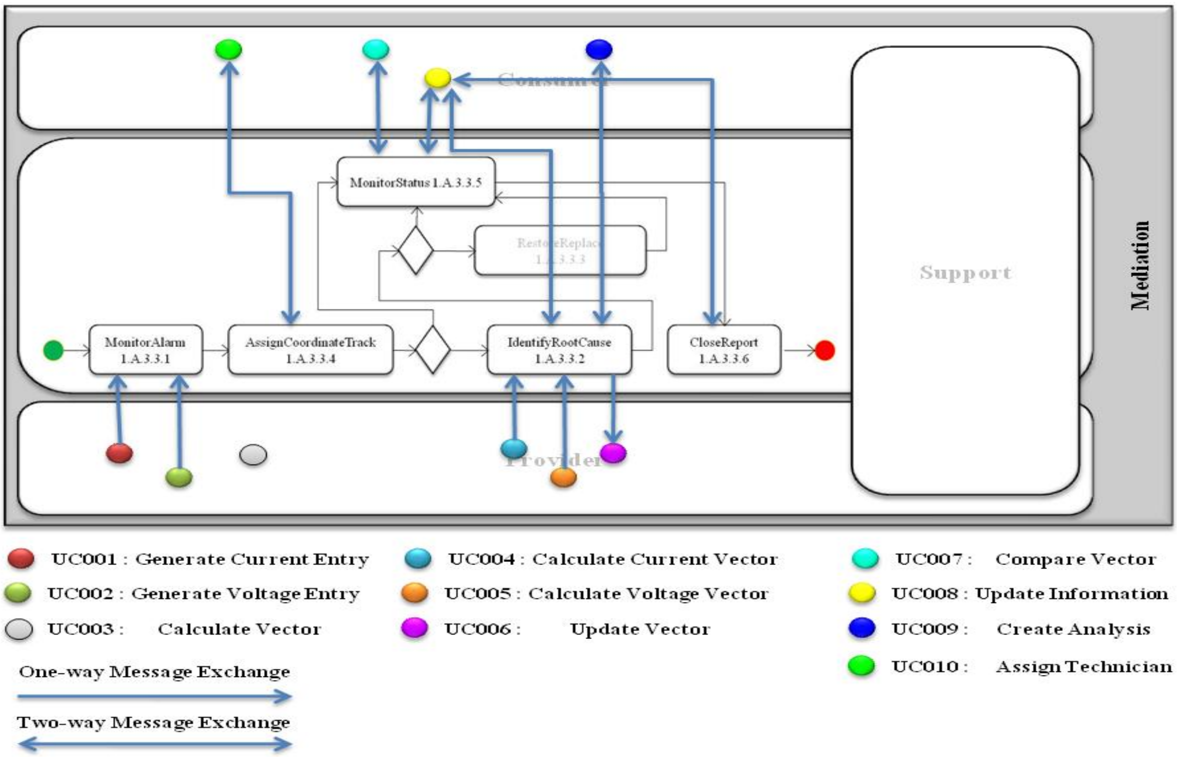

Figure 38 A reordered fault detection process indicating a change to the technician assignment process activity

The final section of this chapter shows a version of the implemented model from a tool perspective. The model is developed in BPMN using an open source business process engine called BonitaOpenSource BPM Version 5.5.1 [56]. The specific data entry page is included for a single process step. The data entry page uses inputs from the AnalogChannel entity from the COMTRADE model [**22**].

Figure 39 indicates the BPMN modelled in a project in the tool. It is not the scope of the dissertation to implement the entire model, but a prototype of a single process step is included for clarity to show that the classification using the process framework works in practise.

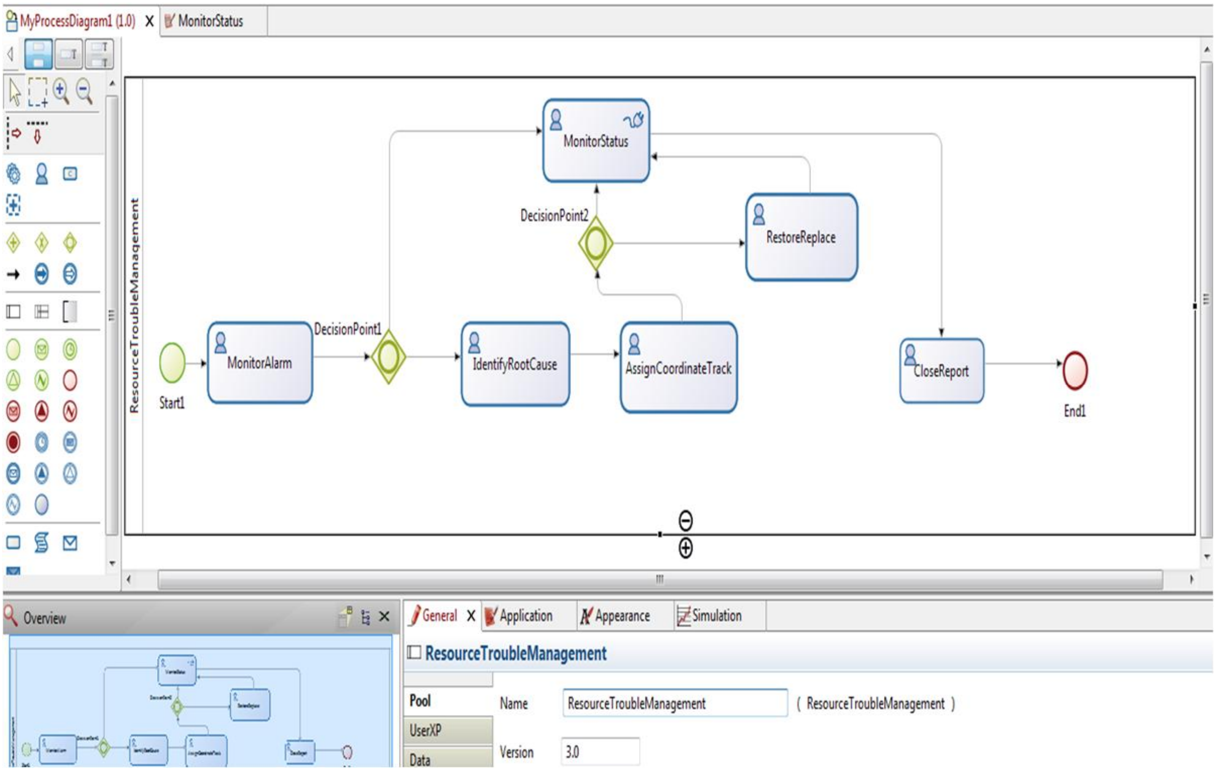

Figure 39 A BPM Tool specific implementation of the fault detection process

Figure 39 shows a tool specific deployment of the process designed in the ***figure 32***. The figure indicates that the process is not complex, however, required complexity can be built into the process using the available components on the tools palette in the left margin of the project workspace. The MonitorStatus process activity contains the appropriate web service connectors indicated by the connector icon in the top right corner of the MonitorStatus process activity. This process activity is links the web service call to the data entry page. ***Figure 40*** indicates the data entry page connected to the process activity via web service. Once the process executes, the data entry page launches in the user's web browser so that the user is able to update data in the COMTRADE format.

The project developed in the BPM tool is exported as a Java archive that is deployed on an application server. This again supports the ability to have a composite application that serves specific functions deployed to multiple application servers across the power system infrastructure. An example where this is useful is by using the information access pattern's deployment strategy indicated in ***figure 11*** *of* ***Chapter 3***.

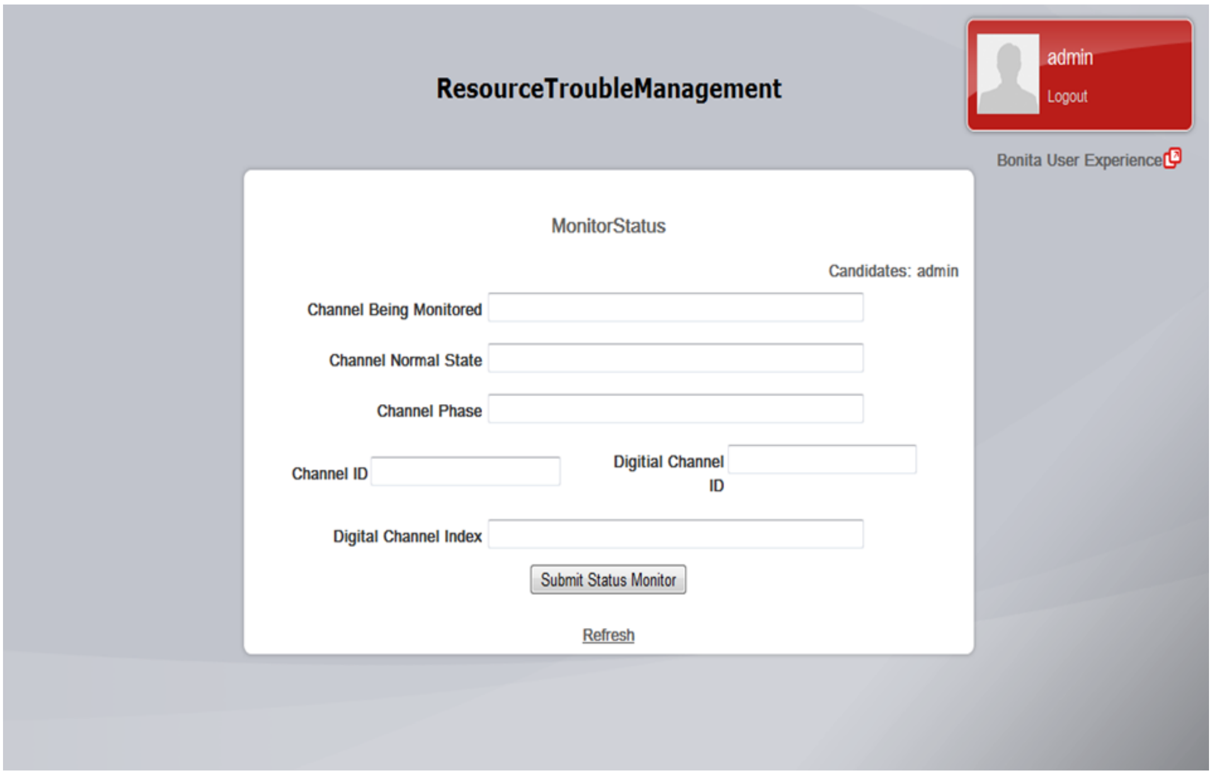

Figure 40 The data entry page of the MonitorStatus process activity

4.10 Conclusion

This chapter focuses on the analysis and design aspects of the service-based fault detection process. The fault detection business process guides the delivery of the artefacts in line with the analysis requirements. The artefacts evolve the requirement from a basic process to a fully documented specification that can be implemented. This enables the ability to frame the final implementation design unambiguously.

The chapter aligns a specific set of process activities to a defined process framework. The modelling process enables the structuring of service components in a composite or atomic nature. The ability to deploy the process in a service bus, controlled by business process controllers provides flexibility to the implementation by ordering and managing atomic functional units. The usage of a reference framework for processes, together with the mapping of the requirements to these processes ensures the linking of service units to their correct service classification. An implementation viewpoint may change some of atomic units by creating more coarse-grained units.

This chapter proves the agility of creating service consumers and providers, and attaching these to the processes and activities composed in the composition layer of the reference architecture. This provides flexibility in ordering process steps and calling services out of the business process layer. It also decouples the deployment of specific services and associated data entry forms for a more flexible application design. The chapter closes using an example of how the BPM process displays a deployed data entry page for updating data in COMTRADE format for a single process activity.

CHAPTER 5
CONCLUSION

The final chapter deals with the interpretation of the design approach used in the previous chapters of this dissertation. The chapter also proposes future research areas.

5.1 Closing Remarks

Availability of correct information at the right time has been a challenge for most organisations. Users encounter many obstacles when trying to source data to create meaningful analysis. Sizing, frequency and quality of data are always a problem. The application design proposed in this dissertation provides a clearer view of the collection, storage and access mechanisms of substation data. The service deployment model used in this dissertation enables a flexible means for changing user requirements and adapting to evolving standards. The procedures for changing from legacy to modern architectures use a functional approach to define the scope of delivery. New requirements are implemented using new architectures that slowly decrease the dependency on non-open standard legacy systems.

Standardisation is part of an organisational change process that can steer the organisation into a different direction. A strategy that that focuses on visibility and transparency in operations is needed if the organisation aims to attract more consumers. Information architectures in substations are important and vital for expansion and integration of technologies. This is the case for analogue information exchange or as the wave of electronic devices grows and digital substation information becomes more accessible. The exchange of this information, no matter which transmission medium, requires high levels of quality, reliability and integrity. There is a fine balance between content and format. This dissertation produces an approach that exposes information that is context driven and can be used by the necessary persons or systems without being concerned about the underlaying architecture.

A model driven approach to the holistic redesign of substation architecture will take some time, however steps are needed to safeguard from creating legacy that is hard to decouple from in future. The fault detection process is one of many operational processes that offer value in exposing accurate information to stakeholders on the state of the power system. Consideration of which events are exposed is necessary as the volume information can become overwhelming. A correct reporting and notification architecture to consumers and other utility personnel should leverage off service-based architecture to ensure maximum agility.

With the explosion of information and industry trying to find more cost effective ways of operating, a new wave of engineers, skilled in areas of renewable energy, telecommunications, and software engineering are required to move the energy industry into a direction that will bring about a change in how energy assets are managed and protected.

5.2 Future Work

The problems encountered with substation data integration requires that more holistic integrity requirements are placed on data. Data quality focuses on the reliability of data either persisted in a database, or transported within a service based architecture. Further work is required to test and deliver the standards that support collection, storage and access of data.

Standards support the creation of application design that aids more efficient integration activities between previously unrelated processes and information. The selected TM Forum, IEC and IEEE standards inform the development of applications that play in both energy and telecommunications sectors. As more systems are required to integrate, a larger wave of alignment efforts will continue to challenge industry vertical models. Future work will focus on end-to-end process mapping using established process frameworks for aligning energy and telecommunications models. Process architectures not only positions reengineering efforts but also stronger coverage on smart grid analytics. Currently no analytics standards exist for smart grid in this area [**2**]. The aim should be to harmonise at a message exchange level rather than entity definitions to generate dynamic model transformations using XML based technologies to create consistent and reusable analytic models.

The information needed for wide area monitoring of power systems should focus on robust data modelling and placement of data to meet the needs of specific information users. A larger number of information providers in form the IEDs mean that there is a need to certify the data being used for operational purposes. More effective control checks results in larger processing overhead for device data. The NIST indicate that distributed clustering of data in parallel processed environments like Apache HADOOP is a possibility [**2**]

Software engineering is an important mechanism in the delivery of sustainable applications. The discipline will continue to grow and evolve constantly changing tools, methods, approaches used in the software delivery process. The implementation of key object-oriented concepts are challenged and updated to reflect more effective and efficient engineering of systems. Model based design from analysis to deployment allows traceability of requirements. This increases the confidence in software delivered to meet the needs of users. Future work in this area will allow forward and reverse model to code generation processes for power system software that will further support model driven architecture and design.

In order to move data effectively across communication networks they need to support reliability and redundant information requirements. Information gathered from IEDs delivered over public and private network infrastructures are vital for power system asset management. The area of substation information integration focuses on the creation of preferred patterns for information collection, storage and access. The measurement of the effectiveness of the implemented patterns that this dissertation proposes is a key area of research. Future activity must be in the study of optimisation methods for collection, storage and access patterns of power system information.

Cyber security, although not covered in this dissertation, is another area that offers a vast research possibility. With the volumes of information and untapped analysis possibilities, requirements for information exchange are important as the analysis of energy usage patterns provides the ability to exploit vulnerabilities in the power grid. As power grid control grows, cyber security demand will grow due to an increase in exposure at key interconnection points.

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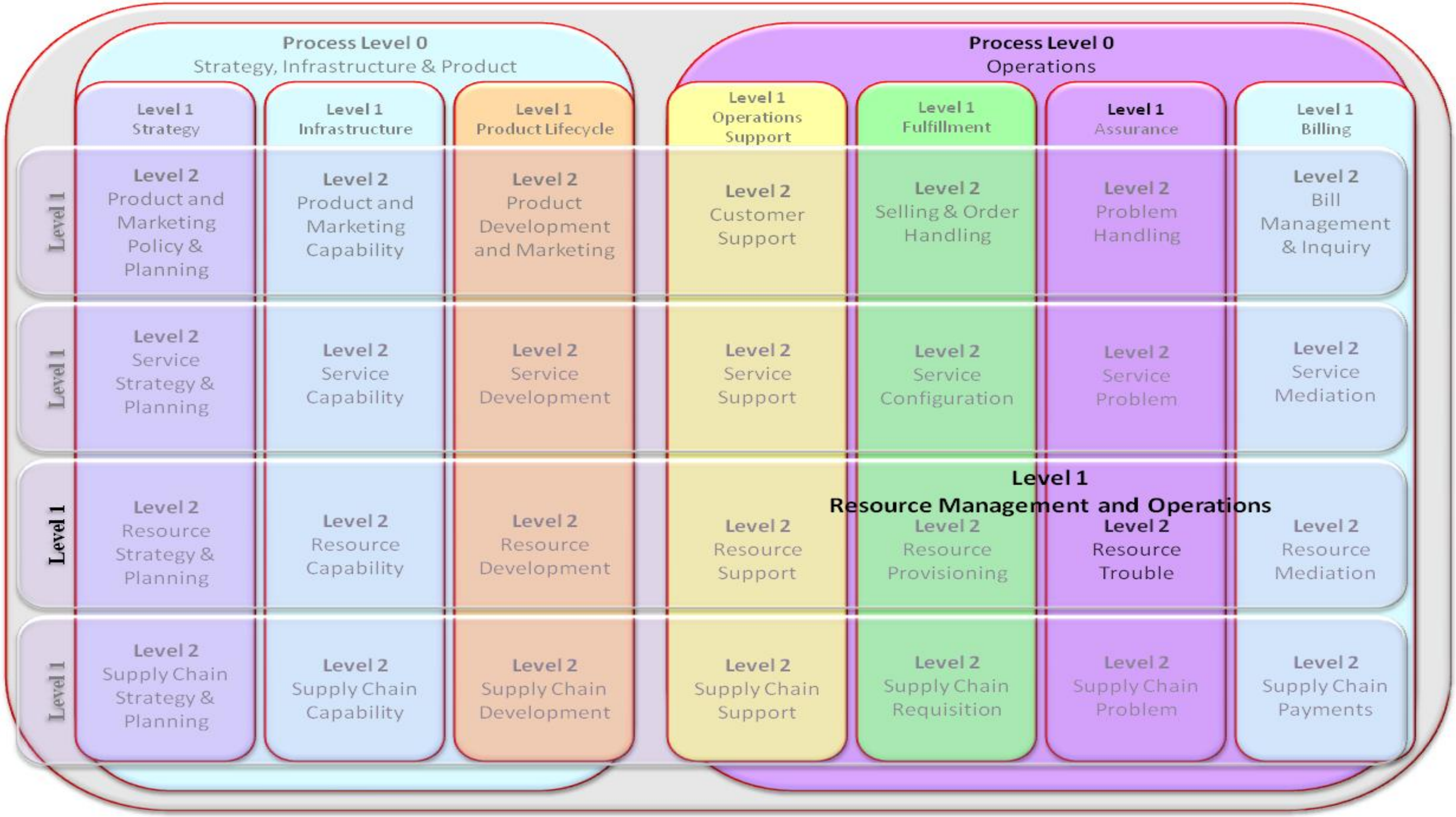
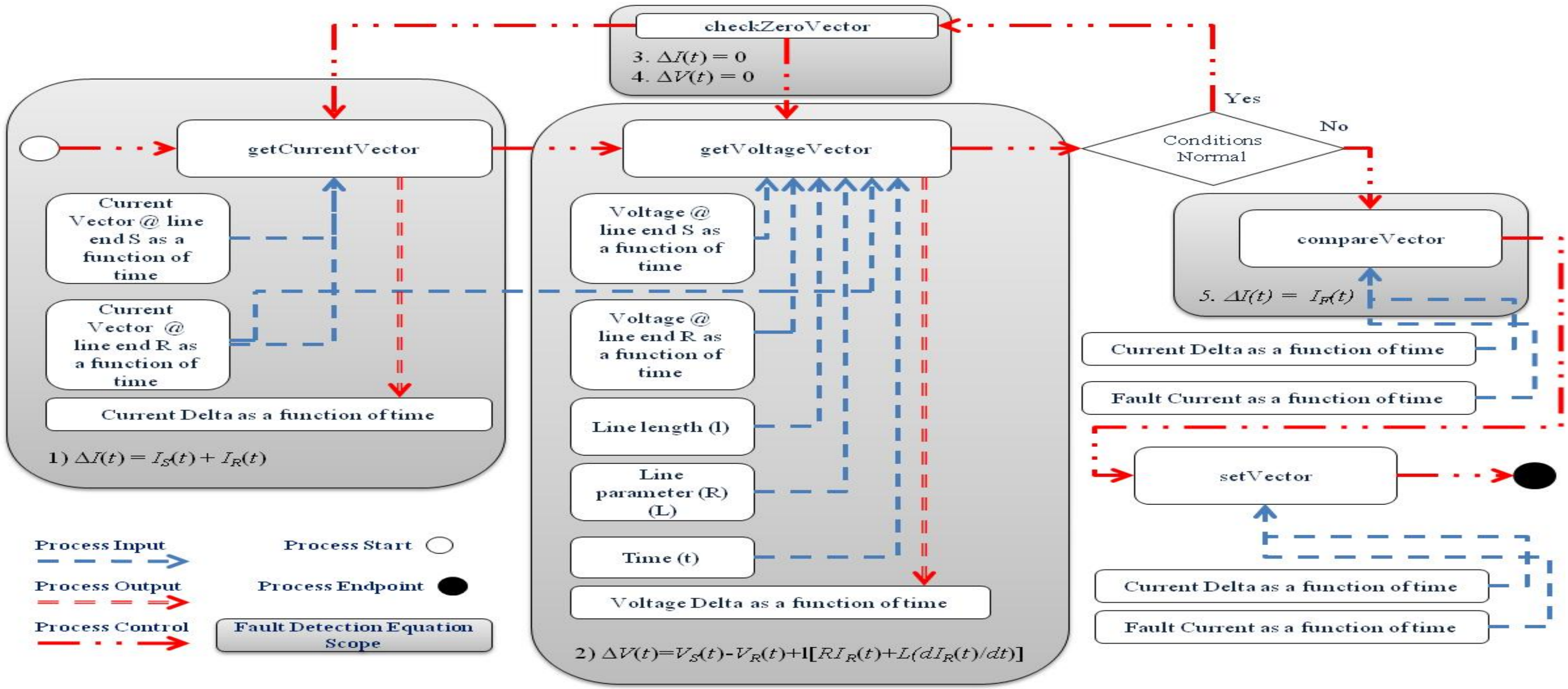
Appendix A A process coverage map indicating the process classification for fault detection web services. Source AMDOCS Online Posters [13]



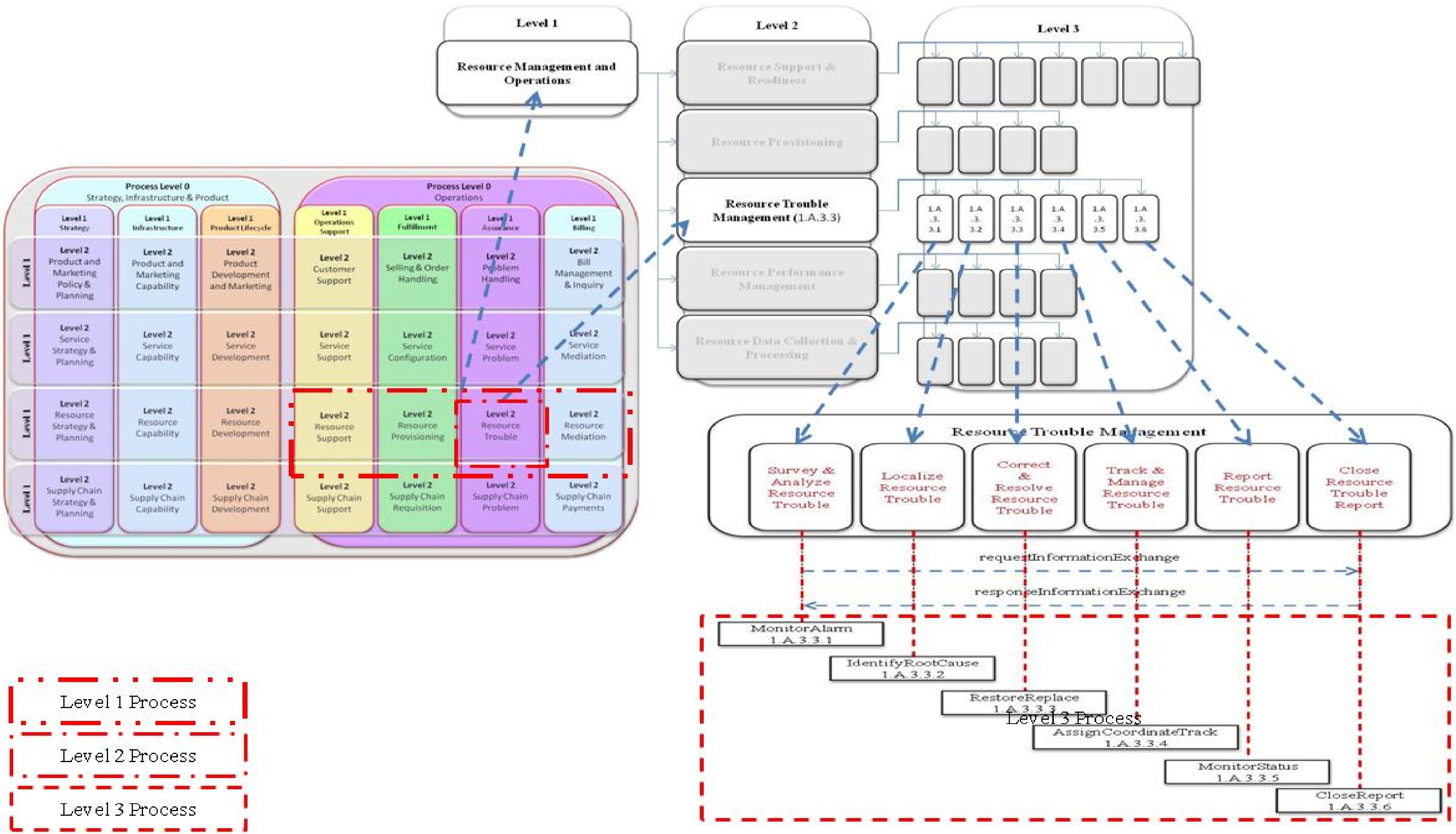
Appendix B A BPM representation of fault detection web services. Source Detection equations (1) to (5) [53]



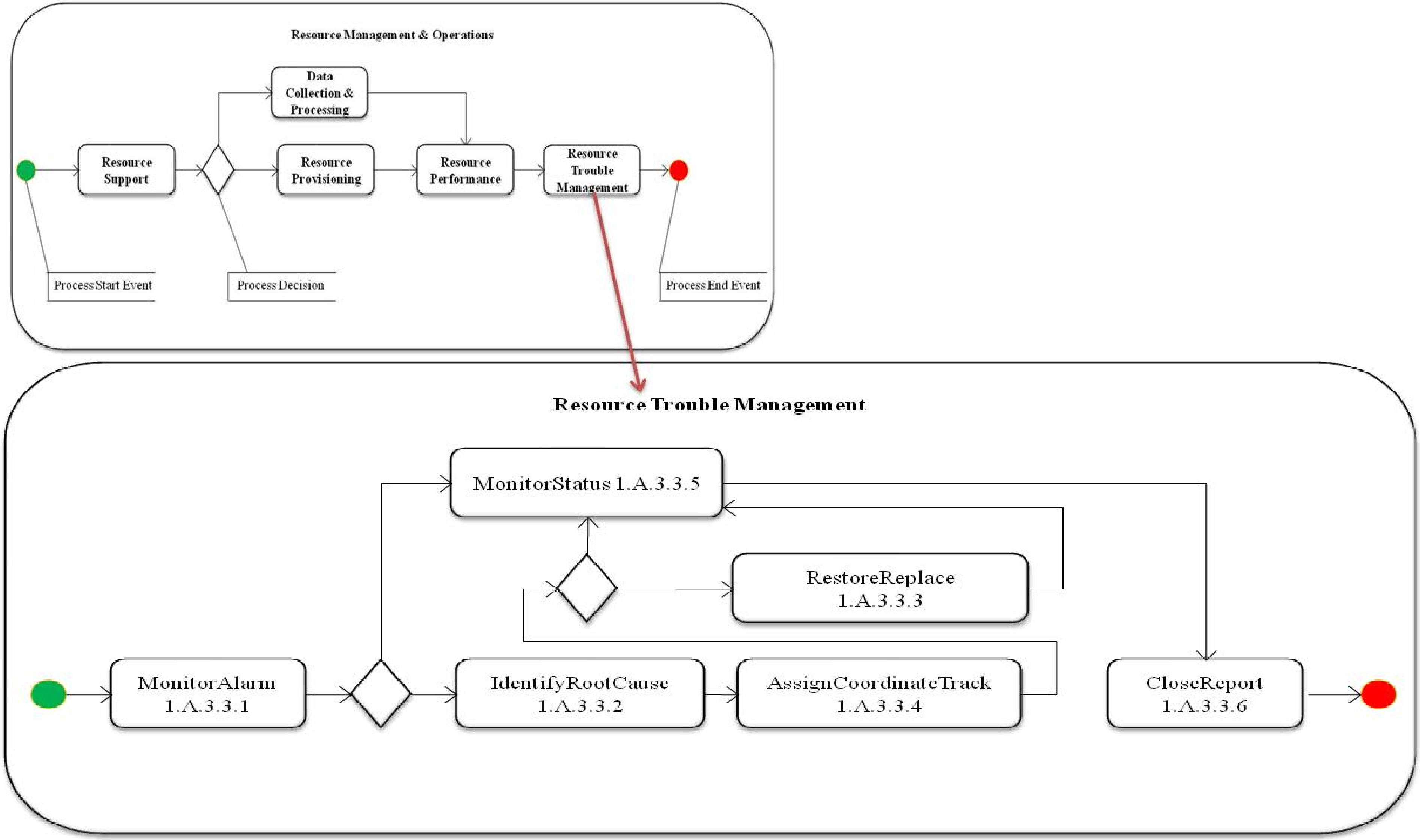
BPM Process Activity	Fault Detection Equation	Equation ID
getCurrentVector	$\Delta I(t) = I_S(t) + I_R(t)$	1
getVoltageVector	$\Delta V(t) = V_S(t) - V_R(t) + l\,[RI_R(t) + L(dI_R(t) / dt\,)]$	2
checkZeroVector	$\Delta I(t) = 0,\ \Delta V(t) = 0$	3,4
compareVector	$\Delta I(t) = \ I_F(t)$	5

Variable Description
VS(t), VR(t) - Vectors of Phase Voltages at line end S and R respectively
IS(t), IR(t), IF(t) - Vectors of Phase Currents at line end S, R, at fault respectively
l – Length of transmission line
R, L – Self and Mutual line parameters

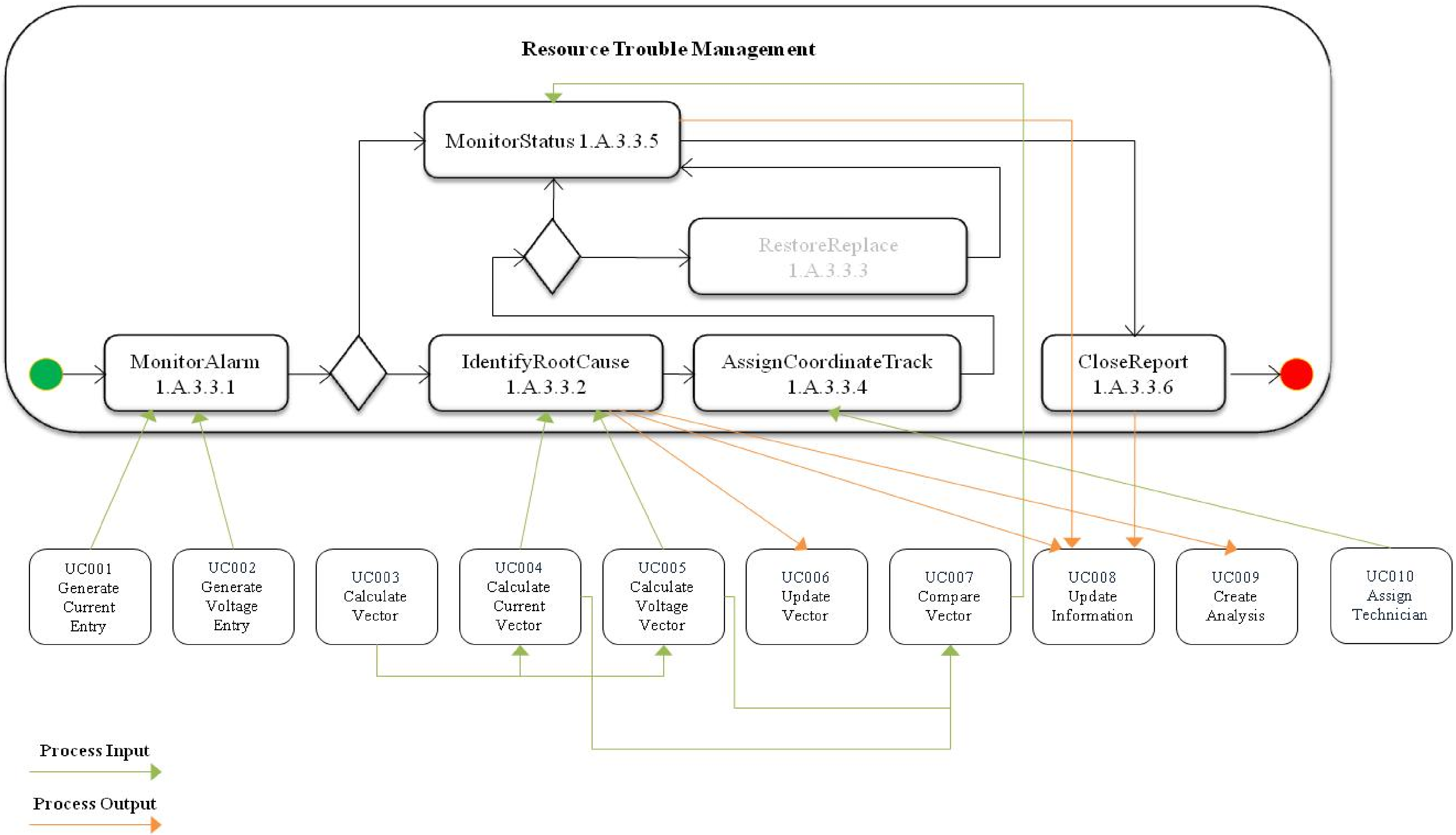
Appendix C A process hierarchy and decomposition to support fault detection web services. Source Resource Trouble Management decomposition into level 3 processes [36]



Appendix D A standardized BPM fault detection process for level 1 to level 3 process flows



Appendix E Fault detection use cases derived from detection equations integrated into a standardized BPM fault detection process



Appendix F A physical deployment view of the BPM process on a service reference architecture for fault detection web services and use cases